Chapter 1: Framing and Context

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Executive Summary

This chapter frames the context, knowledge-base and assessment approaches used to understand the impacts of 1.5°C global warming above pre-industrial levels and related global greenhouse gas emission pathways, building on the IPCC Fifth Assessment Report (AR5), in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty.

Human-induced warming reached approximately 1°C (±0.2°C *likely* range) above pre-industrial levels in 2017, increasing at 0.2°C (±0.1°C) per decade (*high confidence*). Global warming is defined in this report as an increase in combined surface air and sea surface temperatures averaged over the globe and a 30-year period. Unless otherwise specified, warming is expressed relative to the period 1850-1900, used as an approximation of pre-industrial temperatures in AR5. For periods shorter than 30 years, warming refers to the estimated average temperature over the 30 years centered on that shorter period, accounting for the impact of any temperature fluctuations or trend within those 30 years. Accordingly, warming up to the decade 2006-2015 is assessed at 0.87°C (±0.12°C *likely* range). Since 2000, the estimated level of human-induced warming has been equal to the level of observed warming with a *likely* range of ±20% accounting for uncertainty due to contributions from solar and volcanic activity over the historical period (*high confidence*). {1.2.1}

Warming greater than the global average has already been experienced in many regions and seasons, with average warming over land higher than over the ocean (*high confidence*). Most land regions are experiencing greater warming than the global average, while most ocean regions are warming at a slower rate. Depending on the temperature dataset considered, 20-40% of the global human population live in regions that, by the decade 2006-2015, had already experienced warming of more than 1.5°C above pre-industrial in at least one season (*medium confidence*). {1.2.1 & 1.2.2}

Past emissions alone are *unlikely* to raise global-mean temperature to 1.5°C above pre-industrial levels but past emissions do commit to other changes, such as further sea level rise (*high confidence*)**.** If all anthropogenic emissions (including aerosol-related) were reduced to zero immediately, any further warming beyond the 1°C already experienced would *likely* be less than 0.5°C over the next two to three decades (*high confidence*), and *likely* less than 0.5°C on a century timescale (*medium confidence*), due to the opposing effects of different climate processes and drivers. A warming greater than 1.5°C is therefore not geophysically unavoidable: whether it will occur depends on future rates of emission reductions. {1.2.3, 1.2.4}

1.5°C-consistent emission pathways are defined as those that, given current knowledge of the climate response, provide a one-in-two to two-in-three chance of warming either remaining below 1.5°C, or returning to 1.5°C by around 2100 following an overshoot. Overshoot pathways are characterized by the peak magnitude of the overshoot, which may have implications for impacts. All 1.5°C-consistent pathways involve limiting cumulative emissions of long-lived greenhouse gases, including carbon dioxide and nitrous oxide, and substantial reductions in other climate forcers (*high confidence*). Limiting cumulative emissions requires either reducing net global emissions of long-lived greenhouse gases to zero before the cumulative limit is reached, or net negative global emissions (anthropogenic removals) after the limit is exceeded. {1.2.3, 1.2.4, Cross-Chapter Boxes 1 and 2}

This report assesses projected impacts at a global average warming of 1.5°C and higher levels of warming. Global warming of 1.5°C is associated with global average surface temperatures fluctuating naturally on either side of 1.5°C, together with warming substantially greater than 1.5°C in many regions and seasons (*high confidence*), all of which must be taken into account in the assessment of impacts. Impacts at 1.5°C of warming also depend on the emission pathway to 1.5°C. Very different impacts result from pathways that remain below 1.5°C versus pathways that return to

1.5°C after a substantial overshoot, and when temperatures stabilize at 1.5°C versus a transient warming past 1.5°C. (*medium confidence*) {1.2.3, 1.3}

Ethical considerations, and the principle of equity in particular, are central to this report, recognising that many of the impacts of warming up to and beyond 1.5°C, and some potential impacts of mitigation actions required to limit warming to 1.5°C, fall disproportionately on the poor and vulnerable (*high confidence*). Equity has procedural and distributive dimensions and requires fairness in burden sharing, between generations, and between and within nations. In framing the objective of holding the increase in the global average temperature rise to well below 2°C above pre-industrial levels, and to pursue efforts to limit warming to 1.5°C, the Paris Agreement associates the principle of equity with the broader goals of poverty eradication and sustainable development, recognising that effective responses to climate change require a global collective effort that may be guided by the 2015 United Nations Sustainable Development Goals. {1.1.1}

Climate adaptation refers to the actions taken to manage impacts of climate change by reducing vulnerability and exposure to its harmful effects and exploiting any potential benefits. Adaptation takes place at international, national and local levels. Subnational jurisdictions and entities, including urban and rural municipalities, are key to developing and reinforcing measures for reducing weather- and climate-related risks. Adaptation implementation faces several barriers including unavailability of up-to-date and locally-relevant information, lack of finance and technology, social values and attitudes, and institutional constraints (*high confidence*). Adaptation is more likely to contribute to sustainable development when polices align with mitigation and poverty eradication goals (*medium confidence*) {1.1, 1.4}

Ambitious mitigation actions are indispensable to limit warming to 1.5°C while achieving sustainable development and poverty eradication (*high confidence*). Ill-designed responses, however, could pose challenges especially—but not exclusively—for countries and regions contending with poverty and those requiring significant transformation of their energy systems. This report focuses on 'climate-resilient development pathways' , which aim to meet the goals of sustainable development, including climate adaptation and mitigation, poverty eradication and reducing inequalities. But any feasible pathway that remains within 1.5°C involves synergies and trade-offs (*high confidence*). Significant uncertainty remains as to which pathways are more consistent with the principle of equity. {1.1.1, 1.4}

Multiple forms of knowledge, including scientific evidence, narrative scenarios and prospective pathways, inform the understanding of 1.5°C. This report is informed by traditional evidence of the physical climate system and associated impacts and vulnerabilities of climate change, together with knowledge drawn from the perceptions of risk and the experiences of climate impacts and governance systems. Scenarios and pathways are used to explore conditions enabling goal-oriented futures while recognizing the significance of ethical considerations, the principle of equity, and the societal transformation needed. {1.2.3, 1.5.2}

There is no single answer to the question of whether it is feasible to limit warming to 1.5°C and adapt to the consequences. Feasibility is considered in this report as the capacity of a system as a whole to achieve a specific outcome. The global transformation that would be needed to limit warming to 1.5°C requires enabling conditions that reflect the links, synergies and trade-offs between mitigation, adaptation and sustainable development. These enabling conditions have many systemic dimensions—geophysical, environmental-ecological, technological, economic, socio-cultural and institutional—that may be considered through the unifying lens of the Anthropocene, acknowledging profound, differential but increasingly geologically significant human influences on the Earth system as a whole. This framing also emphasises the global interconnectivity of past, present and future human–environment relations, highlighing the need and opportunities for integrated responses to achieve the goals of the Paris Agreement. {1.1, Cross-Chapter Box 1}

1.1 Assessing the knowledge base for a 1.5°C warmer world

Human influence on climate has been the dominant cause of observed warming since the mid-20th century, while global average surface temperature warmed by 0.85°C between 1880 and 2012, as reported in the IPCC Fifth Assessment Report, or AR5 (IPCC, 2013b). Many regions of the world have already experienced greater regional-scale warming, with 20-40% of the global population (depending on the temperature dataset used) having experienced over 1.5°C of warming in at least one season (Figure 1.1 and Chapter 3 Section 3.3). Temperature rise to date has already resulted in profound alterations to human and natural systems, bringing increases in some types of extreme weather, droughts, floods, sea level rise and biodiversity loss, and causing unprecedented risks to vulnerable persons and populations (IPCC, 2012a, 2014b; Mysiak et al., 2016), Chapter 3 Section 3.4). The most affected people live in low and middle income countries, some of which have already experienced a decline in food security, linked in turn to rising migration and poverty (IPCC, 2012a). Small islands, megacities, coastal regions and high mountain ranges are likewise among the most affected (Albert et al., 2017). Worldwide, numerous ecosystems are at risk of severe impacts, particularly warm-water tropical reefs and Arctic ecosystems (IPCC, 2014d).

This report assesses current knowledge of the environmental, technical, economic, financial, socio-cultural, and institutional dimensions of a 1.5°C warmer world (meaning, unless otherwise specified, a world in which warming has been limited to 1.5°C relative to pre-industrial levels). Differences in vulnerability and exposure arise from numerous non-climatic factors (IPCC, 2014b). Global economic growth has been accompanied by increased life expectancy and income in much of the world - but in addition to environmental degradation and pollution, many regions remain characterised by significant poverty, severe inequity in income distribution and access to resources, amplifying vulnerability to climate change (Dryzek, 2016; Pattberg and Zelli, 2016; Bäckstrand et al., 2017; Lövbrand et al., 2017). World population continues to rise, notably in hazard-prone small and medium-sized cities in low- and moderate-income countries (Birkmann et al., 2016). The spread of fossil-fuel-based material consumption and changing lifestyles is a major driver of global resource use, and the main contributor to rising greenhouse gas (GHG) emissions (Fleurbaey et al., 2014).

The overarching context of this report is this: human influence has become a principal agent of change on the planet, shifting the world out of the relatively stable Holocene period into a new geological era, often termed the Anthropocene (Box 1.1). Responding to climate change in the Anthropocene will require approaches that integrate multiple levels of inter-connectivity across the global community.

This chapter is composed of seven sections linked to the remaining four chapters of the report. The introductory section 1.1 situates the basic elements of the assessment within the context of sustainable development, considerations of ethics, equity and human rights, and their link to poverty. Section 1.2 focuses on understanding 1.5°C, global versus regional warming, 1.5°C–consistent pathways and associated emissions. Section 1.3 frames the impacts at 1.5°C and beyond on natural and human systems. The section on strengthening the global response (1.4) frames different responses, governance and implementation, and trade-offs and synergies between mitigation, adaptation and the Sustainable Development Goals (SDGs) under transformation, transformation pathways, and transition. Section 1.5 provides assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development. Section 1.6 defines approaches used to communicate confidence, uncertainty and risk, while 1.7 presents the storyline of the whole report.

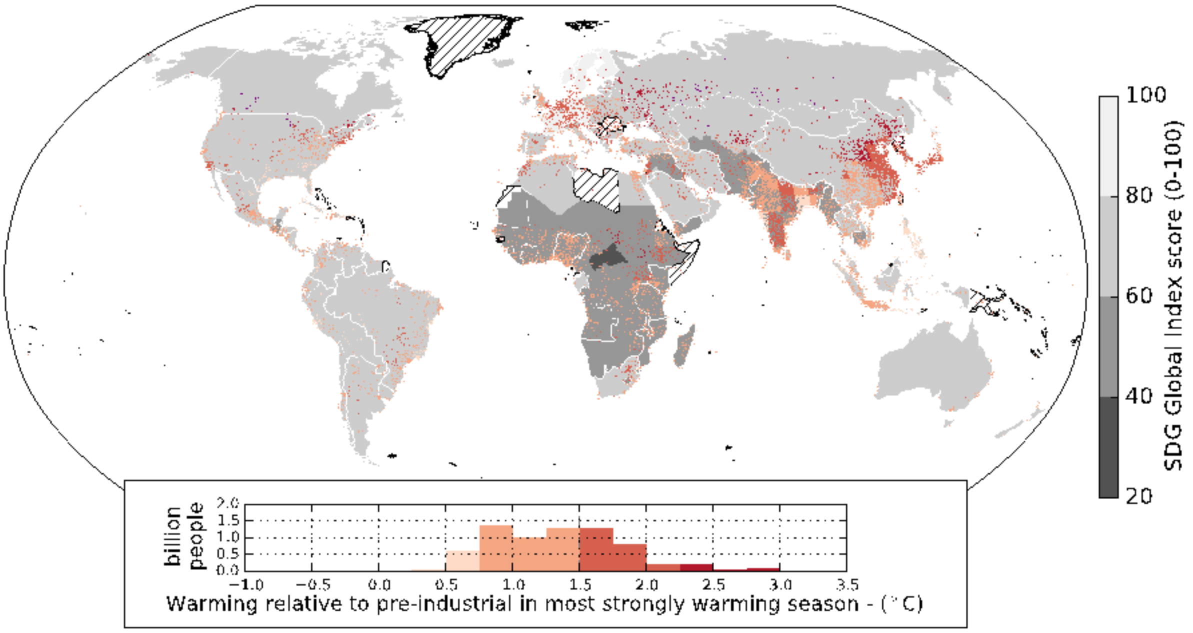

Figure 1.1: **Human experience of present–day warming.** Colours indicated by the inset histogram show estimated warming for the season that has warmed the most at a given location between the periods 1850-1900 and 2006–2015, during which global average temperatures rose by 0.91°C in this dataset (Cowtan and Way, 2014), and 0.87°C in the multi-dataset average (Table 1.1 and Figure 1.3). The density of dots indicates the population (in 2010) in any 1°x1° grid box. The underlay shows national SDG Global Index Scores indicating performance across the 17 Sustainable Development Goals. Hatching indicates missing SDG index data (e.g., Greenland). The histogram shows the number of people of the 2010 global population living in regions experiencing different levels of warming (at 0.25°C increments). See Technical Annex 1.A for further details.

Box 1.1: The Anthropocene: Strengthening the global response to 1.5°C global warming

Introduction

The concept of the Anthropocene can be linked to the aspiration of the Paris Agreement. The abundant empirical evidence of the unprecedented rate and global scale of impact of human influence on the Earth System (Steffen et al., 2016; Waters et al., 2016) has led many scientists to call for an acknowledgement that the Earth has entered a new geological epoch: the Anthropocene (Crutzen and Stoermer, 2000; Crutzen, 2002; Gradstein et al., 2012). Although rates of change in the Anthropocene are necessarily assessed over much shorter periods than those used to calculate long-term baseline rates of change, and therefore present challenges for direct comparison, they are nevertheless striking. The rise in global CO_2 concentration since 2000 is about 20 ppm/decade, which is up to 10 times faster than any sustained rise in CO_2 during the past 800,000 years (Lüthi et al., 2008; Bereiter et al., 2015). AR5 found that the last geological epoch with similar atmospheric CO_2 concentration was the Pliocene, 3.3 to 3.0 Ma (Masson-Delmotte et al., 2013). Since 1970 the global average temperature has been rising at a rate of 1.7°C per century, compared to a long-term decline over the past 7,000 years at a baseline rate of 0.01°C per century (NOAA 2016, Marcott et al. 2013). These global-level rates of human-driven change far exceed the rates of change driven by geophysical or biosphere forces that have altered the Earth System trajectory in the past (e.g., Summerhayes 2015; Foster et al. 2017); even abrupt geophysical events do not approach current rates of human-driven change.

The geological dimension of the Anthropocene and 1.5°C global warming

The process of formalising the Anthropocene is on-going (Zalasiewicz et al., 2017), but a strong majority of the Anthropocene Working Group (AWG) established by the Sub–Committee on Quaternary Stratigraphy of the International Commission on Stratigraphy have agreed that: (i) the Anthropocene has a geological merit; (ii) it should follow the Holocene as a formal epoch in the Geological Time Scale; and, that (iii) its onset should be defined as the mid–20th century. Potential markers in the stratigraphic record include an array of novel manufactured materials of human origin, and "these combined signals render the Anthropocene stratigraphically distinct from the Holocene and earlier epochs" (Waters et al., 2016). The Holocene period, which itself was formally adopted in 1885 by geological science community, began 11,700 years ago with a more stable warm climate providing for emergence of human civilisation and growing human-nature interactions that have expanded to give rise to the Anthropocene (Waters et al., 2016).

The Anthropocene and the Challenge of a 1.5° C warmer world

The Anthropocene can be employed as a "boundary concept" (Brondizio et al., 2016) that frames critical insights into understanding the drivers, dynamics and specific challenges in responding to the ambition of keeping global temperature well below 2°C while pursuing efforts towards and adapting to a 1.5°C warmer world. The UNFCCC and its Paris Accord recognize the ability of humans to influence geophysical planetary processes (Chapter 2, Cross-Chapter Box 1 in this Chapter). The Anthropocene offers a structured understanding of the culmination of past and present human–environmental relations and provides an opportunity to better visualize the future to minimize pitfalls (Pattberg and Zelli, 2016; Delanty and Mota, 2017), while acknowledging the differentiated responsibility and opportunity to limit global warming and invest in prospects for climate-resilient sustainable development (Harrington, 2016) (Chapter 5). The Anthropocene also provides an opportunity to raise questions regarding the regional differences, social inequities and uneven capacities and drivers of global social–environmental changes, which in turn inform the search for solutions as explored in Chapter 4 of this report (Biermann et al., 2016). It links uneven influences of human actions on planetary functions to an uneven distribution of impacts (assessed in Chapter 3) as well as the responsibility and response capacity to for example, limiting global warming to no more than a 1.5°C rise above pre–industrial levels. Efforts to curtail greenhouse gas emissions without incorporating the intrinsic interconnectivity and disparities associated with the Anthropocene world may themselves negatively affect the development ambitions of some regions more than others and negate sustainable development efforts (see Chapter 2 and Chapter 5).

1.1.1 Equity and a 1.5°C warmer world

The AR5 suggested that equity, sustainable development, and poverty eradication are best understood as mutually supportive and co-achievable within the context of climate action, and are underpinned by various other international hard and soft law instruments (Denton et al., 2014; Fleurbaey et al., 2014; Klein et al., 2014; Olsson et al., 2014; Porter et al., 2014; Stavins et al., 2014). The aim of the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) to 'pursue efforts to limit' the rise in global temperatures to 1.5°C above pre-industrial levels raises ethical concerns that have long been central to climate debates (Fleurbaey et al., 2014; Kolstad et al., 2014). The Paris Agreement makes particular reference to the principle of equity, within the context of broader international goals of sustainable development and poverty eradication. Equity is a long-standing principle within international law and climate change law in particular (Dinah, 2008; Bodansky et al., 2017).

The AR5 describes equity as having three dimensions: intergenerational (fairness between generations), international (fairness between states), and national (fairness between individuals) (Fleurbaey et al., 2014). The principle is generally agreed to involve both procedural justice (i.e.

participation in decision making) and distributive justice (i.e. how the costs and benefits of climate actions are distributed) (Kolstad et al., 2014; Savaresi, 2016; Reckien et al., 2017). Concerns regarding equity have frequently been central to debates around mitigation, adaptation and climate governance (Caney, 2005; Schroeder et al., 2012; Ajibade, 2016; Reckien et al., 2017; Shue, 2018). Hence, equity provides a framework for understanding the asymmetries between the distributions of benefits and costs relevant to climate action (Schleussner et al., 2016; Aaheim et al., 2017).

Four key framing asymmetries associated with the conditions of 1.5°C warmer world have been noted (Okereke, 2010; Harlan et al., 2015; Ajibade, 2016; Savaresi, 2016; Reckien et al., 2017) and are reflected in the report's assessment. The first concerns differential contributions to the problem: the observation that the benefits from industrialization have been unevenly distributed and those who benefited most historically also have contributed most to the current climate problem and so bear greater responsibility (Shue, 2013; Otto et al., 2017; Skeie et al., 2017). The second asymmetry concerns differential impact: the worst impacts tend to fall on those least responsible for the problem, within states, between states, and between generations (Fleurbaey et al., 2014; Shue, 2014; Ionesco et al., 2016). The third is the asymmetry in capacity to shape solutions and response strategies, such that the worst-affected states, groups and individuals are not always well-represented (Robinson and Shine, 2018). Fourth, there is an asymmetry in future response capacity: some states, groups and places are at risk of being left behind as the world progresses to a low-carbon economy (Fleurbaey et al., 2014; Shue, 2014; Humphreys, 2017).

A sizeable and growing literature exists on how best to operationalize climate equity considerations, drawing on other concepts mentioned in the Paris Agreement, notably its explicit reference to human rights (OHCHR, 2009; Caney, 2010; Adger et al., 2014; Fleurbaey et al., 2014; IBA, 2014; Knox, 2015; Duyck et al., 2018; Robinson and Shine, 2018). Human rights comprise internationally agreed norms that align with the Paris ambitions of poverty eradication, sustainable development and the reduction of vulnerability (Caney, 2010; Fleurbaey et al., 2014; OHCHR, 2015). In addition to defining substantive rights (such as to life, health and shelter) and procedural rights (such as to information and participation), human rights instruments prioritise the rights of marginalised, children, vulnerable and indigenous persons, and those discriminated against on grounds such as gender, race, age or disability (OHCHR, 2017). Several international human rights obligations that are relevant to the implementation of climate actions and consonant with UNFCCC undertakings in the areas of mitigation, adaptation, finance, and technology transfer (Knox, 2015; OHCHR, 2015; Humphreys, 2017).

Much of this literature is still new and evolving (Holz et al., 2017; Dooley et al., 2018; Klinsky and Winkler, 2018), permitting the present report to examine some broader equity concerns raised both by possible failure to limit warming to 1.5°C and by the range of ambitious mitigation efforts that may be undertaken to achieve that limit. Any comparison between 1.5°C and higher levels of warming implies risk assessments and value judgements, and cannot straightforwardly be reduced to a cost-benefit analysis (Kolstad et al., 2014). However, different levels of warming can nevertheless be understood in terms of their different implications for equity – that is, in the comparative distribution of benefits and burdens for specific states, persons or generations, and in terms of their likely impacts on sustainable development and poverty (see especially sections 2.2.2.3, 2.3.3.1, 3.4.5-3.4.11, 3.6, 5.4.1, 5.4.2, 5.6 and Cross-Chapter boxes 6 in Chapter 3 and 12 in Chapter 5).

1.1.2 Eradication of poverty

This report assesses the role of poverty and its eradication in the context of strengthening the global response to the threat of climate change and sustainable development. A wide range of definitions for *poverty* exist. The AR5 discussed 'poverty' in terms of its multidimensionality, referring to 'material circumstances' (e.g. needs, patterns of deprivation, or limited resources), as well as to economic conditions (e.g. standard of living, inequality, or economic position), and/or social relationships (e.g. social class, dependency, lack of basic security, exclusion, or lack of entitlement – Olsson et al., 2014). The UNDP now uses a Multidimensional Poverty Index, and estimates that about 1.5 billion people globally live in multidimensional poverty, especially in rural areas of South Asia and Sub-Saharan Africa, with an additional billion at risk of falling into poverty (UNDP, 2016).

A large and rapidly growing body of knowledge explores the connections between climate change and poverty. Climatic variability and climate change are widely recognized as factors that may exacerbate poverty, particularly in countries and regions where poverty levels are high (Leichenko and Silva, 2014). The AR5 noted that climate change-driven impacts often act as a threat multiplier in that the impacts of climate change compound other drivers of poverty (Olsson et al., 2014). Many vulnerable and poor people are dependent on activities such as agriculture that are highly susceptible to temperature increases and variability in precipitation patterns (Shiferaw et al., 2014; Miyan, 2015). Even modest changes in rainfall and temperature patterns can push marginalized people into poverty as they lack the means to recover from shocks. Extreme events, such as floods, droughts, and heat waves, especially when they occur in series, can significantly erode poor people's assets and further undermine their livelihoods in terms of labour productivity, housing, infrastructure, and social networks (Olsson et al., 2014).

1.1.3 Sustainable development and a 1.5°C warmer world

AR5 noted with *high confidence* that 'equity is an integral dimension of sustainable development' and that 'mitigation and adaptation measures can strongly affect broader sustainable development and equity objectives' (Fleurbaey et al., 2014). Limiting global warming to 1.5°C will require substantial societal and technological transformations, dependent in turn on global and regional sustainable development pathways. A range of pathways, both sustainable and not, are explored in this report, including implementation strategies to understand the enabling conditions and challenges required for such a transformation. These pathways and connected strategies are framed within the context of sustainable development, and in particular the United Nations 2030 Agenda for Sustainable Development (UNGA, 2015) and Cross-Chapter Box 4 on SDGs (in this Chapter). The feasibility of staying within 1.5°C depends upon a range of enabling conditions with geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional enabling conditions. Limiting warming to 1.5°C also involves identifying technology and policy levers to accelerate the pace of transformation (see Chapter 4). Some pathways are more consistent than others with the requirements for sustainable development (see Chapter 5). Overall, the three-pronged emphasis on sustainable development, resilience, and transformation provides Chapter 5 an opportunity to assess the conditions of simultaneously reducing societal vulnerabilities, addressing entrenched inequalities, and breaking the circle of poverty.

The feasibility of any global commitment to a 1.5°C pathway depends, in part, on the cumulative influence of the nationally determined contributions (NDCs), committing nation states to specific GHG emission reductions. The current NDCs, extending only to 2030, do not limit warming to 1.5°C. Depending on mitigation decisions after 2030, they cumulatively track toward a warming of 3-4°C above preindustrial temperatures by 2100, with the potential for further warming thereafter (Rogelj et al., 2016a; UNFCCC, 2016). The analysis of pathways in this report reveals opportunities for greater decoupling of economic growth from GHG emissions. Progress towards limiting warming to 1.5°C requires a significant acceleration of this trend. AR5 (IPCC, 2014a) concluded that climate change constrains possible development paths, that synergies and trade-offs exist between climate responses and socio-economic contexts, and that opportunities for effective climate responses overlap with opportunities for sustainable development, noting that many existing societal patterns of consumption are intrinsically unsustainable (Fleurbaey et al., 2014).

1.2 Understanding 1.5°C: reference levels, probability, transience, overshoot, stabilization

1.2.1 Working definitions of 1.5°C and 2°C warming relative to pre-industrial levels

What is meant by 'the increase in global average temperature … above pre–industrial levels' referred to in the Paris Agreement depends on the choice of pre–industrial reference period, whether 1.5°C refers to total warming or the human–induced component of that warming, and which variables and geographical coverage are used to define global average temperature change. The cumulative impact of these definitional ambiguities (e.g. Hawkins et al., 2017; Pfleiderer et al., 2018) is comparable to natural multi–decadal temperature variability on continental scales (Deser et al., 2012) and primarily affects the historical period, particularly that prior to the early 20th century when data is sparse and of less certain quality. Most practical mitigation and adaptation decisions do not depend on quantifying historical warming to this level of precision, but a consistent working definition is necessary to ensure consistency across chapters and figures. We adopt definitions that are as consistent as possible with key findings of AR5 with respect to historical warming.

This report defines 'warming', unless otherwise qualified, as an increase in multi-decade global mean surface temperature (GMST) above pre–industrial levels. Specifically, warming at a given point in time is defined as the global average of combined land surface air and sea surface temperatures for a 30–year period centred on that time, expressed relative to the reference period 1850-1900 (adopted for consistency with Box SPM.1 Figure 1 of IPCC (2014e) 'as an approximation of pre–industrial levels', excluding the impact of natural climate fluctuations within that 30–year period and assuming any secular trend continues throughout that period, extrapolating into the future if necessary. There are multiple ways of accounting for natural fluctuations and trends (e.g., Foster and Rahmstorf, 2011; Haustein et al., 2017; Medhaug et al., 2017), but all give similar results. A major volcanic eruption might temporarily reduce observed global temperatures, but would not reduce warming as defined here (Bethke et al., 2017). Likewise, given that the level of warming is currently increasing at 0.3-0.7°C per 30 years (Kirtman et al., 2013), the level of warming in 2017 is 0.15-0.35°C higher than average warming over the 30–year period 1988-2017.

In summary, this report adopts a working definition of '1.5°C relative to pre–industrial levels' that corresponds to global average combined land surface air and sea surface temperatures either 1.5°C warmer than the average of the 51-year period 1850-1900, 0.87°C warmer than the 20-year period 1986–2005, or 0.63°C warmer than the decade 2006–2015. These offsets are based on all available published global datasets, combined and updated, which show that 1986-2005 was 0.63°C (±0.06°C 5–95% range based on observational uncertainties alone), and 2006-2015 was 0.87°C (±0.12°C *likely* range also accounting for the possible impact of natural fluctuations), warmer than 1850–1900. Where possible, estimates of impacts and mitigation pathways are evaluated relative to these more recent periods.

1.2.1.1 Definition of global average temperature

The IPCC has traditionally defined changes in observed GMST as a weighted average of near-surface air temperature (SAT) changes over land and sea surface temperature (SST) changes over the oceans (Morice et al., 2012; Hartmann et al., 2013), while modelling studies have typically used a simple global average SAT. For ambitious mitigation goals, and under conditions of rapid warming, the difference can be significant. Cowtan et al. (2015) and Richardson et al. (2016) show that the use of blended SAT/SST data and incomplete coverage together can give approximately 0.2°C less warming from the 19th century to the present relative to the use of complete global-average SAT (Stocker et al. , 2013), Figure TFE8.1 and Figure 1.2). However, Richardson et al. (2018) show that this is primarily an issue for the interpretation of the historical record to date, not for projection of future changes or for estimated emissions budgets consistent with future changes, particularly under ambitious mitigation scenarios.

The three GMST reconstructions used in AR5 differ in their treatment of missing data. GISTEMP (Hansen et al., 2010) uses interpolation to infer trends in poorly-observed regions like the Arctic (although even this product is spatially incomplete in the early record), while NOAA (Vose et al., 2012) and HadCRUT (Morice et al., 2012) are progressively closer to a simple average of available observations. Since the AR5, considerable effort has been devoted to more sophisticated statistical modelling to account for the impact of incomplete observation coverage (Rohde et al., 2013; Cowtan and Way, 2014; Jones, 2016). The main impact of statistical infilling is to increase estimated warming to date by about 0.1°C (Richardson et al., 2018 and Table 1.1).

We adopt a working definition of warming over the historical period based on an average of the four available global datasets that are supported by peer-reviewed publications: the three datasets used in the AR5, updated (Karl et al., 2015), together with the Cowtan-Way infilled dataset (Cowtan and Way, 2014). A further two datasets, Berkeley Earth (Rohde et al., 2013) and JMA, are provided in Table 1.1. This working definition provides an updated estimate of 0.86°C for the warming 1880-2012 based on a linear trend that was quoted as 0.85°C in the AR5. Hence the inclusion of the Cowtan-Way dataset does not introduce any inconsistency with the AR5, whereas redefining GMST to represent global SAT could increase this figure by up to 20%, (Table 1.1, Figure 1.2 Richardson et al., 2016).

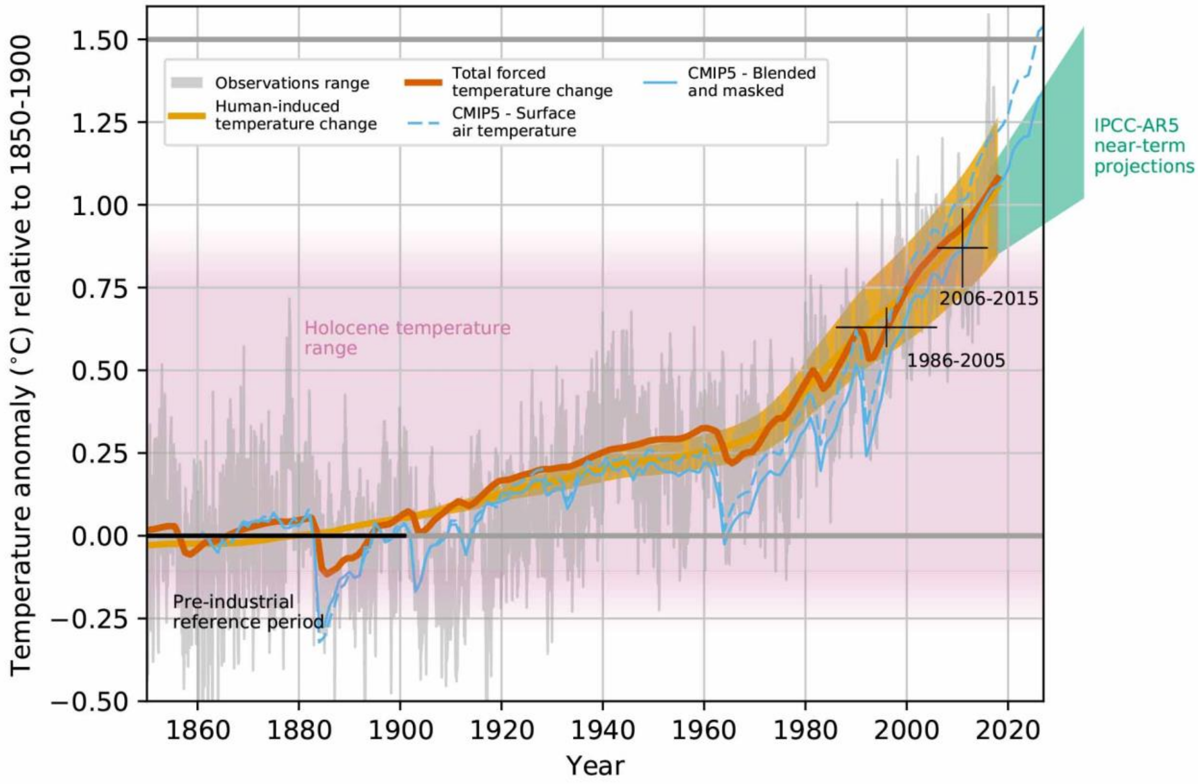

Figure 1.2: Evolution of global mean surface temperature (GMST) over the period of instrumental observations. Grey line shows monthly mean GMST in the HadCRUT4, NOAA, GISTEMP and Cowtan-Way datasets, expressed as departures from 1850–1900, with line thickness indicating inter–dataset range. All observational datasets shown represent GMST as a weighted average of near surface air temperature over land and sea surface temperature over oceans. Human–induced (yellow) and total (human– and naturally–forced, orange) contributions to these GMST changes

are shown calculated following Otto et al. (2015) and Haustein et al. (2017). Fractional uncertainty in the level of human–induced warming in 2017 is set equal to ±20%. Thin blue lines show the modelled global–mean surface air temperature (dashed) and blended surface air and sea surface temperature accounting for observational coverage (solid) from the CMIP5 historical ensemble average extended with RCP8.5 forcing (Cowtan et al., 2015; Richardson et al., 2018). The pink shading indicates a range for temperature fluctuations over the Holocene (Marcott et al., 2013). Light green plume shows AR5 prediction for average GMST over 2016–2035 (Kirtman et al., 2013). See Technical Annex 1.A of this chapter for further details.

1.2.1.2 Choice of reference period

Any choice of reference period used to approximate 'pre–industrial' conditions is a compromise between data coverage and representativeness of typical pre-industrial solar and volcanic forcing conditions. This report adopts the 51-year reference period, 1850–1900 inclusive, assessed as an approximation of pre-industrial conditions in AR5 (Box TS.5, Figure 1 of Field et al., 2014). The years 1880–1900 are subject to strong but uncertain volcanic forcing, but in the HadCRUT4 dataset, average temperatures over 1850–1879, prior to the largest eruptions, are less than 0.01°C from the average for 1850–1900. Temperatures rose by 0.0–0.2°C from 1720–1800 to 1850–1900 (Hawkins et al., 2017), but the anthropogenic contribution to this warming is uncertain (Schurer et al., 2017). The 18th century represents a relatively cool period in the context of temperatures since the mid-Holocene (Marcott et al., 2013; Marsicek et al., 2018), as indicated by the pink shaded region in Figure 1.2.

Projections of responses to emission scenarios, and associated impacts, may use a more recent reference period, offset by historical observations, to avoid conflating uncertainty in past and future changes (e.g. Hawkins et al., 2017; Millar et al., 2017b; Simmons et al., 2017). Two recent reference periods are used in this report: 1986–2005 and 2006–2015. In the latter case, when using a single decade to represent a 30-year average centred on that decade, it is important to consider the potential impact of internal climate variability. The years 2008–2013 were characterised by persistent cool conditions in the Eastern Pacific (Kosaka and Xie, 2013; Medhaug et al., 2017), related to both the El Niño / Southern Oscillation (ENSO) and, potentially, multi–decadal Pacific variability (e.g., England et al., 2014), but these were partially compensated for by El Niño conditions in 2006 and 2015. Likewise, volcanic activity depressed temperatures in 1986–2005, partly offset by the very strong El Niño event in 1998. Figure 1.2 indicates that natural variability (internally generated and externally driven) had little net impact on average temperatures over 2006–2015, in that the average temperature of the decade is similar to the estimated externally–driven warming. When solar, volcanic and ENSO-related variability is taken into account following the procedure of Foster and Rahmstorf (2011), there is no indication of average temperatures in either 1986–2005 or 2006–2015 being substantially biased by short-term variability (see Technical Appendix). The temperature difference between these two reference periods (0.21–0.27°C over 15 years across available datasets) is also consistent with the AR5 assessment of the current warming rate of 0.3–0.7°C over 30 years (Kirtman et al., 2013).

On the definition of warming used here, warming to the decade 2006–2015 comprises an estimate of the 30-year average centered on this decade, or 1996–2025, assuming the current trend continues and that any volcanic eruptions that might occur over the final seven years are corrected for. Given this element of extrapolation, we use the AR5 near-term projection to provide a conservative uncertainty range. Combining the uncertainty in observed warming to 1986–2005 (±0.06°C) with the *likely* range in the current warming trend as assessed by AR5 (±0.2°C/30 years), assuming these are uncorrelated, and using observed warming relative to 1850–1900 to provide the central estimate (no evidence of bias from short-term variability), gives an assessed warming to the decade 2006–2015 of 0.87°C with a ±0.12°C *likely* range. This estimate has the advantage of traceability to the AR5, but more formal methods of quantifying externally-driven warming (e.g., Bindoff et al., 2013; Jones et al., 2016; Haustein et al., 2017; Ribes et al., 2017), which typically give smaller ranges of uncertainty, may be adopted in future.

Table 1.1: Observed increase in global average surface temperature in various datasets. Numbers in square brackets correspond to 5-95% uncertainty ranges from individual datasets, encompassing known sources of observational uncertainty only.

Diagnostic / dataset	1850-1900 to (1) 2006-2015	1850-1900 to (2) 1986-2005	1986-2005 to (3) 2006-2015	1850-1900 to (4) 1981-2010	1850-1900 to (5) 1998-2017	trend (6) 1880-2012	trend (6) 1880-2015
HadCRUT4.6	0.84 [0.79—0.89]	0.60 [0.57—0.66]	0.22 [0.21—0.23]	0.62 [0.58—0.67]	0.83 [0.78—0.88]	0.83 [0.77—0.90]	0.88 [0.83—0.95]
NOAA (7)	0.86	0.62	0.22	0.63	0.85	0.85	0.91
GISTEMP (7)	0.89	0.65	0.23	0.66	0.88	0.89	0.94
Cowtan-Way	0.91 [0.85—0.99]	0.65 [0.60—0.72]	0.26 [0.25—0.27]	0.65 [0.60—0.72]	0.88 [0.82—0.96]	0.88 [0.79—0.98]	0.93 [0.85—1.03]
Average (8)	**0.87**	0.63	0.23	0.64	0.86	0.86	0.92
Berkeley (9)	0.98	0.73	0.25	0.73	0.97	0.97	1.02
JMA (9)	0.82	0.59	0.17	0.60	0.81	0.82	0.87
ERA-Interim	N/A	N/A	0.26	N/A	N/A	N/A	N/A
JRA-55	N/A	N/A	0.23	N/A	N/A	N/A	N/A
CMIP5 global SAT (10)	0.99 [0.65—1.37]	0.62 [0.38—0.94]	0.38 [0.24—0.62]	0.62 [0.34—0.93]	0.89 [0.62—1.29]	0.81 [0.58—1.31]	0.86 [0.63—1.39]
CMIP5 SAT/SST blend—masked	0.86 [0.54—1.18]	0.50 [0.31—0.79]	0.34 [0.19—0.54]	0.48 [0.26—0.79]	0.75 [0.52—1.11]	0.68 [0.45—1.08]	0.74 [0.51—1.14]

Notes:

1) Most recent reference period used in this report.
2) Most recent reference period used in AR5.
3) Difference between recent reference periods.
4) Current WMO standard reference periods.
5) Most recent 20-year period.
6) Linear trends estimated by a straight-line fit, expressed in degrees yr^{-1} multiplied by 133 or 135 years respectively, with uncertainty ranges incorporating observational uncertainty only.
7) To estimate changes in the NOAA and GISTEMP datasets relative to the 1850–1900 reference period, warming is computed relative to 1850–1900 using the HadCRUT4.6 dataset and scaled by the ratio of the linear trend 1880–2015 in the NOAA or GISTEMP dataset with the corresponding linear trend computed from HadCRUT4.
8) Average of diagnostics derived – see (7) – from four peer-reviewed global datasets, HadCRUT4.6, NOAA, GISTEMP & Cowtan-Way. Note that differences between averages may not coincide with average differences because of rounding.
9) No peer-reviewed publication available for these global combined land-sea datasets.
10) CMIP5 changes estimated relative to 1861–80 plus 0.02°C for the offset in HadCRUT4.6 from 1850–1900. CMIP5 values are the mean of the RCP8.5 ensemble, with 5–95% ensemble range. They are included to illustrate the difference between a complete global surface air temperature record (SAT) and a blended surface air and sea surface temperature (SST) record accounting for incomplete coverage (masked), following Richardson et al. (2016). Note that 1986–2005 temperatures in CMIP5 appear to have been depressed more than observed temperatures by the eruption of Mount Pinatubo.

1.2.1.3 Total versus human–induced warming and warming rates

Total warming refers to the actual temperature change, irrespective of cause, while human–induced warming refers to the component of that warming that is attributable to human activities. Mitigation studies focus on human-induced warming (that is not subject to internal climate variability), while studies of climate change impacts typically refer to total warming (often with the impact of internal variability minimised through the use of multi–decade averages).

In the absence of strong natural forcing due to changes in solar or volcanic activity, the difference between total and human-induced warming is small: assessing empirical studies quantifying solar and volcanic contributions to GMST from 1890 to 2010, AR5 (Fig. 10.6 of Bindoff et al., 2013) found their net impact on warming over the full period to be less than ±0.1°C. Figure 1.2 shows that the level of human–induced warming has been indistinguishable from total observed warming since 2000, including over the decade 2006–2015. Bindoff et al. (2013) assessed the magnitude of human-induced warming over the period 1951–2010 to be 0.7°C±0.1°C, slightly greater than the 0.65°C observed warming over this period (Figures 10.4 & 10.5) and a *likely* range of ±14%. The key surface temperature attribution studies underlying this finding finding (Gillett et al., 2013; Jones et al., 2013; Ribes and Terray, 2013) used temperatures since the 19th century to constrain human-induced warming, and so their results are equally applicable to the attribution of causes of warming over longer periods. Jones et al. (2016) show (Figure 10) human-induced warming trends over the period 1905–2005 to be indistinguishable from the corresponding total observed warming trend accounting for natural variability using spatio-temporal detection patterns from 12 out of 15 CMIP5 models and from the multi-model average. Figures from Ribes and Terray (2013), show the anthropogenic contribution to the observed linear warming trend 1880-2012 in the HadCRUT4 dataset (0.83°C in Table 1.1) to be 0.86°C using a multi-model average global diagnostic, with a 5-95% confidence interval of 0.72-1.00°C. In all cases, since 2000 the estimated combined contribution of solar and volcanic activity to warming relative to 1850–1900 is found to be less than ±0.1°C (Gillett et al., 2013), while anthropogenic warming is indistinguishable from, and if anything slightly greater than, the total observed warming, with 5–95% confidence intervals typically around ±20%.

Haustein et al. (2017) give a 5–95% confidence interval for human-induced warming in 2017 of 0.87–1.22°C, with a best estimate of 1.02°C, based on the HadCRUT4 dataset accounting for observational and forcing uncertainty and internal variability. Applying their method to the average of the 4 datasets shown in figure 1.2 gives an average level of human-induced warming in 2017 of 1.04°C. They also estimate a human-induced warming trend over the past 20 years of 0.17°C (0.13–0.33°C) per decade, consistent with estimates of the total observed trend of Foster and Rahmstorf (2011) (0.17±0.03°C/decade uncertainty in linear trend only) and Kirtman et al. (2013) (0.3–0.7°C over 30 years, or 0.1–0.23°C/decade, *likely* range), and a best-estimate warming rate over the past five years of 0.215°C/decade (Leach et al., 2018). Drawing on these multiple lines of evidence, human-induced warming is assessed to have reached 1.0°C in 2017, having increased by 0.13°C from the mid-point of 2006–2015, with a *likely* range of ±0.2°C (reduced from 5–95% to account for additional forcing and model uncertainty), increasing at 0.2°C (±0.1°C) per decade (estimates of human-induced warming given to 0.1°C precision only).

Since warming is here defined in terms of a 30-year average, corrected for short-term natural fluctuations, when warming is considered to be at 1.5°C, global temperatures would fluctuate equally on either side of 1.5°C in the absence of a large cooling volcanic eruption (Bethke et al, 2017). Figure 1.2 indicates there is a substantial chance of GMST in a single month fluctuating over 1.5°C between now and 2020, but this would not constitute temperatures 'reaching 1.5°C' on our working definition. Rogelj et al. (2017) show limiting the probability of annual GMST exceeding 1.5°C to less than one-year-in-20 would require limiting warming, on the definition used here, to 1.31°C or lower.

1.2.2 Global versus regional and seasonal warming

Warming is not observed or expected to be spatially or seasonally uniform (IPCC, 2013b). A 1.5°C increase in GMST will be associated with warming substantially greater than 1.5°C in many land regions, and less than 1.5°C in most ocean regions. This is illustrated by Figure 1.3, which shows an estimate of the observed change in annual and seasonal average temperatures between the 1850-1900 pre-industrial reference period and the decade 2006–2015 in the Cowtan-Way dataset. These regional changes are associated with an observed GMST increase of 0.91°C in the dataset shown here, or

0.87°C in the 4-dataset average (Table 1.1). This observed pattern reflects an on-going transient warming: features such as enhanced warming over land may be less pronounced, but still present, in equilibrium (IPCC, 2013b). This figure illustrates the magnitude of these differences, with many locations, particularly in Northern-Hemisphere mid-latitude winter (December–February), already experiencing regional warming more than double the global average. Individual seasons may be substantially warmer, or cooler, than these expected long–term average changes.

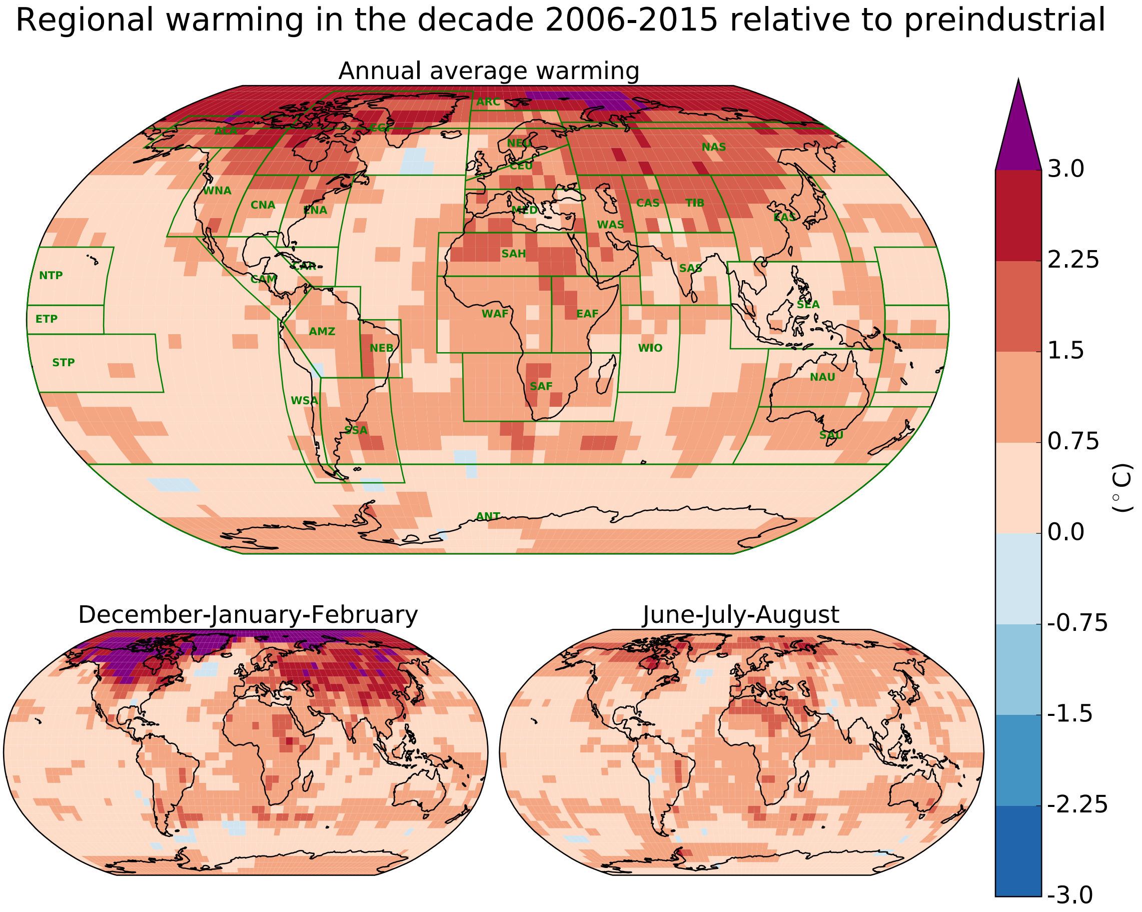

Figure 1.3: Spatial and seasonal pattern of present-day warming: Regional warming for the 2006–2015 decade relative to 1850–1900 for the annual mean (top), the average of December, January and February (bottom left) and for June, July and August (bottom right). Warming is evaluated by regressing regional changes in the (Cowtan and Way, 2014) dataset onto the total (combined human and natural) externally-forced warming (yellow line in Figure 1.2). See Technical Annex 1.A of this chapter for further details and versions using alternative datasets. The definition of regions (green boxes and labels in top panel) is adopted from the AR5 (Christensen et al., 2013).

1.2.3 Definition of 1.5°C-consistent pathways: probability, transience, stabilization and overshoot

Pathways considered in this report, consistent with available literature on 1.5°C, primarily focus on the timescale up to 2100, recognising that the evolution of GMST after 2100 is also important. Two broad categories of 1.5°C-consistent pathways can be used to characterise mitigation options and impacts: pathways in which warming (defined as 30-year averaged GMST relative to pre-industrial levels, see section 1.2.1) remains below 1.5°C throughout the 21st century, and pathways in which warming temporarily exceeds ('overshoots') 1.5°C and returns to 1.5°C either before or soon after

2100. Pathways in which warming exceeds 1.5°C before 2100, but might return to that level in some future century, are not considered 1.5°C-consistent.

Because of uncertainty in the climate response, a ‘prospective’ mitigation pathway (see Cross-Chapter Box 1 in this Chapter), in which emissions are prescribed, can only provide a level of probability of warming remaining below a temperature threshold. This probability cannot be quantified precisely since estimates depend on the method used (Rogelj et al., 2016b; Millar et al., 2017b; Goodwin et al., 2018; Tokarska and Gillett, 2018). This report defines a ‘1.5°C-consistent pathway’ as a pathway of emissions and associated possible temperature responses in which the majority of approaches using presently-available information assign a probability in the range of approximately one-in-two to two-in-three to warming remaining below 1.5°C or, in the case of an overshoot pathway, returning to 1.5°C by around 2100 or earlier. In Chapter 2, the classification of pathways is based on one modeling approach to avoid ambiguity, but probabilities of exceeding 1.5°C are checked against other approaches to verify that they lie within this approximate range. All these absolute probabilities are imprecise, depend on the information used to constrain them, and hence are expected to evolve in the future. Imprecise probabilities can nevertheless be useful for decision-making, provided the imprecision is acknowledged (Hall et al., 2007; Kriegler et al., 2009; Simpson et al., 2016). Relative and rank probabilities can be assessed much more consistently: approaches may differ on the absolute probability assigned to individual outcomes, but typically agree on which outcomes are more probable.

Importantly, 1.5°C-consistent pathways allow a substantial (up to one-in-two) chance of warming still exceeding 1.5°C. An ‘adaptive’ mitigation pathway in which emissions are continuously adjusted to achieve a specific temperature outcome (e.g. Millar et al., 2017b) reduces uncertainty in the temperature outcome while increasing uncertainty in the emissions required to achieve it. It has been argued (Otto et al., 2015; Xu and Ramanathan, 2017) that achieving very ambitious temperature goals will require such an adaptive approach to mitigation, but very few studies have been performed taking this approach (e.g. Jarvis et al., 2012).

Figure 1.4 illustrates these categories of (a) 1.5°C-consistent temperature pathways and associated (b) annual and (c) cumulative emissions of CO_2. It also shows (d) a ‘time-integrated impact’ that continues to increase even after GMST has stabilised, such as sea-level rise. This schematic assumes for illustration that the fractional contribution of non-CO_2 climate forcers to total anthropogenic forcing (which is currently increasing, Myhre et al., 2017) is approximately constant from now on. Consequently, total human-induced warming is proportional to cumulative CO_2 emissions (solid line in c), and GMST stabilises when emissions reach zero. This is only the case in the most ambitious scenarios for non-CO_2 mitigation (Leach et al., 2018). A simple way of accounting for varying non-CO_2 forcing in Figure 1.4 would be to note that every 1 W/m^2 increase in non-CO_2 forcing between now and the decade or two immediately prior to the time of peak warming reduces cumulative CO_2 emissions consistent with the same peak warming by approximately 1200±300 $GtCO_2$ (using values from AR5: Myhre et al, 2013; Jenkins et al, 2018; Allen et al, 2018; Cross-Chapter Box 2 in this Chapter).

1.2.3.1 Pathways remaining below 1.5°C

In this category of 1.5°C-consistent pathways, human-induced warming either rises monotonically to stabilise at 1.5°C (Figure 1.4, brown lines) or peaks at or below 1.5°C and then declines (yellow lines). Figure 1.4, panel b demonstrates that pathways remaining below 1.5°C require net annual CO_2 emissions to peak and decline to near zero or below, depending on the long-term adjustment of the carbon cycle and non-CO_2 emissions (Bowerman et al., 2013; Wigley, 2018). Reducing emissions to zero corresponds to stabilizing cumulative CO_2 emissions (panel c, solid lines) and falling concentrations of CO_2 in the atmosphere (panel c dashed lines) (Matthews and Caldeira, 2008;

Solomon et al., 2009), which is required to stabilize GMST if non-CO_2 climate forcings are constant and positive. Stabilizing atmospheric greenhouse gas concentrations would result in continued warming (see Section 1.2.4).

If starting emission reductions is delayed until temperatures are close to the proposed limit, pathways remaining below 1.5°C necessarily involve much faster rates of net CO_2 emission reductions (Figure 1.4, green lines), combined with rapid reductions in non-CO_2 forcing, and also reach 1.5°C earlier. Note that the emissions associated with these schematic temperature pathways may not correspond to feasible emission scenarios, but they do illustrate the fact that the timing of net zero emissions does not in itself determine peak warming: what matters is total cumulative emissions up to that time. Hence every year's delay before initiating emission reductions reduces by approximately two years the remaining time available to reduce emissions to zero on a pathway remaining below 1.5°C (Allen and Stocker, 2013; Leach et al., 2018).

1.2.3.2 Pathways temporarily exceeding 1.5°C

With the pathways in this category, also referred to as overshoot pathways, GMST rises above 1.5°C before peaking and returning to 1.5°C around or before 2100 (Figure 1.4, blue lines), subsequently either stabilising or continuing to fall. This allows initially slower or delayed emission reductions but lowering GMST requires net negative global CO_2 emissions (net anthropogenic removal of CO_2; Figure 1.4, panel b). Cooling, or reduced warming, through sustained reductions of net non-CO_2 climate forcing (Cross-Chapter Box 2 in this Chapter) is also required, but their role is limited because emissions of most non-CO_2 forcers cannot be reduced to below zero. Hence the feasibility and availability of large–scale CO_2 removal limits the possible rate and magnitude of temperature decline. In this report, overshoot pathways are referred to as 1.5°C-consistent, but qualified by the amount of the temperature overshoot, which can have a substantial impact on irreversible climate change impacts (Mathesius et al., 2015; Tokarska and Zickfeld, 2015).

1.2.3.3 Impacts at 1.5°C warming associated with different pathways: transience versus stabilisation

Figure 1.4 also illustrates timescales associated with different impacts. While many impacts scale with the change in GMST itself, some (such as those associated with ocean acidification) scale with the change in atmospheric CO_2 concentration, indicated by the fraction of cumulative CO_2 emissions remaining in the atmosphere (dotted lines in panel c). Others may depend on the rate of change of GMST, while 'time-integrated impacts', such as sea-level rise, shown in panel (d) continue to increase even after GMST has stabilised.

Hence impacts that occur when GMST reaches 1.5°C could be very different depending on the pathway to 1.5°C. CO_2 concentrations will be higher as GMST rises past 1.5°C (transient warming) than when GMST has stabilized at 1.5°C while sea level and, potentially, global mean precipitation (Pendergrass et al., 2015) would both be lower (see Figure 1.4). These differences could lead to very different impacts on agriculture, on some forms of extreme weather (e.g., Baker et al., 2018), and on marine and terrestrial ecosystems (e.g., Mitchell et al., 2017,)Box 3.1). Sea level would be higher still if GMST returns to 1.5°C after an overshoot (Figure 1.4, panel d), with potentially significantly different impacts in vulnerable regions. Temperature overshoot could also cause irreversible impacts (see Chapter 3).

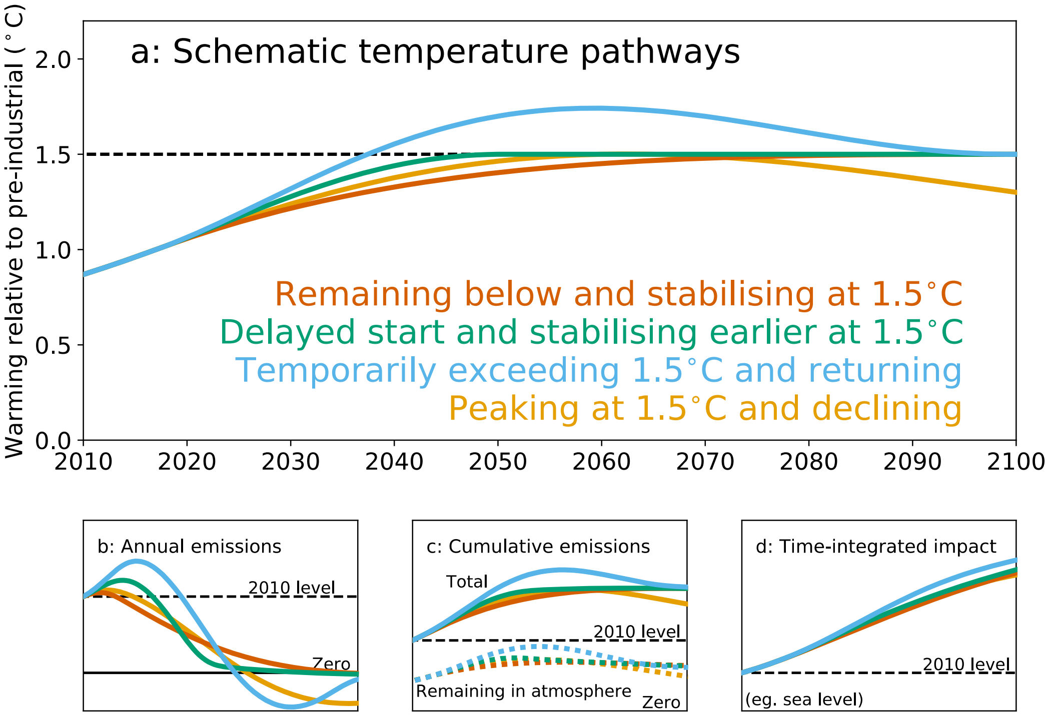

Figure 1.4: Different 1.5°C-consistent pathways[1]: Schematic illustration of the relationship between (a) global mean surface temperature (GMST) change; (b) annual rates of CO_2 emissions, assuming constant fractional contribution of non-CO_2 forcing to total human-induced warming; (c) total cumulative CO_2 emissions (solid lines) and the fraction thereof remaining in the atmosphere (dashed lines; these also indicates changes in atmospheric CO_2 concentrations); and (d) a time-integrated impact, such as sea-level rise, that continues to increase even after GMST has stabilized. Colours indicate different 1.5°C-consistent pathways. Brown: GMST remaining below and stabilizing at 1.5°C in 2100; Green: a delayed start but faster implementation pathway with GMST remaining below and reaching 1.5°C earlier; Blue: a pathway temporarily exceeding 1.5°C, with temperatures reduced to 1.5°C by net negative CO_2 emissions after temperatures peak; and Yellow: a pathway peaking at 1.5°C and subsequently declining. Temperatures are anchored to 0.87°C above pre–industrial in 2010; emissions–temperature relationships are computed using a simple climate model (Myhre et al., 2013; Millar et al., 2017a; Jenkins et al., 2018) with a lower value of the Transient Climate Response (TCR) than used in the quantitative pathway assessments in Chapter 2 to illustrate qualitative differences between pathways: this figure is not intended to provide quantitative information. The time-integrated impact is illustrated by the semi-empirical sea–level–rise model of Kopp et al. (2016).

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[1] FOOTNOTE: An animated version of Figure 1.4 will be embedded in the web-based version of this Special Report

Cross-Chapter Box 1: Scenarios and Pathways

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Climate change scenarios have been used in IPCC assessments since the First Assessment Report (Leggett et al., 1992). The **SRES scenarios** (named after the IPCC Special Report on Emissions Scenarios; IPCC, 2000), published in 2000, consist of four scenarios that do not take into account any future measures to limit greenhouse gas (GHG) emissions. Subsequently, many policy scenarios have been developed based upon them (Morita et al., 2001). The SRES scenarios are superseded by a set of scenarios based on the Representative Concentration Pathways (RCPs) and Shared Socio–Economic Pathways (SSPs) (Riahi et al., 2017). The RCPs comprise a set of four GHG concentration trajectories that jointly span a large range of plausible human–caused climate forcing ranging from 2.6 W m^{-2} (RCP2.6) to 8.5 W m^{-2} (RCP8.5) by the end of the 21st century (van Vuuren et al., 2011). They were used to develop climate projections in the 5th Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) and were assessed in the IPCC 5th Assessment Report (AR5). Based on the CMIP5 ensemble, RCP2.6, provides a better than two in three chance of staying below 2°C and a median warming of 1.6°C relative to 1850–1900 in 2100 (Collins et al., 2013).

The SSPs were developed to complement the RCPs with varying socio-economic challenges to adaptation and mitigation. SSP-based scenarios were developed for a range of climate forcing levels, including the end-of-century forcing levels of the RCPs (Riahi et al., 2017) and a level below RCP2.6 to explore pathways limiting warming to 1.5°C above pre–industrial levels (Rogelj et al., 2018). The SSP-based 1.5°C-consistent pathways are assessed in Chapter 2 of this report. These scenarios offer an integrated perspective on socio–economic, energy-system (Bauer et al., 2017), land use (Popp et al., 2017), air pollution (Rao et al., 2017) and GHG emissions developments (Riahi et al., 2017). Because of their harmonised assumptions, scenarios developed with the SSPs facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation.

Scenarios and Pathways in this Report

This report focuses on pathways that could limit the increase of global mean surface temperature (GMST) to 1.5°C above pre–industrial levels and pathways that align with the goals of sustainable development and poverty eradication. Pace and scale of mitigation and adaptation are assessed in the context of historical evidence to determine where unprecedented change is required (see Chapter 4). Other scenarios are also assessed, primarily as benchmarks for comparison of mitigation, impacts, and/or adaptation requirements. These include baseline scenarios that assume no climate policy; scenarios that assume some kind of continuation of current climate policy trends and plans, many of which are used to assess the implications of the nationally-determined contributions (NDCs); and scenarios holding warming below 2°C above pre–industrial levels. This report assesses the spectrum from global mitigation scenarios to local adaptation choices – complemented by a bottom-up assessment of individual mitigation and adaptation options and their implementation (policies, finance, institutions, governance, see Chapter 4). Regional, national, and local scenarios, as well as decision-making processes over values and difficult trade-offs are important for understanding the challenges of limiting GMST increase to 1.5°C and are thus indispensable when assessing implementation.

Different climate policies result in different temperature pathways, which result in different levels of climate risks and actual climate impacts with associated long-term implications. Temperature pathways are classified into continued warming pathways (in the cases of baseline and reference scenarios), pathways that keep the temperature below a specific limit (like 1.5°C or 2°C), and pathways that temporarily exceed and later fall to a specific limit (overshoot pathways). In the case of a temperature overshoot, net negative CO_2 emissions are required to remove excess CO_2 from the atmosphere.

In a ‘prospective’ mitigation pathway, emissions (or sometimes concentrations) are prescribed, giving a range of GMST outcomes because of uncertainty in the climate response. Prospective pathways are considered ‘1.5°C-consistent’ in this report if, based current knowledge, the majority of available approaches assign an approximate probability of one-in-two to two-in-three to temperatures either remaining below 1.5°C or returning to 1.5°C either before or around 2100. Most pathways assessed in Chapter 2 are prospective pathways, and therefore even ‘1.5°C-consistent pathways’ are also associated with risks of warming higher than 1.5°C, noting that many risks increase non-linearly with increasing GMST. In contrast, the ‘risks of warming of 1.5°C’assessed in Chapter 3 refer to risks in a world in which GMST is either passing through (transient) or stabilized at 1.5°C, without considering probabilities of different GMST levels (unless otherwise qualified). To stay below any desired temperature limit, adjusting mitigation measures and strategies would be required as knowledge of the climate response is updated (Millar et al., 2017b; Emori et al., 2018). Such pathways can be called ‘adaptive’ mitigation pathways. Given there is always a possibility of a greater-than-expected climate response (Xu and Ramanathan, 2017), adaptive mitigation pathways are important to minimise climate risks, but need also to consider the risks and feasibility (see Cross-Chapter Box 3 in this Chapter) of faster-than-expected emission reductions. Aligning mitigation and adaptation pathways with sustainable development pathways and transformative visions for the future that would support avoiding negative impacts on the poorest and most disadvantaged populations and vulnerable sectors are assessed in Chapter 5.

Definitions of Scenarios and Pathways

Climate scenarios and pathways are terms that are sometimes used interchangeably, with a wide range of overlapping definitions (Rosenbloom, 2017).

A ‘**scenario’** is an internally consistent, plausible, and integrated description of a possible future of the human–environment system, including a narrative with qualitative trends and quantitative projections (IPCC, 2000). Climate change scenarios provide a framework for developing and integrating emissions, climate change and climate impact projections, including an assessment of their inherent uncertainties. The long-term and multi–faceted nature of climate change requires climate scenarios to describe how assumptions about inherently uncertain socio-economic trends in the 21st century could influence future energy and land use, resulting in emissions, and climate change as well as human vulnerability and exposure to climate change. Such driving forces include population, GDP, technological innovation, governance, and lifestyles. Climate change scenarios are used for analysing and contrasting climate policy choices.

The notion of a **‘pathway’** can have multiple meanings in the climate literature. It is often used to describe the temporal evolution of a set of scenario features, such as GHG emissions and socioeconomic development. As such, it can describe individual scenario components or sometimes be used interchangeably with the word ‘scenario’. For example, the RCPs describe GHG concentration trajectories (van Vuuren et al., 2011) and the SSPs are a set of narratives of societal futures augmented by quantitative projections of socio-economic determinants such as population, GDP, and urbanization (Kriegler et al., 2012; O’Neill et al., 2014). Socio-economic driving forces consistent with any of the SSPs can be combined with a set of climate policy assumptions (Kriegler et al., 2014) that together would lead to emissions and concentration outcomes consistent with the RCPs (Riahi et al., 2017). This is at the core of the scenario framework for climate change research that aims to facilitate creating scenarios integrating emissions and development pathways dimensions (Ebi et al., 2014; van Vuuren et al., 2014).

In other parts of the literature, ‘pathway’ implies a solution-oriented trajectory describing a pathway from today’s world to achieving a set of future goals. **Sustainable Development Pathways** describe national and global pathways where climate policy becomes part of a larger sustainability transformation (Shukla and Chaturvedi, 2013; Fleurbaey et al., 2014; van Vuuren et al., 2015). The AR5 presented **climate-resilient pathways** as sustainable development pathways that combine the goals of adaptation and mitigation (Denton et al., 2014), more broadly defined as iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with climate change (IPCC, 2014b). The AR5 also introduced the notion of **climate-resilient development pathways,** with a more explicit focus on dynamic livelihoods, multidimensional poverty, structural inequalities, and equity among poor and non-poor people (Olsson et al., 2014). **Adaptation pathways**, understood as a series of adaptation choices involving trade-offs between short-term and long-term goals and values (Reisinger et al., 2014). They are decision-making processes sequenced over time with the purpose of deliberating and identifying socially-salient solutions in specific places (Barnett et al., 2014; Wise et al., 2014; Fazey et al., 2016). There is a range of possible pathways for transformational change, often negotiated through iterative and inclusive processes (Harris et al., 2017; Fazey et al., 2018; Tàbara et al., 2018).

1.2.4 Geophysical warming commitment

It is frequently asked whether limiting warming to 1.5°C is ‘feasible’ (Cross–Chapter Box 3 in this Chapter). There are many dimensions to this question, including the warming ‘commitment’ from past emissions of greenhouse gases and aerosol precursors. Quantifying commitment from past emissions is complicated by the very different behaviour of different climate forcers affected by human activity: emissions of long-lived greenhouse gases such as CO_2 and nitrous oxide (N_2O) have a very persistent impact on radiative forcing (Myhre et al., 2013), lasting from over a century (in the case of N_2O) to hundreds of thousands of years (for CO_2). Short-lived climate forcers (SLCFs) such as methane (CH_4) and aerosols, in contrast, persist for at most about a decade (in the case of methane) down to only a few days. These different behaviours must be taking into account in assessing the implications of any approach to calculating aggregate emissions (Cross-Chapter Box 2 in this Chapter).

Geophysical warming commitment is defined as the unavoidable future warming resulting from physical Earth system inertia. Different variants are discussed in the literature, including (i) the ‘constant composition commitment’ (CCC), defined by Meehl et al. (2007) as the further warming that would result if atmospheric concentrations of GHGs and other climate forcers were stabilised at the current level; and (ii) and the ‘zero emissions commitment’ (ZEC), defined as the further warming that would still occur if all future anthropogenic emissions of greenhouse gases and aerosol precursors were eliminated instantaneously (Meehl et al, 2007; Collins et al., 2013).

The CCC is primarily associated with thermal inertia of the ocean (Hansen et al., 2005), and has led to the misconception that substantial future warming is inevitable (Matthews and Solomon, 2013). The CCC takes into account the warming from past emissions, but also includes warming from future emissions (declining but still non-zero) that are required to maintain a constant atmospheric composition. It is therefore not relevant to the warming commitment from past emissions alone.

The ZEC, although based on equally idealised assumptions, allows for a clear separation of the response to past emissions from the effects of future emissions. The magnitude and sign of the ZEC depend on the mix of GHGs and aerosols considered. For CO_2, which has an effective atmospheric residence time of centuries to millennia (Eby et al., 2009), the multi-century warming commitment from emissions to date is estimated to range from slightly negative (i.e., a slight cooling relative to present-day) to slightly positive (Matthews and Caldeira, 2008; Lowe et al., 2009; Gillett et al., 2011; Collins et al., 2013). Some studies estimate a larger ZEC from CO_2, but for cumulative emissions much higher than those up to present day (Frölicher et al., 2014; Ehlert and Zickfeld, 2017). The ZEC from past CO_2 emissions is small because the continued warming effect from ocean thermal inertia is approximately balanced by declining radiative forcing due to CO_2 uptake by the ocean (Solomon et al., 2009; Williams et al., 2017). Thus, although present-day CO_2-induced warming is irreversible on millennial timescales (without human intervention such as active carbon dioxide removal or solar radiation modification (Section 1.4.1)), past CO_2 emissions do not commit to substantial further warming (Matthews and Solomon, 2013).

For warming SLCFs, meaning those associated with positive radiative forcing such as methane, the ZEC is negative. Eliminating emissions of these substances (also sometimes referred to as short-lived climate pollutants, see Section 4.3.6) results in an immediate cooling relative to the present (Figure 1.5, magenta line) (Frölicher and Joos, 2010; Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017). Cooling SLCFs (those associated with negative radiative forcing) such as sulphate aerosols create a positive ZEC, as elimination of these forcers results in rapid warming (Matthews and Zickfeld, 2012; Mauritsen and Pincus, 2017; Samset et al., 2018). Estimates of the warming commitment from eliminating aerosol emissions are affected by large uncertainties in net aerosol radiative forcing (Myhre et al., 2013, 2017). If present–day emissions of all GHGs (short- and long-lived) and aerosols (including sulphate, nitrate and carbonaceous aerosols) are eliminated (Figure 1.5, yellow line) GMST rises over the following decade. This initial warming is followed by a gradual cooling driven by the decline in radiative forcing of short-lived greenhouse gases (Matthews and Zickfeld, 2012; Collins et al., 2013). Peak warming following elimination of all emissions was assessed at a few tenths of a degree in AR5, and century-scale warming was assessed to change only slightly relative to the time emissions are reduced to zero (Collins et al., 2013). New evidence since AR5 suggests a larger methane forcing (Etminan et al., 2016) but no revision in the range of aerosol forcing (although this remains an active field of research, e.g., Myhre et al., 2017). This revised methane forcing estimate results in a smaller peak warming and a faster temperature decline than assessed in AR5 (Figure 1.5, yellow line).

Expert judgement based on the available evidence (including model simulations, radiative forcing and climate sensitivity) suggests that if all anthropogenic emissions were reduced to zero immediately, any further warming beyond the 1°C already experienced would *likely* be less than 0.5°C over the next two to three decades, and also *likely* less than 0.5°C on a century timescale.

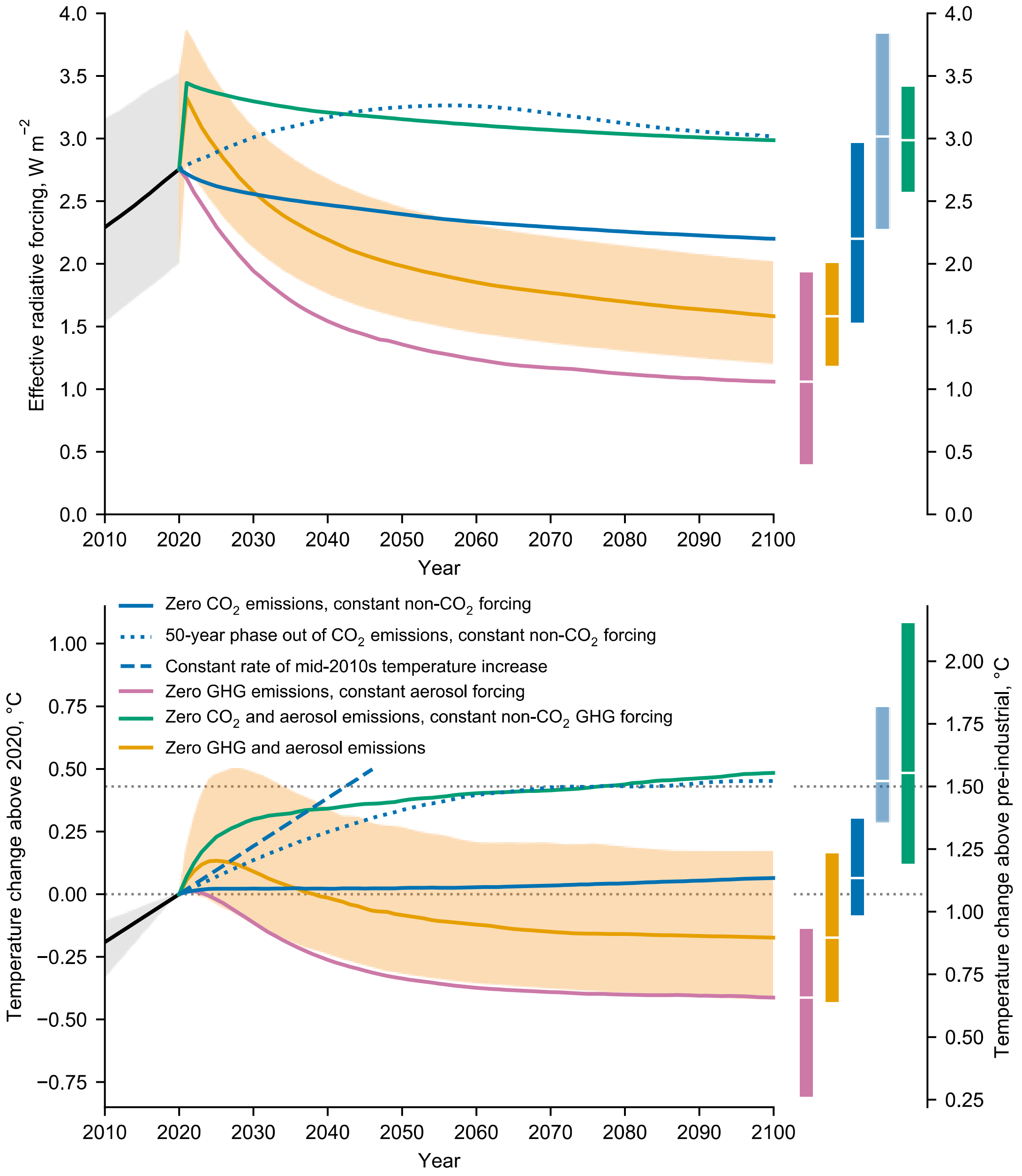

Figure 1.5: **Different interpretations of warming commitment from past emissions:** Radiative forcing (top) and global mean surface temperature change (bottom) for scenarios with different combinations of greenhouse gas and aerosol precursor emissions reduced to zero in 2020. Variables were calculated using a simple climate–carbon cycle model (Millar et al., 2017a) with a simple representation of atmospheric chemistry (Smith et al., 2018). The bars on the right–hand side indicate the median warming in 2100 and 5–95% uncertainty ranges (also indicated by the plume around the yellow line) taking into account one estimate of uncertainty in climate response, effective radiative forcing, and carbon cycle constraining simple model parameters with response ranges from AR5 combined with historical climate observations (Smith et al., 2018). Temperatures continue to increase slightly after elimination of CO_2 emissions (blue line) due to adjusting to the recent increase in non-CO_2 forcing. The dashed blue line extrapolates one estimate of the current rate of warming, while dotted blue lines show a case where CO_2 emissions are reduced linearly to zero assuming constant non-CO_2 forcing after 2020. Under these highly idealized assumptions, the time to stabilize temperatures at 1.5°C is approximately double the time remaining to reach 1.5°C at the current warming rate.

Since most sources of emissions cannot, in reality, be brought to zero instantaneously due to techno-economic inertia, the current rate of emissions also constitutes a conditional commitment to future emissions and consequent warming depending on achievable rates of emission reductions. The current level and rate of human-induced warming determines both the time left before a temperature threshold is exceeded if warming continues (dashed blue line in Figure 1.5) and the time over which the warming rate must be reduced to avoid exceeding that threshold (approximately indicated by the dotted blue line in Figure 1.5). Leach et al. (2018) use a central estimate of human-induced warming of 1.02°C in 2017 increasing at 0.215°C per decade (Haustein et al., 2017), to argue that it will take 13–32 years (one-standard-error range) to reach 1.5°C if the current warming rate continues, allowing 25–64 years to stabilise temperatures at 1.5°C if the warming rate is reduced at a constant rate of deceleration starting immediately. Since the rate of human-induced warming is proportional to the rate of CO_2 emissions (Matthews et al., 2009; Zickfeld et al., 2009) plus a term approximately proportional to the rate of increase in non–CO_2 radiative forcing (Gregory and Forster, 2008; Allen et al., 2018; Cross-Chapter Box 2 in this Chapter), these timescales also provide an indication of minimum emission reduction rates required if a warming greater than 1.5°C is to be avoided (see Technical Annex 1.A and FAQ 1.2).

Cross-Chapter Box 2: Measuring progress to net zero emissions combining long-lived and short-lived climate forcers

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Emissions of many different climate forcers will affect the rate and magnitude of climate change over the next few decades (Myhre et al., 2013). Since these decades will determine when 1.5°C is reached or whether a warming greater than 1.5°C is avoided, understanding the aggregate impact of different forcing agents is particularly important in the context of 1.5°C-consistent pathways. Paragraph 17 of Decision 1 of the 21st Conference of the Parties on the adoption of the Paris Agreement specifically states that this report is to identify aggregate greenhouse gas emission levels compatible with holding the increase in global average temperatures to 1.5°C above preindustrial levels (see Chapter 2). This request highlights the need to consider the implications of different methods of aggregating emissions of different gases, both for future temperatures and for other aspects of the climate system.

To date, reporting of GHG emissions under the UNFCCC has used Global Warming Potentials (GWPs) evaluated over a 100–year time horizon (GWP_{100}) to combine multiple climate forcers. IPCC Working Group 3 reports have also used GWP_{100} to represent multi-gas pathways (Clarke et al., 2014). For reasons of comparability and consistency with current practice, Chapter 2 in this Special Report continues to use this aggregation method. Numerous other methods of combining different climate forcers have been proposed, such as the Global Temperature-change Potential (GTP; Shine et al., 2005) and the Global Damage Potential (Tol et al., 2012; Deuber et al., 2013).

Climate forcers fall into two broad categories in terms of their impact on global temperature (Smith et al., 2012): long-lived GHGs, such as CO_2 and nitrous oxide (N_2O), whose warming impact depends primarily on the total cumulative amount emitted over the past century or the entire industrial epoch; and short-lived climate forcers (SLCFs), such as methane and black carbon, whose warming impact depends primarily on current and recent annual emission rates (Reisinger et al., 2012; Myhre et al., 2013; Smith et al., 2013; Strefler et al., 2014). These different dependencies affect the emissions reductions required of individual forcers to limit warming to 1.5°C or any other level.

Natural processes that remove CO_2 permanently from the climate system are so slow that reducing the rate of CO_2-induced warming to zero requires net zero global anthropogenic CO_2 emissions (Archer and Brovkin, 2008; Matthews and Caldeira, 2008; Solomon et al., 2009), meaning almost all remaining anthropogenic CO_2 emissions must be compensated for by an equal rate of anthropogenic carbon dioxide removal (CDR). Cumulative CO_2 emissions are therefore an accurate indicator of CO_2-induced warming, except in periods of high negative CO_2 emissions (Zickfeld et al., 2016), and potentially in century-long periods of near-stable temperatures (Bowerman et al., 2011; Wigley, 2018). In contrast, sustained constant emissions of a SLCF such as methane, would (after a few decades) be consistent with constant methane concentrations and hence very little additional methane-induced warming (Allen et al., 2018; Fuglestvedt et al., 2018). Both GWP and GTP would equate sustained SLCF emissions with sustained constant CO_2 emissions, which would continue to accumulate in the climate system, warming global temperatures indefinitely. Hence nominally 'equivalent' emissions of CO_2 and SLCFs, if equated conventionally using GWP or GTP, have very different temperature impacts, and these differences are particularly evident under ambitious mitigation characterising 1.5°C-consistent pathways.

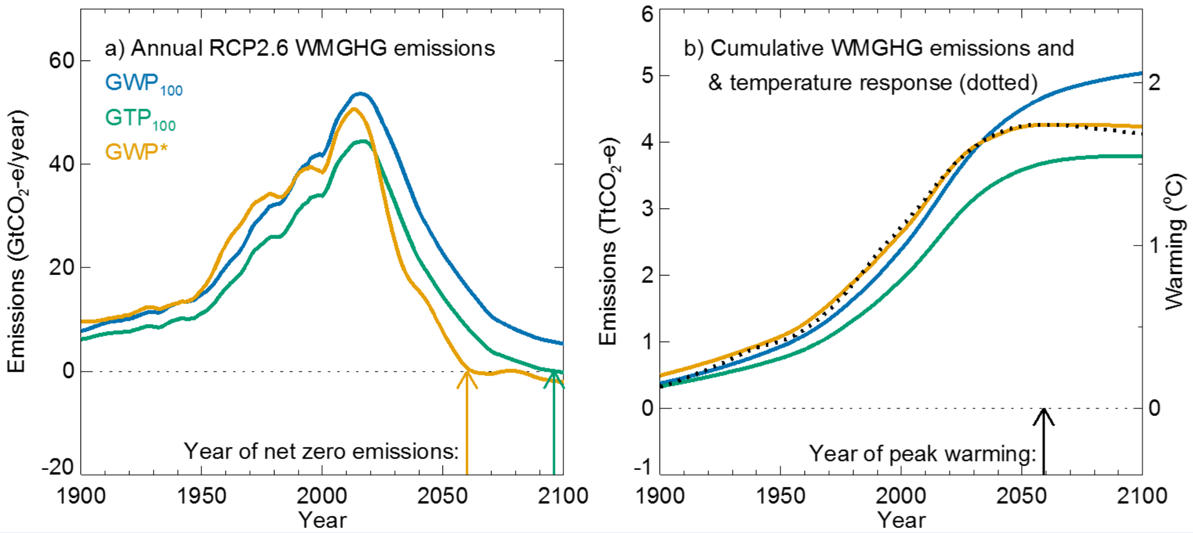
Since the AR5, a revised usage of GWP has been proposed (Lauder et al., 2013; Allen et al., 2016), denoted GWP* (Allen et al., 2018), that addresses this issue by equating a permanently sustained change in the emission *rate* of an SLCF or SLCF-precursor (in tonnes-per-year), or other non-CO_2 forcing (in Watts per square metre), with a one-off *pulse* emission (in tonnes) of a fixed amount of CO_2. Specifically, GWP* equates a 1 tonne-per-year increase in emission rate of an SLCF with a pulse emission of $\mathrm{GWP}_H \times H$ tonnes of CO_2, where GWP_H is the conventional GWP of that SLCF evaluated over time horizon H. While GWP_H for SLCFs decreases with increasing time horizon H, $\mathrm{GWP}_H \times H$ for SLCFs is less dependent on the choice of time horizon. Similarly, a permanent 1 W/m^2 increase in radiative forcing has a similar temperature impact as the cumulative emission of H/AGWP_H tonnes of CO_2, where AGWP_H is the Absolute Global Warming Potential of CO_2 (Shine et al., 2005; Myhre et al., 2013; Allen et al., 2018). This indicates approximately how future changes in non-CO_2 radiative forcing affect cumulative CO_2 emissions consistent with any given level of peak warming.

When combined using GWP*, cumulative aggregate GHG emissions are closely proportional to total GHG-induced warming, while the annual rate of GHG-induced warming is proportional to the annual rate of aggregate GHG emissions (see Cross-Chapter Box 2, Figure 1). This is not the case when emissions are aggregated using GWP or GTP, with discrepancies particularly pronounced when SLCF emissions are falling. Persistent net zero CO_2-equivalent emissions containing a residual positive forcing contribution from SLCFs and aggregated using GWP_{100} or GTP would result in a steady decline of GMST. Net zero global emissions aggregated using GWP* (which corresponds to zero net emissions of CO_2 and other long-lived GHGs like nitrous oxide, combined with constant SLCF forcing – see Figure 1.5) results in approximately stable GMST (Fuglestvedt et al., 2018; Allen et al., 2018 and Cross-Chapter Box 2, Figure 1, below).

Whatever method is used to relate emissions of different greenhouse gases, scenarios achieving stable GMST well below 2°C require both near–zero net emissions of long–lived greenhouse gases and deep reductions in warming SLCFs (Chapter 2), in part to compensate for the reductions in cooling SLCFs that are expected to accompany reductions in CO_2 emissions (Rogelj et al., 2016b; Hienola et al., 2018). Understanding the implications of different methods of combining emissions of different climate forcers is, however, helpful in tracking progress towards temperature stabilisation and 'balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases' as stated in Article 4 of the Paris Agreement. Fuglestvedt et al. (2018) and Tanaka and O'Neill (2018)show that when, and even whether, aggregate GHG emissions need to reach net zero before 2100 to limit warming to 1.5°C depends on the scenario, aggregation method and mix of long-lived and short-lived climate forcers.

The comparison of the impacts of different climate forcers can also consider more than their effects on GMST (Johansson, 2012; Tol et al., 2012; Deuber et al., 2013; Myhre et al., 2013). Climate impacts arise from both magnitude and rate of climate change, and from other variables such as precipitation (Shine et al., 2015). Even if GMST is stabilised, sea-level rise and associated impacts will continue to increase (Sterner et al., 2014), while impacts that depend on CO_2 concentrations such as ocean acidification may begin to reverse. From an economic perspective, comparison of different climate forcers ideally reflects the ratio of marginal economic damages if used to determine the exchange ratio of different GHGs under multi–gas regulation (Tol et al., 2012; Deuber et al., 2013; Kolstad et al., 2014).

Emission reductions can interact with other dimensions of sustainable development (see Chapter 5). In particular, early action on some SLCFs (including actions that may warm the climate such as reducing SO_2 emissions) may have considerable societal co-benefits such as reduced air pollution and improved public health with associated economic benefits (OECD, 2016; Shindell et al., 2016). Valuation of broadly defined social costs attempts to account for many of these additional non–climate factors along with climate-related impacts (Shindell, 2015; Sarofim et al., 2017; Shindell et al., 2017). See Chapter 4, Section 4.3.6, for a discussions of mitigation options, noting that mitigation priorities for different climate forcers depend on multiple economic and social criteria that vary between sectors, regions and countries.



Cross Chapter Box 2, Figure 1: Implications of different approaches to calculating aggregate greenhouse gas emissions on a pathway to net zero (a) Aggregate emissions of well–mixed greenhouse gases (WMGHGs) under the RCP2.6 mitigation scenario expressed as CO_2–equivalent using GWP_{100} (blue); GTP_{100} (green) and GWP* (yellow). Aggregate WMGHG emissions appear to fall more rapidly if calculated using GWP* than using either GWP or GTP, primarily because GWP* equates falling methane emissions with negative CO_2 emissions, as only active CO_2 removal would have the same impact on radiative forcing and GMST as a reduction in methane emission rates. (b) Cumulative emissions of WMGHGs combined as in panel (a) (blue, green & yellow lines & left hand axis) and warming response to combined emissions (black dotted line & right hand axis, Millar et al. (2017a). The temperature response under ambitious mitigation is closely correlated with cumulative WMGHG emissions aggregated using GWP*, but with neither emission rate nor cumulative emissions if aggregated using GWP or GTP.

1.3 Impacts at 1.5°C and beyond

1.3.1 Definitions

Consistent with the AR5 (IPCC, 2014e) , 'impact' in this report refers to the effects of climate change on human and natural systems. Impacts may include the effects of changing hazards, such as the frequency and intensity of heat waves. 'Risk' refers to potential negative impacts of climate change where something of value is at stake, recognizing the diversity of values. Risks depend on hazards, exposure, vulnerability (including sensitivity and capacity to respond) and likelihood. Climate change risks can be managed through efforts to mitigate climate change forcers, adaptation of impacted systems and remedial measures (Section 1.4.1).

In the context of this report, *regional* impacts of *global* warming at 1.5°C and 2°C are assessed in Chapter 3. The '*warming experience at 1.5°C*' is that of regional climate change (temperature, rainfall, and other changes) at the time when global average temperatures, as defined in Section 1.2.1, reach 1.5°C above pre-industrial (the same principle applies to impacts at any other global mean temperature). Over the decade 2006-2015, many regions have experienced higher than average levels of warming and some are already now 1.5°C warmer with respect to the pre-industrial period (Figure 1.3). At a global warming of 1.5°C, some seasons will be substantially warmer than 1.5°C above pre–industrial (Seneviratne et al., 2016). Therefore, most regional impacts of a global mean warming of 1.5°C will be different from those of a regional warming by 1.5°C.

The impacts of 1.5°C global warming will vary in both space and time (Ebi et al., 2016). For many regions, an increase in global mean temperature by 1.5°C or 2°C implies substantial increases in the occurrence and/or intensity of some extreme events (Fischer and Knutti, 2015; Karmalkar and Bradley, 2017; King et al., 2017), resulting in different impacts (see Chapter 3). By comparing impacts at 1.5°C *vs.* those at 2°C, this report discusses the 'avoided impacts' by maintaining global temperature increase at or below 1.5°C as compared to 2°C, noting that these also depend on the pathway taken to 1.5°C (see Section 1.2.3 and Cross-Chapter Box 8 in Chapter 3 on 1.5°C warmer worlds). Many impacts take time to observe, and because of the warming trend, impacts over the past 20 years were associated with a level of human-induced warming that was, on average, 0.1–0.23°C colder than its present level, based on the AR5 estimate of the warming trend over this period (Section 1.2.1 and Kirtman et al., 2013). Attribution studies (e.g., van Oldenborgh et al., 2017) can address this bias, but informal estimates of 'recent impact experience' in a rapidly warming world necessarily understate the temperature-related impacts of the current level of warming.

1.3.2 Drivers of Impacts

Impacts of climate change are due to multiple environmental drivers besides rising temperatures, such as rising atmospheric CO_2, shifting rainfall patterns, rising sea levels, increasing ocean acidification, and extreme events, such as floods, droughts, and heat waves (IPCC, 2014e). For example, changes in rainfall affect the hydrological cycle and water availability (Schewe et al., 2014). Several impacts depend on atmospheric composition, for example, increasing atmospheric carbon dioxide levels leading to changes in plant productivity (Forkel et al., 2016), but also to ocean acidification (Hoegh-Guldberg et al., 2007). Other impacts are driven by changes in ocean heat content, for example, the destabilization of coastal ice-sheets and sea-level rise (Bindoff et al., 2007; Chen et al., 2017), whereas impacts due to heat waves depend directly on ambient air or ocean temperature (Matthews et al., 2017). Impacts can be direct, for example, coral bleaching due to ocean warming, and indirect, for example, reduced tourism due to coral bleaching. Indirect impacts can also arise from mitigation efforts such as changed agricultural management (Section 3.6.2) or remedial measures such as solar radiation modification (Section 4.3.8, Cross-Chapter Box 10 in Chapter 4).

Impacts may also be triggered by combinations of factors, including 'impact cascades' (Cramer et al., 2014) through secondary consequences of changed systems. Changes in agricultural water availability caused by upstream changes in glacier volume are a typical example. Recent studies also identify compound events (e.g., droughts and heat waves), that is, when impacts are induced by the combination of several climate events (AghaKouchak et al., 2014; Leonard et al., 2014; Martius et al., 2016; Zscheischler and Seneviratne, 2017).

There are now techniques to attribute impacts formally to anthropogenic global warming and associated rainfall changes (Rosenzweig et al., 2008; Cramer et al., 2014; Hansen et al., 2016), taking into account other drivers such as land use change (Oliver and Morecroft, 2014) and pollution (e.g., tropospheric ozone; Sitch et al., 2007). There are multiple lines of evidence that climate change has observable and often severely negative effects on people, especially where climate-sensitive biophysical conditions and socioeconomic / political constraints on adaptive capacities combine to create high vulnerabilities (IPCC, 2012c; World Bank, 2013; IPCC, 2014e). The character and severity of impacts depend not only on the hazards (e.g. changed climate averages and extremes) but also on the vulnerability (including sensitivities and adaptive capacities) of different communities and their exposure to climate threats. These impacts also affect a range of natural and human systems such as terrestrial, coastal and marine ecosystems and their services, agricultural production, infrastructure, the built environment, human health and other socio–economic systems (Rosenzweig et al., 2017).

Sensitivity to changing drivers varies markedly across systems and regions. Impacts of climate change on natural and managed ecosystems can imply loss or increase in growth, biomass or diversity at the level of species populations, interspecific relationships such as pollination, landscapes or entire biomes. Impacts occur in addition to the natural variation in growth, ecosystem dynamics, disturbance, succession and other processes, rendering attribution of impacts at lower levels of warming difficult in certain situations. The same magnitude of warming can be lethal during one phase of the life of an organism and irrelevant during another. Many ecosystems (notably forests, coral reefs and others) undergo long-term successional processes characterised by varying levels of resilience to environmental change over time. Organisms and ecosystems may adapt to environmental change to a certain degree, for example, through changes in physiology, ecosystem structure, species composition or evolution. Large-scale shifts in ecosystems may cause important feedbacks, for example, in terms of changing water and carbon fluxes through impacted ecosystems – these can amplify or dampen atmospheric change at regional to continental scale. For example, of particular concern, is the response of most of the world's forests and seagrass ecosystems, which play key roles as carbon sinks (Settele et al., 2014; Marbà et al., 2015).

Some ambitious efforts to constrain atmospheric greenhouse gas concentrations may themselves impact ecosystems. In particular, changes in land use, potentially required for massively enhanced production of biofuels (either as simple replacement of fossil fuels, or as part of Bioenergy with Carbon Capture and Storage, BECCS) impact all other land ecosystems through competition for land (e.g., Creutzig, 2016) (see Cross-Chapter Box 7 in Chapter 3, Section 3.6.2.1).

Human adaptive capacity to a 1.5°C warmer world varies markedly for individual sectors and across sectors such as water supply, public health, infrastructure, ecosystems and food supply. For example, density and risk exposure, infrastructure vulnerability and resilience, governance and institutional capacity all drive different impacts across a range of human settlement types (Dasgupta et al., 2014; Revi et al., 2014; Rosenzweig et al., 2018). Additionally, the adaptive capacity of communities and human settlements in both rural and urban areas, especially in highly populated regions, raises equity, social justice and sustainable development issues. Vulnerabilities due to gender, age, level of education and culture act as compounding factors (Arora-Jonsson, 2011; Cardona et al., 2012; Resurrección, 2013; Olsson et al., 2014; Vincent et al., 2014).

1.3.3 Uncertainty and non-linearity of impacts

Uncertainties in projections of future climate change and impacts come from a variety of different sources, including the assumptions made regarding future emission pathways (Moss et al., 2010), the inherent limitations and assumptions of the climate models used for the projections, including limitations in simulating regional climate variability (James et al., 2017), downscaling and bias-correction methods (Ekström et al., 2015), and in impact models (e.g., Asseng et al., 2013). The evolution of climate change also affects uncertainty with respect to impacts. For example, the impacts of overshooting 1.5°C and stabilization at a later stage, compared to stabilization at 1.5°C without overshoot may differ in magnitude (Schleussner et al., 2016).

AR5 IPCC (2013b) and World Bank (2013) underscored the non-linearity of risks and impacts as temperature rises from 2°C to 4°C of warming, particularly in relation to water availability, heat extremes, bleaching of coral reefs, and more. Recent studies (Schleussner et al., 2016; James et al., 2017; King et al., 2018) assess the impacts of 1.5°C versus 2°C warming, with the same message of non-linearity. The resilience of ecosystems, meaning their ability either to resist change or to recover after a disturbance, may change, and often decline, in a non-linear way. An example are reef ecosystems, with some studies suggesting that reefs will change, rather than disappear entirely, and particular species showing greater tolerance to coral bleaching than others (Pörtner et al., 2014). A key issue is therefore whether ecosystems such as coral reefs survive an overshoot scenario, and to what extent would they be able to recover after stabilization at 1.5°C or higher levels of warming (see Box 3.4).

1.4 Strengthening the global response

This section frames the implementation options, enabling conditions (discussed further in Cross-Chapter Box 3 on feasibility in this Chapter), capacities and types of knowledge and their availability (Blicharska et al., 2017) that can allow institutions, communities and societies to respond to the 1.5°C challenge in the context of sustainable development and the Sustainable Development Goals (SDGs). It also addresses other relevant international agreements such as the Sendai Framework for Disaster Risk Reduction. Equity and ethics are recognised as issues of importance in reducing vulnerability and eradicating poverty.

The connection between the enabling conditions for limiting global warming to 1.5°C and the ambitions of the SDGs are complex across scale and multifaceted (Chapter 5). Climate mitigation-adaptation linkages, including synergies and trade-offs, are important when considering opportunities and threats for sustainable development. The IPCC AR5 acknowledged that ‘adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses’ (Denton et al., 2014). Climate mitigation and adaptation measures and actions can reflect and enforce specific patterns of development and governance that differ amongst the world’s regions (Gouldson et al., 2015; Termeer et al., 2017). The role of limited adaptation and mitigation capacity, limits to adaptation and mitigation, and conditions of mal-adaptation and mal-mitigation are assessed in this report (Chapters 4 and 5).

1.4.1 Classifying Response Options

Key broad categories of responses to the climate change problem are framed here. **Mitigation** refers to efforts to reduce or prevent the emission of greenhouse gases, or to enhance the absorption of gases already emitted, thus limiting the magnitude of future warming (IPCC, 2014c). Mitigation requires the use of new technologies, clean energy sources, reduced deforestation, improved sustainable agricultural methods, and changes in individual and collective behaviour. Many of these may provide substantial co-benefits for air quality, biodiversity and sustainable development. Mal-mitigation includes changes that could reduce emissions in the short-term but could lock in technology choices or practices that include significant trade-offs for effectiveness of future adaptation and other forms of mitigation (Chapters 2 and 4).

Carbon dioxide removal (CDR) or ‘negative emissions’ activities are considered a distinct type of mitigation. While most types of mitigation focus on reducing the amount of carbon dioxide or greenhouse gases emitted, CDR aims to reduce concentrations already in the atmosphere. Technologies for CDR are mostly in their infancy despite their importance to ambitious climate change mitigation pathways (Minx et al., 2017). Although some CDR activities such as reforestation and ecosystem restoration are well understood, the feasibility of massive-scale deployment of many CDR technologies remains an open question (IPCC, 2014d; Leung et al., 2014) (Chapters 2 and 4). Technologies for the active removal of other greenhouse gases, such as methane, are even less developed, and are briefly discussed in Chapter 4.

Climate change **adaptation** refers to the actions taken to manage the impacts of climate change (IPCC, 2014e). The aim is to reduce vulnerability and exposure to the harmful effects of climate change (e.g. sea–level rise, more intense extreme weather events or food insecurity). It also includes exploring the potential beneficial opportunities associated with climate change (for example, longer growing seasons or increased yields in some regions). Different adaptation-pathways can be undertaken. Adaptation can be incremental, or transformational, meaning fundamental attributes of the system are changed (Chapter 3 and 4). There can be limits to ecosystem-based adaptation or the ability of humans to adapt (Chapter 4). If there is no possibility for adaptive actions that can be applied to avoid an intolerable risk, these are referred to as hard adaptation limits, while soft adaptation limits are identified when there are currently no options to avoid intolerable risks, but they are theoretically possible (Chapter 3 and 4). While climate change is a global issue, impacts are experienced locally. Cities and municipalities are at the frontline of adaptation (Rosenzweig et al., 2018), focusing on reducing and managing disaster risks due to extreme and slow-onset weather and climate events, installing flood and drought early warning systems, and improving water storage and use (Chapters 3 and 4 and Cross-Chapter Box 12 in Chapter 5). Agricultural and rural areas, including often highly vulnerable remote and indigenous communities, also need to address climate-related risks by strengthening and making more resilient agricultural and other natural resource extraction systems.

Remedial measures are distinct from mitigation or adaptation, as the aim is to temporarily reduce or offset warming (IPCC, 2012b). One such measure is Solar Radiation Modification (SRM), also referred to as Solar Radiation Management in the literature, which involves deliberate changes to the albedo of the Earth system, with the net effect of increasing the amount of solar radiation reflected from the Earth to reduce the peak temperature from climate change (The Royal Society, 2009; Smith and Rasch, 2013; Schäfer et al., 2015). It should be noted that while some radiation modification measures, such as cirrus cloud thinning (Kristjánsson et al., 2016), aim at enhancing outgoing long-wave radiation, SRM is used in this report to refer to all direct interventions on the planetary radiation budget. This report does not use the term ‘geo-engineering’ because of inconsistencies in the literature, which uses this term to cover SRM, CDR or both, whereas this report explicitly differentiates between CDR and SRM. Large-scale SRM could potentially be used to supplement mitigation in overshoot scenarios to keep the global mean temperature below 1.5°C and temporarily reduce the severity of near-term impacts (e.g., MacMartin et al., 2018). The impacts of SRM (both biophysical and societal), costs, technical feasibility, governance and ethical issues associated need to be carefully considered (Schäfer et al., 2015; Section 4.3.8 and Cross-Chapter Box 10 in Chapter 4).

1.4.2 Governance, implementation and policies

A challenge in meeting the enabling conditions of 1.5°C warmer world is the governance capacity of institutions to develop, implement and evaluate the changes needed within diverse and highly interlinked global social-ecological systems (Busby, 2016) (Chapter 4). Policy arenas, governance structures and robust institutions are key enabling conditions for transformative climate action

(Chapter 4). It is through governance that justice, ethics and equity within the adaptation-mitigation-sustainable development nexus can be addressed (Stechow et al., 2016) (Chapter 5).

Governance capacity includes a wide range of activities and efforts needed by different actors to develop coordinated climate mitigation and adaptation strategies in the context of sustainable development taking into account equity, justice and poverty eradication. Significant governance challenges include the ability to incorporate multiple stakeholder perspectives in the decision-making process to reach meaningful and equitable decisions, interactions and coordination between different levels of government, and the capacity to raise financing and support for both technological and human resource development. For example, Lövbrand et al. (2017), argue that the voluntary pledges submitted by states and non-state actors to meet the conditions of the Paris Agreement will need to be more firmly coordinated, evaluated and upscaled.

Barriers for transitioning from climate change mitigation and adaptation planning to practical policy implementation include finance, information, technology, public attitudes, social values and practices (Whitmarsh et al., 2011; Corner and Clarke, 2017) and human resource constraints. Institutional capacity to deploy available knowledge and resources is also needed (Mimura et al., 2014). Incorporating strong linkages across sectors, devolution of power and resources to sub-national and local governments with the support of national government and facilitating partnerships among public, civic, private sectors and higher education institutions (Leal Filho et al., 2018) can help in the implementation of identified response options (Chapter 4). Implementation challenges of 1.5ºC pathways are larger than for those that are consistent with limiting warming to well below 2ºC, particularly concerning scale and speed of the transition and the distributional impacts on ecosystems and socio-economic actors. Uncertainties in climate change at different scales and different capacities to respond combined with the complexities of coupled social and ecological systems point to a need for diverse and adaptive implementation options within and among different regions involving different actors. The large regional diversity between highly carbon-invested economies and emerging economies are important considerations for sustainable development and equity in pursuing efforts to limit warming to 1.5°C. Key sectors, including energy, food systems, health, and water supply, also are critical to understanding these connections.

Cross-Chapter Box 3: Framing feasibility: Key concepts and conditions for limiting global temperature increases to 1.5°C

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This Cross-Chapter Box describes the concept of feasibility in relation to efforts to limit global warming to 1.5°C in the context of sustainable development and efforts to eradicate poverty and draws from the understanding of feasibility emerging within the IPCC (IPCC, 2017). Feasibility can be assessed in different ways, and no single answer exists as to the question of whether it is feasible to limit warming to 1.5°C. This implies that an assessment of feasibility would go beyond a ‘yes’ or a ‘no’. Rather, feasibility provides a frame to understand the different conditions and potential responses for implementing adaptation and mitigation pathways, and options compatible with a 1.5°C warmer world. This report assesses the overall feasibility of a 1.5°C world, and the feasibility of adaptation and mitigation options compatible with a 1.5°C warmer world in six dimensions:

Geophysical: What global emission pathways could be consistent with conditions of a 1.5°C warmer world? What are the physical potentials for adaptation?

Environmental-ecological: What are the ecosystem services and resources, including geological storage capacity and related rate of needed land use change, available to promote transformations, and to what extent are they compatible with enhanced resilience?
Technological: What technologies are available to support transformation?
Economic: What economic conditions could support transformation?
Socio-cultural: What conditions could support transformations in behaviour and lifestyles? To what extent are the transformations socially acceptable and consistent with equity?
Institutional: What institutional conditions are in place to support transformations, including multi-level governance, institutional capacity, and political support?

The report starts by assessing which mitigation pathways would lead to a 1.5°C world, which indicates that rapid and deep deviations from current emission pathways are necessary (Chapter 2). In the case of adaptation, an assessment of feasibility starts from an evaluation of the risks and impacts of climate change (Chapter 3). To mitigate and adapt to climate risks, system-wide technical, institutional and socio-economic transitions would be required, as well as the implementation of a range of specific mitigation and adaptation options. Chapter 4 applies various indicators categorised in these six dimensions to assess the feasibility of illustrative examples of relevant mitigation and adaptation options (Section 4.5.1). Such options and pathways have different effects on sustainable development, poverty eradication and adaptation capacity (Chapter 5).

The six feasibility dimensions interact in complex, and place-specific ways. Synergies and trade-offs may occur between the feasibility dimensions, and between specific mitigation and adaptation options (Section 4.5.4). The presence or absence of enabling conditions would affect the options that comprise feasibility pathways (Section 4.4), and can reduce trade-offs and amplify synergies between options.

Sustainable development, eradicating poverty and reducing inequalities are not only preconditions for feasible transformations, but the interplay between climate action (both mitigation and adaptation options) and the development patterns on which they apply may actually enhance the feasibility of particular options (see Chapter 5).

The connections between the feasibility dimensions can be specified across three types of effects (discussed below). Each of these dimensions presents challenges and opportunities in realizing conditions consistent with a 1.5°C warmer world.

Systemic effects: Conditions that have embedded within them system level functions that could include linear and non-linear connections and feedbacks. For example, the deployment of technology and large installations (e.g., renewable or low carbon energy mega–projects) depends upon economic conditions (costs, capacity to mobilize investments for R&D), social or cultural conditions (acceptability), and institutional conditions (political support; e.g., Sovacool et al., 2015). Case studies can demonstrate system level interactions and positive or negative feedback effects between the different conditions (Jacobson et al., 2015; Loftus et al., 2015). This suggests that each set of conditions and their interactions need to be considered to understand synergies, inequities and unintended consequences.

Dynamic effects: Conditions that are highly dynamic and vary over time, especially under potential conditions of overshoot or no overshoot. Some dimensions might be more time sensitive or sequential than others (i.e., if conditions are such that it is no longer geophysically feasible to avoid overshooting 1.5°C, the social and institutional feasibility of avoiding overshoot will be no longer relevant). Path dependencies, risks of legacy locks-ins related to existing infrastructures, and possibilities of acceleration permitted by cumulative effects like learning-by-doing driving dramatic costs decreases are all key features to be captured. The effects can play out over various time scales and thus require understanding the connections between near-term (meaning within the next several years to two decades) and their long-term implications (meaning over the next several decades) when assessing feasibility conditions.

Spatial effects: Conditions that are spatially variable and scale dependent, according to context-specific factors such as regional-scale environmental resource limits and endowment; economic wealth of local populations; social organisation, cultural beliefs, values and worldviews; spatial organisation, including conditions of urbanisation; and financial and institutional and governance capacity. This means that the conditions for achieving the global transformation required for a 1.5°C world will be heterogeneous and vary according to the specific context. On the other hand, the satisfaction of these conditions may depend upon global-scale drivers, such as international flows of finance, technologies or capacities. This points to the need for understanding feasibility to capture the interplay between the conditions at different scales.

With each effect, the interplay between different conditions influences the feasibility of both pathways (Chapter 2) and options (Chapter 4), which in turn affect the likelihood of limiting warming to 1.5°C. The complexity of these interplays triggers unavoidable uncertainties, requiring transformations that remain robust under a range of possible futures that limit warming to 1.5°C.

1.4.3 Transformation, transformation pathways, and transition: evaluating trade-offs and synergies between mitigation, adaptation and sustainable development goals

Embedded in the goal of limiting warming to 1.5°C is the opportunity for intentional societal transformation (see Box 1.1 on the Anthropocene). The form and process of transformation are varied and multifaceted (Pelling, 2011; O’Brien et al., 2012; O’Brien and Selboe, 2015; Pelling et al., 2015). Fundamental elements of 1.5°C-related transformation include a decoupling of economic growth from energy demand and CO_2 emissions, leap-frogging development to new and emerging low-carbon, zero-carbon and carbon-negative technologies, and synergistically linking climate mitigation and adaptation to global scale trends (e.g., global trade and urbanization) that will enhance the prospects for effective climate action, as well as enhanced poverty reduction and greater equity (Tschakert et al., 2013; Rogelj et al., 2015; Patterson et al., 2017) (Chapters 4 and 5). The connection between transformative climate action and sustainable development illustrates a complex coupling of systems that have important spatial and time scale lag effects and implications for process and procedural equity including intergenerational equity and for non-human species (Cross-Chapter Box 4 in this Chapter, Chapter 5). Adaptation and mitigation transition pathways highlight the importance of cultural norms and values, sector specific context, and proximate (i.e. occurrence of an extreme event) drivers that when acting together enhance the conditions for societal transformation (Solecki et al., 2017; Rosenzweig et al., 2018) (Chapters 4 and 5).

Diversity and flexibility in implementation choices exist for adaptation, mitigation (including carbon dioxide removal, CDR) and remedial measures (such as solar radiation modification, SRM), and a potential for trade-offs and synergies between these choices and sustainable development (IPCC, 2014f; Olsson et al., 2014). The responses chosen could act to synergistically enhance mitigation, adaptation and sustainable development or they may result in trade-offs which positively impact some aspects and negatively impact others. Climate change is expected to increase the likelihood of not achieving the Sustainable Development Goals (SDGs), while some strategies limiting warming towards 1.5°C are expected to significantly lower that risk and provide synergies for climate adaptation and mitigation (Chapter 5).

Dramatic transformations required to achieve the enabling conditions for a 1.5°C warmer world could impose trade-offs on dimensions of development (IPCC, 2014f; Olsson et al., 2014). Some choices of adaptation methods also could adversely impact development (Olsson et al., 2014).This report recognizes the potential for adverse impacts and focuses on finding the synergies between limiting warming, sustainable development, and eradicating poverty, thus highlighting pathways that do not constrain other goals, such as sustainable development and eradicating poverty.

The report is framed to address these multiple goals simultaneously and assesses the conditions to achieve a cost-effective and socially acceptable solution, rather than addressing these goals piecemeal (Stechow et al., 2016) (Section 4.5.4 and Chapter 5), although there may be different synergies and trade-offs between a 2°C (Stechow et al., 2016) and 1.5°C warmer world (Kainuma et al., 2017). Climate-resilient development pathways (see Cross-Chapter Box 12 in Chapter 5 and Glossary) are trajectories that strengthen sustainable development, including mitigating and adapting to climate change and efforts to eradicate poverty while promoting fair and cross-scalar resilience in a changing climate. They take into account dynamic livelihoods, the multiple dimensions of poverty, structural inequalities, and equity between and among poor and non-poor people (Olsson et al., 2014). Climate-resilient development pathways can be considered at different scales, including cities, rural areas, regions or at global level (Denton et al., 2014; Chapter 5).

Cross-Chapter Box 4: Sustainable Development and the Sustainable Development Goals

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Sustainable development is most often defined as ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (WCED, 1987) and includes balancing social wellbeing, economic prosperity and environmental protection. The AR5 used this definition and linked it to climate change (Denton et al., 2014). The most significant step since AR5 is the adoption of the UN Sustainable Development Goals, and the emergence of literature that links them to climate (von Stechow et al., 2015; Wright et al., 2015; Epstein et al., 2017; Hammill and Price-Kelly, 2017; Kelman, 2017; Lofts et al., 2017; Maupin, 2017; Gomez-Echeverri, 2018).

In September 2015, the UN endorsed a universal agenda – ‘Transforming our World: the 2030 Agenda for Sustainable Development’ – which aims ‘to take the bold and transformative steps which are urgently needed to shift the world onto a sustainable and resilient path’. Based on a participatory process, the resolution in support of the 2030 agenda adopted 17 non-legally-binding Sustainable Development Goals (SDGs) and 169 targets to support people, prosperity, peace, partnerships and the planet (Kanie and Biermann, 2017).

The SDGs expanded efforts to reduce poverty and other deprivations under the UN Millennium Development Goals (MDGs). There were improvements under the MDGs between 1990 and 2015, including reducing overall poverty and hunger, reducing infant mortality, and improving access to drinking water (United Nations, 2015). However, greenhouse gas emissions increased by more than 50% from 1990 to 2015, and 1.6 billion people were still living in multidimensional poverty with persistent inequalities in 2015 (Alkire et al., 2015).

The SDGs raise the ambition for eliminating poverty, hunger, inequality and other societal problems while protecting the environment. They have been criticised: as too many and too complex, needing more realistic targets, overly focused on 2030 at the expense of longer term objectives, not embracing all aspects of sustainable development, and even contradicting each other (Horton, 2014; Death and Gabay, 2015; Biermann et al., 2017; Weber, 2017; Winkler and Satterthwaite, 2017).

Climate change is an integral influence on sustainable development, closely related to the economic, social and environmental dimensions of the SDGs. The IPCC has woven the concept of sustainable development into recent assessments, showing how climate change might undermine sustainable development, and the synergies between sustainable development and responses to climate change (Denton et al., 2014). Climate change is also explicit in the SDGs. SDG13 specifically requires ‘urgent action to address climate change and its impacts’. The targets include strengthening resilience and adaptive capacity to climate-related hazards and natural disasters; integrating climate change measures into national policies, strategies and planning; and improving education, awareness-raising and human and institutional capacity.

Targets also include implementing the commitment undertaken by developed-country parties to the UNFCCC to the goal of mobilizing jointly $100 billion annually by 2020 and operationalizing the Green Climate Fund, as well as promoting mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and Small Island Developing States, including focusing on women, youth and local and marginalised communities. SDG13 also acknowledges that the United Nations Framework Convention on Climate Change (UNFCCC) is the primary international, intergovernmental forum for negotiating the global response to climate change.

Climate change is also mentioned in SDGs beyond SDG13, for example in goal targets 1.5, 2.4, 11.B, 12.8.1 related to poverty, hunger, cities and education respectively. The UNFCCC addresses other SDGs in commitments to ‘control, reduce or prevent anthropogenic emissions of greenhouse gases […] in all relevant sectors, including the energy, transport, industry, agriculture, forestry and waste management sectors’ (Art4, 1(c)) and to work towards ‘the conservation and enhancement, as appropriate, of […] biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems’ (Art4, 1(d)). This corresponds to SDGs that seek clean energy for all (Goal 7), sustainable industry (Goal 9) and cities (Goal 11) and the protection of life on land and below water (14 and 15).

The SDGs and UNFCCC also differ in their time horizons. The SDGs focus primarily on 2030 whereas the Paris Agreement sets out that ‘Parties aim […] to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century’.

The IPCC decision to prepare this report of the impacts of 1.5°C and associated emission pathways explicitly asked for the assessment to be in the context of sustainable development and efforts to eradicate poverty. Chapter 1 frames the interaction between sustainable development, poverty eradication and ethics and equity. Chapter 2 assesses how risks and synergies of individual mitigation measures interact with1.5°C pathways within the context of the SDGs, and how these vary according to the mix of measures in alternative mitigation portfolios (Section 2.5). Chapter 3 examines the impacts of 1.5°C global warming on natural and human systems with comparison to 2°C and provides the basis for considering the interactions of climate change with sustainable development in Chapter 5. Chapter 4 analyses strategies for strengthening the response to climate change, many of which interact with sustainable development. Chapter 5 takes sustainable development, eradicating poverty and reducing inequalities as its focal point for the analysis of pathways to 1.5°C, and discusses explicitly the linkages between achieving SDGs while eradicating poverty and reducing inequality.

Cross-Chapter Box 4, Figure 1: Climate action is number 13 of the UN Sustainable Development Goals.

1.5 Assessment frameworks and emerging methodologies that integrate climate change mitigation and adaptation with sustainable development

This report employs information and data that are global in scope and include region-scale analysis. It also includes syntheses of municipal, sub-national, and national case studies. Global level statistics including physical and social science data are used, as well as detailed and illustrative case study material of particular conditions and contexts. The assessment provides the state of knowledge, including an assessment of confidence and uncertainty. The main timescale of the assessment is the 21st century and the time is separated into the near-, medium-, and long-term. Spatial and temporal contexts are illustrated throughout including: assessment tools that include dynamic projections of emission trajectories and the underlying energy and land transformation (Chapter 2); methods for assessing observed impacts and projected risks in natural and managed ecosystems and at 1.5°C and higher levels of warming in natural and managed ecosystems and human systems (Chapter 3); assess the feasibility of mitigation and adaptation options (Chapter 4); and linkages of the Shared Socioeconomic Pathways (SSPs) and Sustainable Development Goals (SDGs) (Cross-Chapter Boxes 1 and 4 in this Chapter, Chapter 2 and Chapter 5).

1.5.1 Knowledge sources and evidence used in the report

This report is based on a comprehensive assessment of documented evidence of the enabling conditions to pursuing efforts to limit the global average temperature to 1.5°C and adapt to this level of warming in the overarching context of the Anthropocene (Delanty and Mota, 2017). Two sources of evidence are used; peer-reviewed scientific literature and 'grey' literature in accordance with procedure on the use of literature in IPCC reports (IPCC, 2013a, Annex 2 to Appendix A), with the former being the dominant source. Grey literature is largely used on key issues not covered in peer-reviewed literature.

The peer-reviewed literature includes the following sources: 1) knowledge regarding the physical climate system and human-induced changes, associated impacts, vulnerabilities and adaptation options, established from work based on empirical evidence, simulations, modelling and scenarios, with emphasis on new information since the publication of the IPCC AR5 to the cut-off date for this report (15th of May 2018); 2) Humanities and social science theory and knowledge from actual human experiences of climate change risks and vulnerability in the context of the social-ecological systems, development, equity, justice, and the role of governance, and from indigenous knowledge systems; and 3) Mitigation pathways based on climate projections into the future.

The grey literature category extends to empirical observations, interviews, and reports from government, industry, research institutes, conference proceedings and international or other organisations. Incorporating knowledge from different sources, settings and information channels while building awareness at various levels will advance decision making and motivate implementation of context specific responses to 1.5°C warming (Somanathan et al., 2014). The assessment does not assess non–written evidence and does not use oral evidence, media reports, or newspaper publications. With important exceptions, such as China, published knowledge from the most vulnerable parts of the world to climate change is limited (Czerniewicz et al., 2017).

1.5.2 Assessment frameworks and methodologies

Climate models and associated simulations

The multiple sources of climate model information used in this assessment are provided in Chapter 2 (Section 2.2) and Chapter 3 (Section 3.2). Results from global simulations, which have also been assessed in previous IPCC reports and that are conducted as part of the World Climate Research Programme (WCRP) Coupled Models Inter-comparison Project (CMIP) are used. The IPCC AR4 and Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) reports were mostly based on simulations from the CMIP3 experiment, while the AR5 was mostly based on simulations from the CMIP5 experiment. The simulations of the CMIP3 and CMIP5 experiments were found to be very similar (e.g.; Knutti and Sedláček, 2012; Mueller and Seneviratne, 2014). In addition to the CMIP3 and CMIP5 experiments, results from coordinated regional climate model experiments (e.g.; the Coordinated Regional Climate Downscaling Experiment, CORDEX) have been assessed, which are available for different regions (Giorgi and Gutowski, 2015). For instance, assessments based on publications from an extension of the IMPACT2C project (Vautard et al., 2014; Jacob and Solman, 2017) are newly available for 1.5°C projections. Recently, simulations from the 'Half a degree Additional warming, Prognosis and Projected Impacts' (HAPPI) multi-model experiment have been performed to specifically assess climate changes at 1.5°C vs 2°C global warming (Mitchell et al., 2016). The HAPPI protocol consists of coupled land-atmosphere initial condition ensemble simulations with prescribed sea surface temperatures (SSTs), sea-ice, GHG and aerosol concentrations, solar and volcanic activity that coincide with three forced climate states: present-day (2006–2015) (see section 1.2.1), and future (2091–2100) either with 1.5°C or 2°C global warming (prescribed by modified SSTs).

Detection and attribution of change in climate and impacted systems

Formalized scientific methods are available to detect and attribute impacts of greenhouse gas forcing on observed changes in climate (e.g. Hegerl et al., 2007; Seneviratne et al., 2012; Bindoff et al., 2013) and impacts of climate change on natural and human systems (e.g. Stone et al., 2013; Hansen and Cramer, 2015; Hansen et al., 2016). The reader is referred to these sources, as well as to the AR5 for more background on these methods.

Global climate warming has already reached approximately 1°C (see Section 1.2.1) relative to pre–industrial conditions, and thus 'climate at 1.5°C global warming' corresponds to approximately the addition of only half a degree of warming compared to the present day, comparable to the warming that has occurred since the 1970s (Bindoff et al., 2013). Methods used in the attribution of observed changes associate with this recent warming are therefore also applicable to assessments of future changes in climate at 1.5°C warming, especially in cases where no climate model simulations or analyses are available.

Impacts of 1.5°C global warming can be assessed in part from regional and global climate changes that have already been detected and attributed to human influence (e.g., Schleussner et al., 2017) and are components of the climate system that are most responsive to current and projected future forcing. For this reason, when specific projections are missing for 1.5°C global warming, some of the assessments of climate change provided in Chapter 3 (Section 3.3) build upon joint assessments of a) changes that were observed and attributed to human influence up to the present, i.e. for 1°C global warming and b) projections for higher levels of warming (e.g., 2°C, 3°C or 4°C) to assess the changes at 1.5°C. Such assessments are for transient changes only (see Chapter 3, Section 3.3).

Besides quantitative detection and attribution methods, assessments can also be based on indigenous and local knowledge (see Chapter 4, Box 4.3). While climate observations may not be available to assess impacts from a scientific perspective, local community knowledge can also indicate actual impacts (Brinkman et al., 2016; Kabir et al., 2016). The challenge is that a community's perception of loss due to the impacts of climate change is an area that requires further research (Tschakert et al., 2017).

Costs and benefits analysis

Cost-benefit analyses are common tools used for decision-making, whereby the costs of impacts are compared to the benefits from different response actions (IPCC, 2014d, e). However, for the case of climate change, recognising the complex inter-linkages of the Anthropocene, cost-benefit analyses tools can be difficult to use because of disparate impacts versus costs and complex interconnectivity within the global social-ecological system (see Box 1.1 and Cross-Chapter Box 5 in Chapter 2). Some costs are relatively easily quantifiable in monetary terms but not all. Climate change impacts humans' lives and livelihoods, culture and values and whole ecosystem. It has unpredictable feedback loops and impacts on other regions, (IPCC, 2014e) giving rise to indirect, secondary, tertiary and opportunity costs that are typically extremely difficult to quantify. Monetary quantification is further complicated by the fact that costs and benefits can occur in different regions at very different times, possibly spanning centuries, while it is extremely difficult if not impossible to meaningfully estimate discount rates for future costs and benefits. Thus standard cost–benefit analyses become difficult to justify (IPCC, 2014e; Dietz et al., 2016) and are not used as an assessment tool in this report.

1.6 Confidence, uncertainty and risk

This report relies on the IPCC's uncertainty guidance provided in Mastrandrea et al. (2011), and sources given therein. Two metrics for qualifying key findings are used:

Confidence: Five qualifiers are used to express levels of confidence in key findings, ranging from *very low*, through *low*, *medium*, *high*, to *very high*. The assessment of confidence involves at least two dimensions, one being the type, quality, amount or internal consistency of individual lines of evidence, and the second being the level of agreement between different lines of evidence. Very high confidence findings must either be supported by a high level of agreement across multiple lines of mutually independent and individually robust lines of evidence or, if only a single line of evidence is available, by a very high level of understanding underlying that evidence. Findings of low or very low confidence are presented only if they address a topic of major concern.

Likelihood: A calibrated language scale is used to communicate assessed probabilities of outcomes, ranging from *exceptionally unlikely* (<1%), *extremely unlikely* (<5%), *very unlikely* (<10%), *unlikely* (<33%), *about as likely as not* (33–66%), *likely* (>66%), *very likely* (>90%), *extremely likely* (>95%)

to *virtually certain* (>99%). These terms are normally only applied to findings associated with high or very high confidence. Frequency of occurrence within a model ensemble does not correspond to actual assessed probability of outcome unless the ensemble is judged to capture and represent the full range of relevant uncertainties.

Three specific challenges arise in the treatment of uncertainty and risk in this report. First, the current state of the scientific literature on 1.5°C means that findings based on multiple lines of robust evidence for which quantitative probabilistic results can be expressed may be few, and not the most policy-relevant. Hence many key findings are expressed using confidence qualifiers alone.

Second, many of the most important findings of this report are conditional because they refer to ambitious mitigation scenarios. Conditional probabilities often depend strongly on how conditions are specified, such as whether temperature goals are met through early emission reductions, reliance on negative emissions, or through a low climate response. Whether a certain risk is deemed likely at 1.5°C may therefore depend strongly on how 1.5°C is specified, whereas a statement that a certain risk may be substantially higher at 2°C relative to 1.5°C may be much more robust.

Third, achieving ambitious mitigation goals will require active, goal-directed efforts aiming explicitly for specific outcomes and incorporating new information as it becomes available (Otto et al., 2015). This shifts the focus of uncertainty from the climate outcome itself to the level of mitigation effort that may be required to achieve it. Probabilistic statements about human decisions are always problematic, but in the context of robust decision-making, many near-term policies that are needed to keep open the option of achieving 1.5°C may be the same, regardless of the actual probability that the goal will be met (Knutti et al., 2015).

1.7 Storyline of the report

The storyline of this report (Figure 1.6) includes a set of interconnected components. The report consists of five chapters, a Technical Summary and a Summary for Policymakers. It also includes a set of boxes to elucidate specific or cross-cutting themes, as well as Frequently Asked Questions for each chapter and a Glossary.

At a time of unequivocal and rapid global warming, this report emerges from the long-term temperature goal of the Paris Agreement; strengthening the global response to the threat of climate change by pursuing efforts to limit warming to 1.5°C through reducing emissions to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases. The assessment focuses first, in Chapter 1, on how 1.5°C is defined and understood, what is the current level of warming to date, and the present trajectory of change. The framing presented in Chapter 1 provides the basis through which to understand the enabling conditions of a 1.5°C warmer world and connections to the SDGs, poverty eradication, and equity and ethics.

In Chapter 2, scenarios of a 1.5°C warmer world and the associated pathways are assessed. The pathways assessment builds upon the AR5 with a greater emphasis on sustainable development in mitigation pathways. All pathways begin now, and involve rapid and unprecedented societal transformation. An important framing device for this report is the recognition that choices that determine emissions pathways, whether ambitious mitigation or ‘no policy’ scenarios, do not occur independently of these other changes and are, in fact, highly interdependent.

Projected impacts that emerge in a 1.5°C warmer world and beyond are dominant narrative threads of the report and are assessed in Chapter 3. The chapter focuses on observed and attributable global and regional climate changes and impacts and vulnerabilities. The projected impacts have diverse and uneven spatial, temporal, and human, economic, and ecological system-level manifestations. Central to the assessment is the reporting of impacts at 1.5°C and 2°C, potential impacts avoided through limiting warming to 1.5°C, and, where possible, adaptation potential and limits to adaptive capacity.

Response options and associated enabling conditions emerge next, in Chapter 4. Attention is directed to exploring questions of adaptation and mitigation implementation and integration and transformation in a highly interdependent world, with consideration of synergies and trade-offs. Emission pathways, in particular, are broken down into policy options and instruments. The role of technological choices, institutional capacity and large-scale global scale trends like urbanization and changes in ecosystems are assessed.

Chapter 5 covers linkages between achieving the SDGs and a 1.5°C warmer world and turns toward identifying opportunities and challenges of transformation. This is assessed within a transition to climate-resilient development pathways, and connection between the evolution towards 1.5°C, associated impacts, and emission pathways. Positive and negative effects of adaptation and mitigation response measures and pathways for a 1.5°C warmer world are examined. Progress along these pathways involves inclusive processes, institutional integration, adequate finance and technology, and attention to issues of power, values, and inequalities to maximize the benefits of pursuing climate stabilisation at 1.5°C and the goals of sustainable development at multiple scales of human and natural systems from global, regional, national to local and community levels.

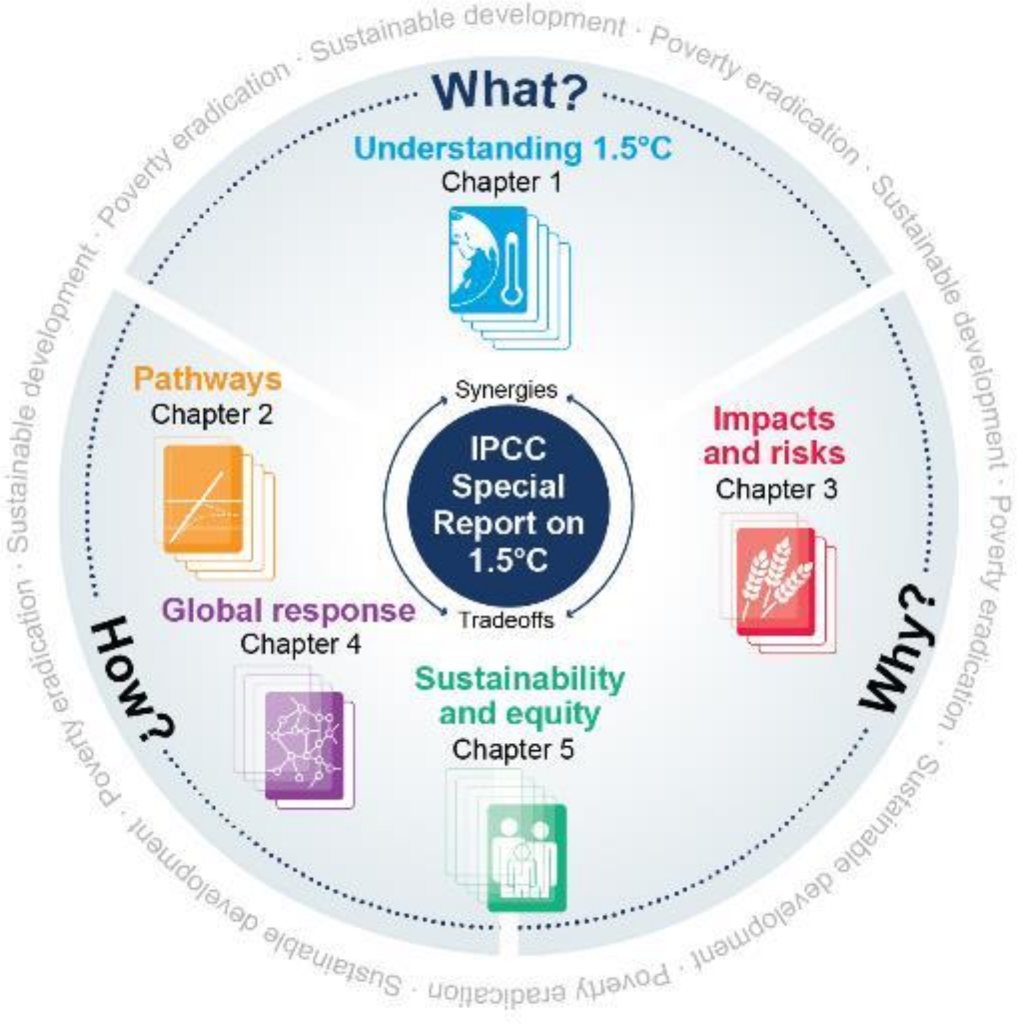

Figure 1.6: Schematic of report storyline.

Frequently Asked Questions

FAQ 1.1: Why are we talking about 1.5°C?

Summary: Climate change represents an urgent and potentially irreversible threat to human societies and the planet. In recognition of this, the overwhelming majority of countries around the world adopted the Paris Agreement in December 2015, the central aim of which includes pursuing efforts to limit global temperature rise to 1.5°C. In doing so, these countries, through the United Nations Framework Convention on Climate Change (UNFCCC) also invited the IPCC to provide a Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emissions pathways.

At the 21st Conference of the Parties (COP21) in December 2015, 195 nations adopted the Paris Agreement[2]. The first instrument of its kind, the landmark agreement includes the aim to strengthen the global response to the threat of climate change by 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels'.

The first UNFCCC document to mention a limit to global warming of 1.5°C was the Cancun Agreement, adopted at the sixteenth COP (COP16) in 2010. The Cancun Agreement established a process to periodically review the 'adequacy of the long-term global goal (LTGG) in the light of the ultimate objective of the Convention and the overall progress made towards achieving the LTGG, including a consideration of the implementation of the commitments under the Convention'. The definition of LTGG in the Cancun Agreement was 'to hold the increase in global average temperature below 2°C above pre-industrial levels'. The agreement also recognised the need to consider 'strengthening the long term global goal on the basis of the best available scientific knowledge… to a global average temperature rise of 1.5°C'.

Beginning in 2013 and ending at the COP21 in Paris in 2015, the first review period of the long term global goal largely consisted of the Structured Expert Dialogue (SED). This was a fact-finding, face-to-face exchange of views between invited experts and UNFCCC delegates. The final report of the SED[3] concluded that 'in some regions and vulnerable ecosystems, high risks are projected even for warming above 1.5°C'. The SED report also suggested that Parties would profit from restating the temperature limit of the long-term global goal as a 'defence line' or 'buffer zone', instead of a 'guardrail' up to which all would be safe, adding that this new understanding would 'probably also favour emission pathways that will limit warming to a range of temperatures below 2°C'. Specifically on strengthening the temperature limit of 2°C, the SED's key message was: 'While science on the 1.5°C warming limit is less robust, efforts should be made to push the defence line as low as possible'. The findings of the SED, in turn, fed into the draft decision adopted at COP21.

With the adoption of the Paris Agreement, the UNFCCC invited the IPCC to provide a Special Report in 2018 on 'the impacts of global warming of 1.5°C above pre–industrial levels and related global greenhouse gas emissions pathways'. The request was that the report, known as SR1.5, should not only assess what a 1.5°C warmer world would look like but also the different pathways by which global temperature rise could be limited to 1.5°C. In 2016, the IPCC accepted the invitation, adding that the Special Report would also look at these issues in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty.

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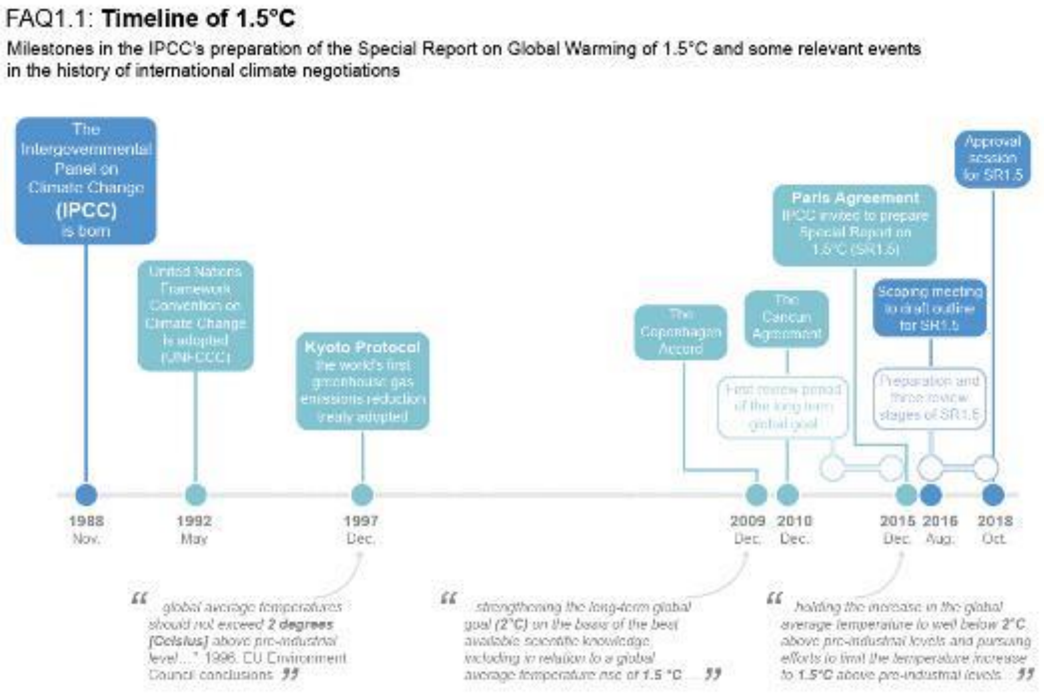
[2] FOOTNOTE: Paris Agreement FCCC/CP/2015/10/Add.1 https://unfccc.int/documents/9097

[3] FOOTNOTE: Structured Expert Dialogue (SED) final report FCCC/SB/2015/INF.1 https://unfccc.int/documents/8707

The combination of rising exposure to climate change and the fact that there is a limited capacity to adapt to its impacts amplifies the risks posed by warming of 1.5°C and 2°C. This is particularly true for developing and island countries in the tropics and other vulnerable countries and areas. The risks posed by global warming of 1.5°C are greater than for present day conditions but lower than at 2°C.



FAQ1.1, Figure 1: A timeline of notable dates in preparing the IPCC Special Report on Global Warming of 1.5°C (blue) embedded within processes and milestones of the United Nations Framework Convention on Climate Change (UNFCCC; grey), including events that may be relevant for discussion of temperature limits.

FAQ 1.2: How close are we to 1.5°C?

Summary: *Human-induced warming has already reached about 1°C above pre-industrial levels at the time of writing of this Special Report. By the decade 2006–2015, human activity had warmed the world by 0.87°C (±0.12°C) compared pre-industrial times (1850–1900). If the current warming rate continues, the world would reach human–induced global warming of 1.5°C around 2040.*

Under the 2015 Paris Agreement, countries agreed to cut greenhouse gas emissions with a view to ‘holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels’. While the overall intention of strengthening the global response to climate change is clear, the Paris Agreement does not specify precisely what is meant by ‘global average temperature’, or what period in history should be considered ‘pre-industrial’. To answer the question of how close are we to 1.5°C of warming, we need to first be clear about how both terms are defined in this Special Report.

The choice of pre-industrial reference period, along with the method used to calculate global average temperature, can alter scientists’ estimates of historical warming by a couple of tenths of a degree Celsius. Such differences become important in the context of a global temperature limit just half a degree above where we are now. But provided consistent definitions are used, they do not affect our understanding of how human activity is influencing the climate.

In principle, ‘pre-industrial levels’ could refer to any period of time before the start of the industrial revolution. But the number of direct temperature measurements decreases as we go back in time. Defining a ‘pre-industrial’ reference period is, therefore, a compromise between the reliability of the temperature information and how representative it is of truly pre-industrial conditions. Some pre-industrial periods are cooler than others for purely natural reasons. This could be because of spontaneous climate variability or the response of the climate to natural perturbations, such as volcanic eruptions and variations in the sun’s activity. This IPCC Special Report on Global Warming of 1.5°C uses the reference period 1850 to 1900 to represent pre-industrial conditions. This is the earliest period with near-global observations and is the reference period used as an approximation of pre-industrial temperatures in the IPCC Fifth Assessment Report.

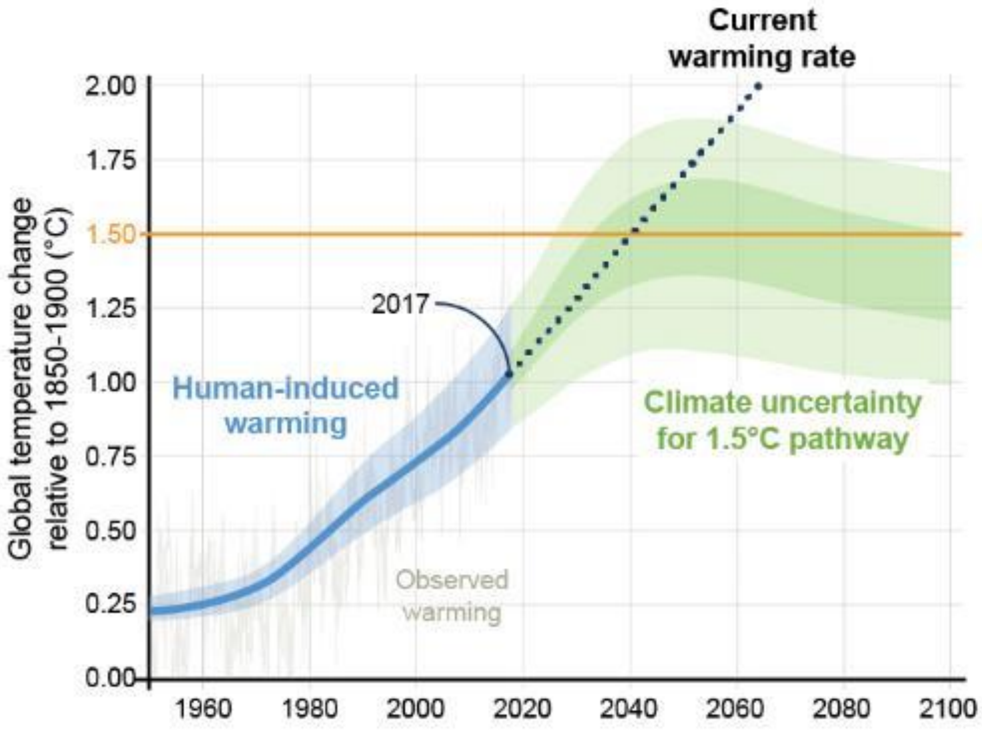
Once scientists have defined ‘pre-industrial’, the next step is to calculate the amount of warming at any given time relative to that reference period. In this report, warming is defined as the increase in the 30-year global average of combined temperature over land and at the ocean surface. The 30-year timespan accounts for the effect of natural variability, which can cause global temperatures to fluctuate from one year to the next. For example, 2015 and 2016 were both affected by a strong El Niño event, which amplified the underlying human-caused warming.

In the decade 2006–2015, warming reached 0.87°C (±0.12°C) relative to 1850–1900, predominantly due to human activity increasing the amount of greenhouse gases in the atmosphere. Given that global temperature is currently rising by 0.2°C (±0.1°C) per decade, human–induced warming reached 1°C above pre-industrial levels around 2017 and, if this pace of warming continues, would reach 1.5°C around 2040.

While the change in global average temperature tells researchers about how the planet as a whole is changing, looking more closely at specific regions, countries and seasons reveals important details. Since the 1970s, most land regions have been warming faster than the global average, for example. This means that warming in many regions has already exceeded 1.5°C above pre-industrial levels. Over a fifth of the global population live in regions that have already experienced warming in at least one season that is greater than 1.5°C above pre-industrial levels.

FAQ1.2:How close are we to 1.5°C?

Human-induced warming reached approximately 1°C above pre-industrial levels in 2017



FAQ1.2, Figure 1: Human-induced warming reached approximately 1°C above pre-industrial levels in 2017. At the present rate, global temperatures would reach 1.5°C around 2040.

References

Aaheim, A., T. Wei, and B. Romstad, 2017: Conflicts of economic interests by limiting global warming to +3 °C. *Mitigation and Adaptation Strategies for Global Change*, **22(8)**, 1131-1148, doi:10.1007/s11027-016-9718-8.

Adger, W.N. et al., 2014: Human Security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755-791.

AghaKouchak, A., L. Cheng, O. Mazdiyasni, and A. Farahmand, 2014: Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought. *Geophysical Research Letters*, **41(24)**, 8847-8852, doi:10.1002/2014GL062308.

Ajibade, I., 2016: Distributive justice and human rights in climate policy: the long road to Paris. *Journal of Sustainable Development Law and Policy (The)*, **7(2)**, 65, doi:10.4314/jsdlp.v7i2.4.

Albert, S. et al., 2017: Heading for the hills: climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, 1-12, doi:10.1007/s10113-017-1256-8.

Alkire, S., C. Jindra, G. Robles Aguilar, S. Seth, and A. Vaz, 2015: Multidimensional poverty index. *OPHI Briefing 42*.

Allen, M.R. and T.F. Stocker, 2013: Impact of delay in reducing carbon dioxide emissions. *Nature Climate Change*, **4(1)**, 23-26, doi:10.1038/nclimate2077.

Allen, M.R. et al., 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change*, **6(May)**, 1-5, doi:10.1038/nclimate2998.

Allen, M.R. et al., 2018: A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science* (in press).

Archer, D. and V. Brovkin, 2008: The millennial atmospheric lifetime of anthropogenic CO_2. *Climatic Change*, **90(3)**, 283-297, doi:10.1007/s10584-008-9413-1.

Arora-Jonsson, S., 2011: Virtue and vulnerability: Discourses on women, gender and climate change. *Global Environmental Change*, **21(2)**, 744-751, doi:10.1016/j.gloenvcha.2011.01.005.

Asseng, S. et al., 2013: Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*, **3(9)**, 827-832, doi:10.1038/nclimate1916.

Bäckstrand, K., J.W. Kuyper, B.O. Linnér, and E. Lövbrand, 2017: Non-state actors in global climate governance: from Copenhagen to Paris and beyond. *Environmental Politics*, **26(4)**, 561-579, doi:10.1080/09644016.2017.1327485.

Baker, H.S. et al., 2018: Higher CO_2 concentrations increase extreme event risk in a 1.5°C world. *Nature Climate Change* (in press).

Barnett, J. et al., 2014: A local coastal adaptation pathway. *Nature Climate Change*, **4(12)**, 1103-1108, doi:10.1038/nclimate2383.

Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives. *Global Environmental Change*, **42**, 316-330, doi:10.1016/j.gloenvcha.2016.07.006.

Bereiter, B. et al., 2015: Revision of the EPICA Dome C CO_2 record from 800 to 600-kyr before present. *Geophysical Research Letters*, **42(2)**, 542-549, doi:10.1002/2014GL061957.

Bethke, I. et al., 2017: Potential volcanic impacts on future climate variability. *Nature Climate Change*, **7(11)**, 799-805, doi:10.1038/nclimate3394.

Biermann, F., N. Kanie, and R.E. Kim, 2017: Global governance by goal-setting: the novel approach of the UN Sustainable Development Goals. *Current Opinion in Environmental Sustainability*, **26-27**, 26-31, doi:10.1016/j.cosust.2017.01.010.

Biermann, F. et al., 2016: Down to Earth: Contextualizing the Anthropocene. *Global Environmental Change*, **39**, 341-350, doi:10.1016/j.gloenvcha.2015.11.004.

Bindoff, N.L. et al., 2007: Observations: Oceanic Climate Change and Sea Level. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*.

Bindoff, N.L. et al., 2013: Detection and Attribution of Climate Change: from Global to Regional. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge

University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 426-488.

Birkmann, J., T. Welle, W. Solecki, S. Lwasa, and M. Garschagen, 2016: Boost resilience of small and mid-sized cities. *Nature*, **537(7622)**, 605-608, doi:10.1038/537605a.

Blicharska, M. et al., 2017: Steps to overcome the North-South divide in research relevant to climate change policy and practice. *Nature Climate Change*, **7(1)**, 21-27, doi:10.1038/nclimate3163.

Bodansky, D., J. Brunnée, and L. Rajamani, 2017: *International Climate Change Law*. Oxford University Press, 416 pp.

Bowerman, N.H.A., D.J. Frame, C. Huntingford, J.A. Lowe, and M.R. Allen, 2011: Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369(1934)**, 45-66, doi:10.1098/rsta.2010.0288.

Bowerman, N.H.A. et al., 2013: The role of short-lived climate pollutants in meeting temperature goals. *Nature Climate Change*, **3(12)**, 1021-1024, doi:10.1038/nclimate2034.

Brinkman, T.J. et al., 2016: Arctic communities perceive climate impacts on access as a critical challenge to availability of subsistence resources. *Climatic Change*, **139(3-4)**, 413-427, doi:10.1007/s10584-016-1819-6.

Brondizio, E.S. et al., 2016: Re-conceptualizing the Anthropocene: A call for collaboration. *Global Environmental Change*, **39**, 318-327, doi:10.1016/j.gloenvcha.2016.02.006.

Busby, J., 2016: After Paris: Good enough climate governance. *Current History*, **15(777)**, 3-9.

Caney, S., 2005: Cosmopolitan Justice, Responsibility, and Global Climate Change. *Leiden Journal of International Law*, **18(04)**, 747-75, doi:10.1017/S0922156505002992.

Caney, S., 2010: Climate change and the duties of the advantaged. *Critical Review of International Social and Political Philosophy*, **13(1)**, 203-228, doi:10.1080/13698230903326331.

Cardona, O.D. et al., 2012: Determinants of Risk: Exposure and Vulnerablity. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* [Field, C.B., V.R. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 65-108.

Chen, X. et al., 2017: The increasing rate of global mean sea-level rise during 1993-2014. *Nature Climate Change*, **7(7)**, 492-495, doi:10.1038/nclimate3325.

Christensen, J.H. et al., 2013: Climate Phenomena and their Relevance for Future Regional Climate Change Supplementary Material. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 62.

Clarke, L.E. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413-510.

Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. pp. 1029-1136.

Corner, A. and J. Clarke, 2017: *Talking Climate - From Research to Practice in Public Engagement*. Palgrave Macmillan, Oxford, UK, 146 pp.

Cowtan, K. and R.G. Way, 2014: Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society*, **140(683)**, 1935-1944, doi:10.1002/qj.2297.

Cowtan, K. et al., 2015: Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures. *Geophysical Research Letters*, **42(15)**, 6526-6534, doi:10.1002/2015GL064888.

Cramer, W. et al., 2014: Detection and attribution of observed impacts. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, pp. 979-1037.

Creutzig, F., 2016: Economic and ecological views on climate change mitigation with bioenergy and negative emissions. *GCB Bioenergy*, **8(1)**, 4-10, doi:10.1111/gcbb.12235.

Crutzen, P.J., 2002: Geology of mankind. *Nature*, **415(6867)**, 23, doi:10.1038/415023a.

Crutzen, P.J. and E.F. Stoermer, 2000: The Anthropocene. *Global Change Newsletter*, **41**, 17-18.

Czerniewicz, L., S. Goodier, and R. Morrell, 2017: Southern knowledge online? Climate change research discoverability and communication practices.. *Information, Communication & Society*, **20(3)**, 386-405, doi:10.1080/1369118X.2016.1168473.

Dasgupta, P. et al., 2014: Rural areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 613-657.

Death, C. and C. Gabay, 2015: Doing biopolitics differently? Radical potential in the post-2015 MDG and SDG debates. *Globalizations*, **12(4)**, 597-612, doi:10.1080/14747731.2015.1033172.

Delanty, G. and A. Mota, 2017: Governing the Anthropocene. *European Journal of Social Theory*, **20(1)**, 9-38, doi:10.1177/1368431016668535.

Denton, F. et al., 2014: Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131.

Deser, C., R. Knutti, S. Solomon, and A.S. Phillips, 2012: Communication of the Role of Natural Variability in Future North American Climate. *Nature Climate Change*, **2(11)**, 775-779, doi:10.1038/nclimate1562.

Deuber, O., G. Luderer, and O. Edenhofer, 2013: Physico-economic evaluation of climate metrics: A conceptual framework. *Environmental Science & Policy*, **29**, 37-45, doi:10.1016/j.envsci.2013.01.018.

Dietz, S., B. Groom, and W.A. Pizer, 2016: Weighing the Costs and Benefits of Climate Change to Our Children. *The Future of Children*, **26(1)**, 133-155.

Dinah, S., 2008: Equity. In: *The Oxford Handbook of International Environmental Law* [Bodansky, D., J. Brunnée, and E. Hey (eds.)]. Oxford University Press, Oxford, UK.

Dooley, K., J. Gupta, and A. Patwardhan, 2018: INEA editorial: Achieving 1.5 °C and climate justice. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 1-9, doi:10.1007/s10784-018-9389-x.

Dryzek, J.S., 2016: Institutions for the Anthropocene: Governance in a Changing Earth System. *British Journal of Political Science*, **46(04)**, 937-956, doi:10.1017/S0007123414000453.

Duyck, S., S. Jodoin, and A. Johl (eds.), 2018: *Routledge Handbook of Human Rights and Climate Governance*. Routledge, Abingdon, Oxon, 430 pp.

Ebi, K.L., L.H. Ziska, and G.W. Yohe, 2016: The shape of impacts to come: lessons and opportunities for adaptation from uneven increases in global and regional temperatures. *Climatic Change*, **139(3)**, 341-349, doi:10.1007/s10584-016-1816-9.

Ebi, K.L. et al., 2014: A new scenario framework for climate change research: Background, process, and future directions. *Climatic Change*, **122(3)**, 363-372, doi:10.1007/s10584-013-0912-3.

Eby, M. et al., 2009: Lifetime of anthropogenic climate change: Millennial time scales of potential CO_2 and surface temperature perturbations. *Journal of Climate*, **22(10)**, 2501-2511, doi:10.1175/2008JCLI2554.1.

Ehlert, D. and K. Zickfeld, 2017: What determines the warming commitment after take back cessation of CO_2 emissions? *Environmental Research Letters*, **12(1)**, doi:10.1088/1748-9326/aa564a.

Ekström, M., M.R. Grose, and P.H. Whetton, 2015: An appraisal of downscaling methods used in climate change research. *Wiley Interdisciplinary Reviews: Climate Change*, **6(3)**, 301-319, doi:10.1002/wcc.339.

Emori, S. et al., 2018: Risk implications of long-term global climate goals: overall conclusions of the ICA-RUS project. *Sustainability Science*, **13(2)**, 279-289.

England, M.H. et al., 2014: Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change*, **4(3)**, 222-227, doi:10.1038/nclimate2106.

Epstein, A.H., and S.L.H. Theuer, 2017: *Sustainable development and climate action: thoughts on an integrated* *approach to SDG and climate policy implementation*, 50 pp.

Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614-12,623, doi:10.1002/2016GL071930.

Fazey, I. et al., 2016: Past and future adaptation pathways. *Climate and Development*, **8(1)**, 26-44, doi:10.1080/17565529.2014.989192.

Fazey, I. et al., 2018: Community resilience for a 1.5°C world. *Current Opinion in Environmental Sustainability*, **31**, 30-40, doi:10.1016/j.cosust.2017.12.006.

Field, C.B. et al., 2014: Technical Summary. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94.

Fischer, E.M. and R. Knutti, 2015: Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Climate Change*, **5(6)**, 560-564, doi:10.1038/nclimate2617.

Fleurbaey, M. et al., 2014: Sustainable Development and Equity. In: *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, P.E. K. Seyboth, A. Adler, I. Baum, S. Brunner, and T.Z.J.C.M. B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow (eds.)]. Cambridge University Press, Cambridge, Cambridge, United Kingdom and New York, NY, USA, pp. 283-350.

Forkel, M. et al., 2016: Enhanced seasonal CO_2 exchange caused by amplified plant productivity in northern ecosystems. *Science*, **351(6274)**, 696 LP - 699.

Foster, G. and S. Rahmstorf, 2011: Global temperature evolution 1979-2010. *Environmental Research Letters*, **6(4)**, 044022, doi:10.1088/1748-9326/6/4/044022.

Frölicher, T.L. and F. Joos, 2010: Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model. *Climate Dynamics*, **35(7)**, 1439-1459, doi:10.1007/s00382-009-0727-0.

Frölicher, T.L., M. Winton, and J.L. Sarmiento, 2014: Continued global warming after CO_2 emissions stoppage. *Nature Climate Change*, **4(1)**, 40-44, doi:10.1038/nclimate2060.

Fuglestvedt, J. et al., 2018: Implications of possible interpretations of 'greenhouse gas balance' in the Paris Agreement. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0445.

Gillett, N.P., V.K. Arora, D. Matthews, and M.R. Allen, 2013: Constraining the ratio of global warming to cumulative CO_2 emissions using CMIP5 simulations. *Journal of Climate*, **26(18)**, 6844-6858, doi:10.1175/JCLI-D-12-00476.1.

Gillett, N.P., V.K. Arora, K. Zickfeld, S.J. Marshall, and W.J. Merryfield, 2011: Ongoing climate change following a complete cessation of carbon dioxide emissions. *Nature Geoscience*, **4**, 83-87, doi:10.1038/ngeo1047.

Giorgi, F. and W.J. Gutowski, 2015: Regional Dynamical Downscaling and the CORDEX Initiative. *Annual Review of Environment and Resources*, **40(1)**, 467-490, doi:10.1146/annurev-environ-102014-021217.

Gomez-Echeverri, L., 2018: Climate and development: enhancing impact through stronger linkages in the implementation of the Paris Agreement and the Sustainable Development Goals (SDGs).. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, **376(2119)**, 20160444, doi:10.1098/rsta.2016.0444.

Goodwin, P. et al., 2018: Pathways to 1.5 °c and 2 °c warming based on observational and geological constraints. *Nature Geoscience*, **11(2)**, 102-107, doi:10.1038/s41561-017-0054-8.

Gouldson, A. et al., 2015: Exploring the economic case for climate action in cities. *Global Environmental Change*, **35**, 93-105, doi:10.1016/j.gloenvcha.2015.07.009.

Gradstein, F.M., J.G. Ogg, M.D. Schmitz, and G.M. Ogg (eds.), 2012: *The Geologic Time Scale*. Elsevier BV, Boston, MA, USA, 1144 pp.

Gregory, J.M. and P.M. Forster, 2008: Transient climate response estimated from radiative forcing and observed temperature change. *Journal of Geophysical Research Atmospheres*, **113(23)**, doi:10.1029/2008JD010405.

Hall, J., G. Fu, and J. Lawry, 2007: Imprecise probabilities of climate change: Aggregation of fuzzy scenarios and model uncertainties. *Climatic Change*, **81(3-4)**, 265-281, doi:10.1007/s10584-006-9175-6.

Hammill, B.A. and H. Price-Kelly, 2017: *Using NDCs , NAPs and the SDGs to Advance Climate-Resilient Development*. Cambridge University Press, Cambridge, United Kingdom, 1-10 pp.

Hansen, G. and W. Cramer, 2015: Global distribution of observed climate change impacts. *Nature Climate Change***, 5(3)**, 182-185, doi:10.1038/nclimate2529.

Hansen, G., D. Stone, M. Auffhammer, C. Huggel, and W. Cramer, 2016: Linking local impacts to changes in climate: a guide to attribution. *Regional Environmental Change***, 16(2)**, 527-541, doi:10.1007/s10113-015-0760-y.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Reviews of Geophysics***, 48(4)**, RG4004, doi:10.1029/2010RG000345.

Hansen, J. et al., 2005: Earth's energy imbalance: confirmation and implications.. *Science***, 308(November)**, 1431-1435, doi:10.1126/science.1110252.

Harlan, S.L. et al., 2015: Climate Justice and Inequality: Insights from Sociology. In: *Climate Change and Society: Sociological Perspectives* [Dunlap, R.E. and R.J. Brulle (eds.)]. Oxford University Press, New York, NY, USA, pp. 127-163.

Harrington, C., 2016: The Ends of the World: International Relations and the Anthropocene. *Millennium: Journal of International Studies***, 44(3)**, 478-498, doi:10.1177/0305829816638745.

Harris, L.M., E.K. Chu, and G. Ziervogel, 2017: Negotiated resilience. *Resilience***, 3293**, 1-19, doi:10.1080/21693293.2017.1353196.

Hartmann, D.J. et al., 2013: Observations: Atmosphere and Surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 159-254.

Haustein, K. et al., 2017: A real-time Global Warming Index. *Scientific Reports***, 7(1)**, 15417, doi:10.1038/s41598-017-14828-5.

Hawkins, E. et al., 2017: Estimating changes in global temperature since the pre-industrial period. *Bulletin of the American Meteorological Society*, BAMS-D-16-0007.1, doi:10.1175/BAMS-D-16-0007.1.

Hegerl, G.C. et al., 2007: Understanding and Attributing Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 663-745.

Hienola, A. et al., 2018: The impact of aerosol emissions on the 1.5 °C pathways. *Environmental Research Letters***, 13(4)**, 44011.

Hoegh-Guldberg, O. et al., 2007: Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science***, 318(5857)**, 1737 LP - 1742, doi:10.1126/science.1152509.

Holz, C., S. Kartha, and T. Athanasiou, 2017: Fairly sharing 1.5: national fair shares of a 1.5 °C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics***, 18(1)**, 1-18, doi:10.1007/s10784-017-9371-z.

Horton, R., 2014: Why the sustainable development goals will fail. *The Lancet***, 383(9936)**, 2196, doi:10.1016/S0140-6736(14)61046-1.

Humphreys, S., 2017: Climate, Technology, Justice. In: *Protecting the Environment for Future Generations: Principles and Actors in International Environmental Law*. Erich Schmidt Verlag, Berlin.

IBA, 2014: *Achieving Justice and Human Rights in an Era of Climate Disruption*. 240 pp.

IPCC, 2000: Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. [Nakićenović, N. and R. Swart (eds.)]. 570 pp.

IPCC, 2012a: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 582 pp.

IPCC, 2012b: Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Geoengineering. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, C. Field, V. Barros, T.F. Stocker, Q. Dahe, J. Minx, K. Mach, G.K. Plattner, S. Schlömer, G. Hansen, and M. Mastrandrea (eds.)]. IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research, Potsdam, Germany, 99 pp.

IPCC, 2012c: Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V.R. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3-21.

IPCC, 2013a: *Principles Governing IPCC Work*. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 2 pp.

IPCC, 2013b: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33.

IPCC, 2014a: Climate Change 2014 Synthesis Report. [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 1-112 pp.

IPCC, 2014b: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. , 1132.

IPCC, 2014c: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, 1454 pp.

IPCC, 2014d: Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-30.

IPCC, 2014e: Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

IPCC, 2014f: Summary for Policymakers. In: *Climate Change 2014 Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. pp. 2-34.

IPCC, 2017: Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Mitigation, Sustainability and Climate Stabilization Scenarios. [Shukla, P.R., J. Skea, R. Diemen, E. Huntley, M. Pathak, J. Portugal-Pereira, J. Scull, and R. Slade (eds.)]. IPCC Working Group III Technical Support Unit, Imperial College London, London, UK, 44 pp.

Jacob, D. and S. Solman, 2017: IMPACT2C - An introduction. *Climate Services*, **7**, 1-2, doi:10.1016/j.cliser.2017.07.006.

Jacobson, M.Z. et al., 2015: 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy Environ. Sci.*, **8(7)**, 2093-2117, doi:10.1039/C5EE01283J.

James, R., R. Washington, C.F. Schleussner, J. Rogelj, and D. Conway, 2017: Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets. *Wiley Interdisciplinary Reviews: Climate Change*, **8(2)**, e457--n/a, doi:10.1002/wcc.457.

Jarvis, A.J., D.T. Leedal, and C.N. Hewitt, 2012: Climate-society feedbacks and the avoidance of dangerous climate change. *Nature Climate Change*, **2(9)**, 668-671, doi:10.1038/nclimate1586.

Jenkins, S., R.J. Millar, N. Leach, and M.R. Allen, 2018: Framing Climate Goals in Terms of Cumulative CO_2-Forcing-Equivalent Emissions. *Geophysical Research Letters*, **45(6)**, 2795-2804, doi:10.1002/2017GL076173.

Johansson, D.J.A., 2012: Economics- and physical-based metrics for comparing greenhouse gases. *Climatic Change*, **110(1-2)**, 123-141, doi:10.1007/s10584-011-0072-2.

Jones, G.S., P.A. Stott, and N. Christidis, 2013: Attribution of observed historical near-surface temperature variations to anthropogenic and natural causes using CMIP5 simulations. *Journal of Geophysical Research: Atmospheres*, **118(10)**, 4001-4024, doi:10.1002/jgrd.50239.

Jones, G.S., P.A. Stott, and J.F.B. Mitchell, 2016: Uncertainties in the attribution of greenhouse gas warming and implications for climate prediction. *Journal of Geophysical Research: Atmospheres*, **121(12)**, 6969-6992, doi:10.1002/2015JD024337.

Jones, P., 2016: The reliability of global and hemispheric surface temperature records. *Advances in Atmospheric Sciences*, **33(3)**, 269-282, doi:10.1007/s00376-015-5194-4.

Kabir, M.I. et al., 2016: Knowledge and perception about climate change and human health: findings from a baseline survey among vulnerable communities in Bangladesh. *BMC Public Health*, **16(1)**, 266, doi:10.1186/s12889-016-2930-3.

Kainuma, M., R. Pandey, T. Masui, and S. Nishioka, 2017: Methodologies for leapfrogging to low carbon and sustainable development in Asia. *Journal of Renewable and Sustainable Energy*, **9(2)**, doi:10.1063/1.4978469.

Kanie, N. and F. Biermann, 2017: Governing through goals: Sustainable development goals as governance innovation.

Karl, T.R. et al., 2015: Possible artifacts of data biases in the recent global surface warming hiatus. *Science*, **348(6242)**, 1469-1472, doi:10.1126/science.aaa5632.

Karmalkar, A. and R.S. Bradley, 2017: Consequences of Global Warming of 1.5°C and 2°C for Regional Temperature and Precipitation Changes in the Contiguous United States. *PLOS ONE*, **12(1)**, e0168697, doi:10.1371/journal.pone.0168697.

Kelman, I., 2017: Linking disaster risk reduction, climate change, and the sustainable development goals. *Disaster Prevention and Management: An International Journal*, **26(3)**, 254-258, doi:10.1108/DPM-02-2017-0043.

King, A.D., D.J. Karoly, and B.J. Henley, 2017: Australian climate extremes at 1.5°C and 2°C of global warming. *Nature Climate Change*, **7(6)**, 412-416, doi:10.1038/nclimate3296.

King, A.D. et al., 2018: Reduced Heat Exposure by Limiting Global Warming to 1.5°C. *Nature Climate Change* (in press).

Kirtman, B., A. Adedoyin, and N. Bindoff, 2013: Near-term Climate Change: Projections and Predictability. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 953-1028.

Klein, R.J.T. et al., 2014: Adaptation opportunities, constraints, and limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 899-943.

Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0461.

Knox, J.H., 2015: Human Rights Principles and Climate Change. In: *Oxford Handbook of International Climate Change Law* [Carlarne, C., K.R. Gray, and R. Tarasofsky (eds.)]. Oxford University Press, Oxford.

Knutti, R. and J. Sedláček, 2012: Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, **3(4)**, 369-373, doi:10.1038/nclimate1716.

Knutti, R., J. Rogelj, J. Sedláček, and E.M. Fischer, 2015: A scientific critique of the two-degree climate change target. *Nature Geoscience*, **9(1)**, 13-18, doi:10.1038/ngeo2595.

Kolstad, C. et al., 2014: Social, Economic, and Ethical Concepts and Methods. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Inter- governmental Panel on Climate Changegovernmental Panel on Climate Change,* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207-282.

Kopp, R.E. et al., 2016: Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences*, **113(11)**, 1-8, doi:10.1073/pnas.1517056113.

Kosaka, Y. and S.P. Xie, 2013: Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, **501(7467)**, 403-407, doi:10.1038/nature12534.

Kriegler, E., J.W. Hall, H. Held, R. Dawson, and H.J. Schellnhuber, 2009: Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences*, **106(13)**, 5041-5046, doi:10.1073/pnas.0809117106.

Kriegler, E. et al., 2012: The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change*, **22(4)**, 807-822, doi:10.1016/j.gloenvcha.2012.05.005.

Kriegler, E. et al., 2014: A new scenario framework for climate change research: The concept of shared climate policy assumptions. *Climatic Change*, **122(3)**, 401-414, doi:10.1007/s10584-013-0971-5.

Kristjánsson, J.E., M. Helene, and S. Hauke, 2016: The hydrological cycle response to cirrus cloud thinning. *Geophysical Research Letters*, **42(24)**, 10,807-810,815, doi:10.1002/2015GL066795.

Lauder, A.R. et al., 2013: Offsetting methane emissions - An alternative to emission equivalence metrics. *International Journal of Greenhouse Gas Control*, **12**, 419-429, doi:10.1016/j.ijggc.2012.11.028.

Leach, N.J. et al., 2018: Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nature Geoscience* (in press).

Leal Filho, W. et al., 2018: Implementing climate change research at universities: Barriers, potential and actions. *Journal of Cleaner Production*, **170**, 269-277, doi:10.1016/j.jclepro.2017.09.105.

Leggett, J. et al., 1992: Emissions scenarios for the IPCC: an update. In: *Climate change 1992: The Supplementary Report to the IPCC Scientific Assessment* [Houghton, J.T., B.A. Callander, and S.K. Varney (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 69-95.

Leichenko, R. and J.A. Silva, 2014: Climate change and poverty: Vulnerability, impacts, and alleviation strategies. *Wiley Interdisciplinary Reviews: Climate Change*, **5(4)**, 539-556, doi:10.1002/wcc.287.

Leonard, M. et al., 2014: A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change*, **5(1)**, 113-128, doi:10.1002/wcc.252.

Leung, D.Y.C., G. Caramanna, and M.M. Maroto-Valer, 2014: An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, **39**, 426-443, doi:10.1016/j.rser.2014.07.093.

Lofts, K., S. Shamin, T.S. Zaman, and R. Kibugi, 2017: Brief on Sustainable Development Goal 13 on Taking Action on Climate Change and Its Impacts: Contributions of International Law, Policy and Governance,. *McGill Journal of Sustainable Development Law*, **11(1)**, 183-192, doi:10.3868/s050-004-015-0003-8.

Loftus, P.J., A.M. Cohen, J.C.S. Long, and J.D. Jenkins, 2015: A critical review of global decarbonization scenarios: What do they tell us about feasibility? *Wiley Interdisciplinary Reviews: Climate Change*, **6(1)**, 93-112, doi:10.1002/wcc.324.

Lövbrand, E., M. Hjerpe, and B.O. Linnér, 2017: Making climate governance global: how UN climate summitry comes to matter in a complex climate regime. *Environmental Politics*, **26(4)**, 580-599, doi:10.1080/09644016.2017.1319019.

Lowe, J.A. et al., 2009: How difficult is it to recover from dangerous levels of global warming? *Environmental Research Letters*, **4(1)**, 014012, doi:10.1088/1748-9326/4/1/014012.

Lüthi, D. et al., 2008: High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature*, **453(7193)**, 379-382, doi:10.1038/nature06949.

MacMartin, D.G., K.L. Ricke, and D.W. Keith, 2018: Solar geoengineering as part of an overall strategy for meeting the 1.5C Paris target. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0454.

Marbà, N. et al., 2015: Impact of seagrass loss and subsequent revegetation on carbon sequestration and stocks. *Journal of Ecology*, **103(2)**, 296-302, doi:10.1111/1365-2745.12370.

Marcott, S.A., J.D. Shakun, P.U. Clark, and A.C. Mix, 2013: A reconstruction of regional and global temperature for the past 11,300 years. *Science*, **339(6124)**, 1198-201, doi:10.1126/science.1228026.

Marsicek, J., B.N. Shuman, P.J. Bartlein, S.L. Shafer, and S. Brewer, 2018: Reconciling divergent trends and millennial variations in Holocene temperatures. *Nature*, **554**, 92.

Martius, O., S. Pfahl, and C. Chevalier, 2016: A global quantification of compound precipitation and wind extremes. *Geophysical Research Letters*, **43(14)**, 7709-7717, doi:10.1002/2016GL070017.

Masson-Delmotte, V. et al., 2013: Information from Paleoclimate Archives. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge Univeristy Press, Cambridge, UK and New York, NY , USA.

Mastrandrea, M.D. et al., 2011: The IPCC AR5 guidance note on consistent treatment of uncertainties: a common approach across the working groups. *Climatic Change*, **108(4)**, 675-691, doi:10.1007/s10584-011-0178-6.

Mathesius, S., M. Hofmann, K. Caldeira, and H.J. Schellnhuber, 2015: Long-term response of oceans to CO_2 removal from the atmosphere. *Nature Climate Change*, **5(12)**, 1107-1113, doi:10.1038/nclimate2729.

Matthews, H.D. and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.*, **35(4)**, L04705, doi:10.1029/2007GL032388.

Matthews, H.D. and K. Zickfeld, 2012: Climate response to zeroed emissions of greenhouse gases and aerosols. *Nature Climate Change*, **2(5)**, 338-341, doi:10.1038/nclimate1424.

Matthews, H.D. and S. Solomon, 2013: Irreversible Does Not Mean Unavoidable. *Science*, **340(6131)**, 438-439, doi:10.1126/science.1236372.

Matthews, H.D., N.P. Gillett, P. Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon emissions. *Nature*, **459(7248)**, 829-32, doi:10.1038/nature08047.

Matthews, T.K.R., R.L. Wilby, and C. Murphy, 2017: Communicating the deadly consequences of global warming for human heat stress. *Proceedings of the National Academy of Sciences*, **114(15)**, 3861-3866, doi:10.1073/pnas.1617526114.

Maupin, A., 2017: The SDG13 to combat climate change: an opportunity for Africa to become a trailblazer? *African Geographical Review*, **36(2)**, 131-145, doi:10.1080/19376812.2016.1171156.

Mauritsen, T. and R. Pincus, 2017: Committed warming inferred from observations. *Nature Climate Change*, **2(July)**, 1-5, doi:10.1038/nclimate3357.

Medhaug, I., M.B. Stolpe, E.M. Fischer, and R. Knutti, 2017: Reconciling controversies about the 'global warming hiatus'. *Nature*, **545(7652)**, 41-47, doi:10.1038/nature22315.

Meehl, G.A. et al., 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 747-845.

Millar, R.J., Z.R. Nicholls, P. Friedlingstein, and M.R. Allen, 2017a: A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmospheric Chemistry and Physics*, **17(11)**, 7213-7228, doi:10.5194/acp-17-7213-2017.

Millar, R.J. et al., 2017b: Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nature Geoscience*, **10(10)**, 741-747, doi:10.1038/NGEO3031.

Mimura, N. et al., 2014: Adaptation planning and implementation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 869-898.

Minx, J.C., W.F. Lamb, M.W. Callaghan, L. Bornmann, and S. Fuss, 2017: Fast growing research on negative emissions. *Environmental Research Letters*, **12(3)**, doi:10.1088/1748-9326/aa5ee5.

Mitchell, D. et al., 2016: Realizing the impacts of a 1.5°C warmer world. *Nature Climate Change*, **6(8)**, 735-737, doi:10.1038/nclimate3055.

Mitchell, D. et al., 2017: Half a degree Additional warming, Projections, Prognosis and Impacts (HAPPI): Background and Experimental Design. *Geoscientific Model Development*, **10**, 571-583, doi:10.5194/gmd-10-571-2017.

Miyan, M.A., 2015: Droughts in Asian Least Developed Countries: Vulnerability and sustainability. *Weather and Climate Extremes*, **7**, 8-23, doi:10.1016/J.WACE.2014.06.003.

Morice, C.P., J.J. Kennedy, N.A. Rayner, and P.D. Jones, 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of Geophysical Research Atmospheres*, **117(8)**, doi:10.1029/2011JD017187.

Morita, T. et al., 2001: Greenhouse Gas Emission Mitigation Scenarios and Implications. In: *Climate Change 2001: Mitigation. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., O. Davidson, R. Swart, and J. Pan (eds.)]. Cambridge University Press, Cambridge, pp. 115-164.

Moss, R.H. et al., 2010: The next generation of scenarios for climate change research and assessment. *Nature*, **463(7282)**, 747-756, doi:10.1038/nature08823.

Mueller, B. and S.I. Seneviratne, 2014: Systematic land climate and evapotranspiration biases in CMIP5 simulations. *Geophysical Research Letters*, **41(1)**, 128-134, doi:10.1002/2013GL058055.

Myhre, G. et al., 2013: Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 658-740.

Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990-2015. *Atmospheric Chemistry and Physics*, **17(4)**, 2709-2720, doi:10.5194/acp-17-2709-2017.

Mysiak, J., S. Surminski, A. Thieken, R. Mechler, and J. Aerts, 2016: Brief communication: Sendai framework for disaster risk reduction - Success or warning sign for Paris? *Natural Hazards and Earth System Sciences*, **16(10)**, 2189-2193, doi:10.5194/nhess-16-2189-2016.

O'Brien, K. and E. Selboe, 2015: Social transformation. In: *The Adaptive Challenge of Climate Change*

[OBrien, K. and E. Selboe (eds.)]. Cambridge University Press, Cambridge, UK, pp. 311-324.

O'Brien, K. et al., 2012: Toward a sustainable and resilient future. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 437-486.

OECD, 2016: *The OECD supporting action on climate change*. Organisation for Economic Co-operation and Development (OECD), Paris, France, 18 pp.

OHCHR, 2009: *Report of the Office of the United Nations High Commissioner for Human Rights on the relationship between climate change and human rights*. A/HRC/10/61, 32 pp.

OHCHR, 2015: *Understanding Human Rights and Climate Change*. Office of the United Nations High Commissioner for Human Rights (OHCHR), 28 pp.

OHCHR, 2017: *Analytical study on the relationship between climate change and the full and effective enjoyment of the rights of the child*. UN Doc. A/HRC/35/13, 18 pp.

Okereke, C., 2010: Climate justice and the international regime. *Wiley Interdisciplinary Reviews: Climate Change***, 1(3)**, 462-474, doi:10.1002/wcc.52.

Oliver, T.H. and M.D. Morecroft, 2014: Interactions between climate change and land use change on biodiversity: attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate Change***, 5(3)**, 317-335, doi:10.1002/wcc.271.

Olsson, L. et al., 2014: Livelihoods and poverty. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 798-832.

O'Neill, B.C. et al., 2014: A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change***, 122(3)**, 387-400, doi:10.1007/s10584-013-0905-2.

Otto, F.E.L., D.J. Frame, A. Otto, and M.R. Allen, 2015: Embracing uncertainty in climate change policy. *Nature Climate Change***, 5(August)**, 1-5, doi:10.1038/nclimate2716.

Otto, F.E.L., R.B. Skeie, J.S. Fuglestvedt, T. Berntsen, and M.R. Allen, 2017: Assigning historic responsibility for extreme weather events. *Nature Climate Change***, 7(11)**, 757-759, doi:10.1038/nclimate3419.

Pattberg, P. and F. Zelli (eds.), 2016: *Environmental politics and governance in the anthropocene: Institutions and legitimacy in a complex world*. Routledge, 268 pp.

Patterson, J. et al., 2017: Exploring the governance and politics of transformations towards sustainability. *Environmental Innovation and Societal Transitions***, 24**, 1-16, doi:10.1016/j.eist.2016.09.001.

Pelling, M., 2011: *Adaptation to Climate Change: From Resilience to Transformation*. Routledge, Abingdon, Oxon, UK and New York, NY, USA, 274 pp.

Pelling, M., K. O'Brien, and D. Matyas, 2015: Adaptation and transformation. *Climatic Change***, 133(1)**, 113-127, doi:10.1007/s10584-014-1303-0.

Pendergrass, A.G., F. Lehner, B.M. Sanderson, and Y. Xu, 2015: Does extreme precipitation intensity depend on the emissions scenario? *Geophysical Research Letters***, 42(20)**, 8767-8774, doi:10.1002/2015GL065854.

Pfleiderer, P., C.F. Schleussner, M. Mengel, and J. Rogelj, 2018: Global mean temperature indicators linked to warming levels avoiding climate risk. *Environmental Research Letters*.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change***, 42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002.

Porter, J.R. et al., 2014: Food security and food production systems. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

Pörtner, H.O. et al., 2014: Ocean systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University

Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484.

Rao, S. et al., 2017: Future Air Pollution in the Shared Socio-Economic Pathways. *Global Environmental Change*, **42(January)**, 346-358, doi:10.1016/j.gloenvcha.2016.05.012.

Reckien, D. et al., 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environment & Urbanization*, **29(1)**, 159-182, doi:10.1177/0956247816677778.

Reisinger, A. et al., 2012: Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. *Climatic Change*, 1-14, doi:10.1007/s10584-012-0593-3.

Reisinger, A. et al., 2014: Australasia. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1371-1438.

Resurrección, B.P., 2013: Persistent women and environment linkages in climate change and sustainable development agendas. *Women's Studies International Forum*, **40(Supplement C)**, 33-43, doi:10.1016/j.wsif.2013.03.011.

Revi, A. et al., 2014: Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009.

Ribes, A. and L. Terray, 2013: Application of regularised optimal fingerprinting to attribution. Part II: application to global near-surface temperature. *Climate Dynamics*, **41(11)**, 2837-2853, doi:10.1007/s00382-013-1736-6.

Ribes, A., F.W. Zwiers, J.M. Azaïs, and P. Naveau, 2017: A new statistical approach to climate change detection and attribution. *Climate Dynamics*, **48(1)**, 367-386, doi:10.1007/s00382-016-3079-6.

Richardson, M., K. Cowtan, and R.J. Millar, 2018: Global temperature definition affects achievement of long-term climate goals. *Environmental Research Letters*, **13(5)**, 054004.

Richardson, M., K. Cowtan, E. Hawkins, and M.B. Stolpe, 2016: Reconciled climate response estimates from climate models and the energy budget of Earth. *Nature Climate Change*, **6**, 931-935.

Robinson, M. and T. Shine, 2018: Achieving a climate justice pathway to 1.5°C. *Nature Clim. Change* (in press).

Rogelj, J., C.F. Schleussner, and W. Hare, 2017: Getting It Right Matters: Temperature Goal Interpretations in Geoscience Research. *Geophysical Research Letters*, **44(20)**, 10,662-10,665, doi:10.1002/2017GL075612.

Rogelj, J. et al., 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, **5(6)**, 519-527, doi:10.1038/nclimate2572.

Rogelj, J. et al., 2016a: Paris Agreement climate proposals need boost to keep warming well below 2°C. *Nature Climate Change*, **534(June)**, 631-639, doi:10.1038/nature18307.

Rogelj, J. et al., 2016b: Differences between carbon budget estimates unravelled. *Nature Climate Change*, **6(3)**, 245-252, doi:10.1038/nclimate2868.

Rogelj, J. et al., 2018: Transition pathways towards limiting climate change below 1.5°C. *Nature Climate Change*, **8(4)**, 325-332.

Rohde, R. et al., 2013: Berkeley Earth Temperature Averaging Process. *Geoinformatics & Geostatistics: An Overview*, **1(2)**, 1-13, doi:10.4172/2327-4581.1000103.

Rosenbloom, D., 2017: Pathways: An emerging concept for the theory and governance of low-carbon transitions. *Global Environmental Change*, **43**, 37-50, doi:10.1016/j.gloenvcha.2016.12.011.

Rosenzweig, C. et al., 2008: Attributing physical and biological impacts to anthropogenic climate change. *Nature*, **453(7193)**, 353-357, doi:10.1038/nature06937.

Rosenzweig, C. et al., 2017: Assessing inter-sectoral climate change risks: the role of ISIMIP. *Environmental Research Letters*, **12(1)**, 10301.

Rosenzweig, C., W. Solecki, P. Romeo-Lankao, M. Shagun, S. Dhakal, and S. Ali Ibrahim (eds.), 2018: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Samset, B.H. et al., 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical*

*Research Letters***, 45(2)**, 1020-1029, doi:10.1002/2017GL076079.

Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg, 2017: Valuing the Ozone-Related Health Benefits of Methane Emission Controls. *Environmental and Resource Economics***, 66(1)**, 45-63, doi:10.1007/s10640-015-9937-6.

Savaresi, A., 2016: The Paris Agreement: a new beginning? *Journal of Energy & Natural Resources Law***, 34(1)**, 16-26, doi:10.1080/02646811.2016.1133983.

Schäfer, S., M. Lawrence, H. Stelzer, W. Born, and S. Low (eds.), 2015: *The European Transdisciplinary Assessment of Climate Engineering (EuTRACE): Removing Greenhouse Gases from the Atmosphere and Reflecting Sunlight away from Earth*. 170 pp.

Schewe, J. et al., 2014: Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences***, 111(9)**, 3245-3250.

Schleussner, C.F., P. Pfleiderer, and E.M. Fischer, 2017: In the observational record half a degree matters. *Nature Climate Change***, 7(7)**, 460-462, doi:10.1038/nclimate3320.

Schleussner, C.F. et al., 2016: Differential climate impacts for policy relevant limits to global warming: the case of 1.5°C and 2°C. *Earth System Dynamics***, 7(2)**, 327-351, doi:10.5194/esd-7-327-2016.

Schroeder, H., M.T. Boykoff, and L. Spiers, 2012: Equity and state representations in climate negotiations. *Nature Climate Change***, 2**, 834-836, doi:10.1038/nclimate1742.

Schurer, A.P., M.E. Mann, E. Hawkins, S.F.B. Tett, and G.C. Hegerl, 2017: Importance of the pre-industrial baseline for likelihood of exceeding Paris goals. *Nature Climate Change*, doi:10.1038/nclimate3345.

Seneviratne, S.I., M.G. Donat, A.J. Pitman, R. Knutti, and R.L. Wilby, 2016: Allowable CO_2 emissions based on regional and impact-related climate targets. *Nature***, 529(7587)**, 477-483, doi:10.1038/nature16542.

Seneviratne, S.I. et al., 2012: Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 109-230.

Settele, J. et al., 2014: Terrestrial and inland water systems. In: *Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271-359.

Shiferaw, B. et al., 2014: Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather and Climate Extremes***, 3**, 67-79, doi:10.1016/J.WACE.2014.04.004.

Shindell, D.T., 2015: The social cost of atmospheric release. *Climatic Change***, 130(2)**, 313-326, doi:10.1007/s10584-015-1343-0.

Shindell, D.T., Y. Lee, and G. Faluvegi, 2016: Climate and health impacts of US emissions reductions consistent with 2C. *Nature Climate Change***, 6**, 503-509.

Shindell, D.T., J.S. Fuglestvedt, and W.J. Collins, 2017: The social cost of methane: theory and applications. *Faraday Discussions***, 6**, 773, doi:10.1039/C7FD00009J.

Shine, K.P., J.S. Fuglestvedt, K. Hailemariam, and N. Stuber, 2005: Alternatives to the Global Warming Potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change***, 68(3)**, 281-302, doi:10.1007/s10584-005-1146-9.

Shine, K.P., R.P. Allan, W.J. Collins, and J.S. Fuglestvedt, 2015: Metrics for linking emissions of gases and aerosols to global precipitation changes. *Earth System Dynamics***, 6(2)**, 525-540, doi:10.5194/esd-6-525-2015.

Shue, H., 2013: Climate Hope: Implementing the Exit Strategy. *Chicago Journal of International Law***, 13(2)**, 381.

Shue, H., 2014: *Climate Justice: Vulnerability and Protection*. Oxford University Press, Oxford, UK, 366 pp.

Shue, H., 2018: Mitigation gambles: uncertainty, urgency and the last gamble possible. *Philosophical Transactions of the Royal Society*, doi:10.1098/rsta.2017.0105.

Shukla, P.R. and V. Chaturvedi, 2013: Sustainable energy transformations in India under climate policy. *Sustainable Development***, 21(1)**, 48-59, doi:10.1002/sd.516.

Simmons, A.J. et al., 2017: A reassessment of temperature variations and trends from global reanalyses and monthly surface climatological datasets. *Quarterly Journal of the Royal Meteorological Society***, 143(702)**, 101-119, doi:10.1002/qj.2949.

Simpson, M. et al., 2016: Decision Analysis for Management of Natural Hazards. *Annual Review of*

Environment and Resources, **41(1)**, 489-516, doi:10.1146/annurev-environ-110615-090011.

Sitch, S., P.M. Cox, W.J. Collins, and C. Huntingford, 2007: Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature*, **448**, 791.

Skeie, R.B. et al., 2017: Perspective has a strong effect on the calculation of historical contributions to global warming. *Environmental Research Letters*, **12(2)**, doi:10.1088/1748-9326/aa5b0a.

Smith, C.J. et al., 2018: FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development* (in press), doi:10.5194/gmd-2017-266.

Smith, S.J. and P.J. Rasch, 2013: The long-term policy context for solar radiation management. *Climatic Change*, **121(3)**, 487-497, doi:10.1007/s10584-012-0577-3.

Smith, S.J., J. Karas, J. Edmonds, J. Eom, and A. Mizrahi, 2013: Sensitivity of multi-gas climate policy to emission metrics. *Climatic Change*, **117(4)**, 663-675, doi:10.1007/s10584-012-0565-7.

Smith, S.M. et al., 2012: Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Climate Change*, **2(7)**, 535-538, doi:10.1038/nclimate1496.

Solecki, W., M. Pelling, and M. Garschagen, 2017: Transitions between risk management regimes in cities. *Ecology and Society*, **22(2)**, art38, doi:10.5751/ES-09102-220238.

Solomon, S., G.K.G. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions.. *Proceedings of the National Academy of Sciences of the United States of America*, **106(6)**, 1704-9, doi:10.1073/pnas.0812721106.

Somanathan, E. et al., 2014: National and Sub-national Policies and Institutions. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sovacool, B.K., B.O. Linnér, and M.E. Goodsite, 2015: The political economy of climate adaptation. *Nature Climate Change*, **5(7)**, 616-618, doi:10.1038/nclimate2665.

Stavins, R. et al., 2014: International Cooperation: Agreements and Instruments. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1001-1082.

Stechow, C. et al., 2016: 2°C and the SDGs: United they stand, divided they fall? *Environmental Research Letters*, **11(3)**, 34022, doi:10.1088/1748-9326/11/3/034022.

Steffen, W. et al., 2016: Stratigraphic and Earth System approaches to defining the Anthropocene. *Earth's Future*, **4(8)**, 324-345, doi:10.1002/2016EF000379.

Sterner, E., D.J.A. Johansson, and C. Azar, 2014: Emission metrics and sea level rise. *Climatic Change*, **127(2)**, 335-351, doi:10.1007/s10584-014-1258-1.

Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33-115.

Stone, D. et al., 2013: The challenge to detect and attribute effects of climate change on human and natural systems. *Climatic Change*, **121(2)**, 381-395, doi:10.1007/s10584-013-0873-6.

Strefler, J., G. Luderer, T. Aboumahboub, and E. Kriegler, 2014: Economic impacts of alternative greenhouse gas emission metrics: a model-based assessment. *Climatic Change*, **125(3-4)**, 319-331, doi:10.1007/s10584-014-1188-y.

Tàbara, J.D. et al., 2018: Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability*, **31**, 120-129, doi:10.1016/j.cosust.2018.01.012.

Tanaka, K. and B.C. O'Neill, 2018: The Paris Agreement zero-emissions goal is not always consistent with the 1.5°C and 2°C temperature targets. *Nature Climate Change*, **8(4)**, 319-324, doi:10.1038/s41558-018-0097-x.

Taylor, K.E., R.J. Stouffer, and G.A. Meehl, 2012: An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, **93(4)**, 485-498, doi:10.1175/BAMS-D-11-00094.1.

Termeer, C.J.A.M., A. Dewulf, and G.R. Biesbroek, 2017: Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *Journal of Environmental Planning and Management*, **60(4)**, 558-576, doi:10.1080/09640568.2016.1168288.

The Royal Society, 2009: *Geoengineering the climate: science, governance and uncertainty*. 1-5 pp.

Tokarska, K.B. and K. Zickfeld, 2015: The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Env. Res. Lett.*, **10**, 94013, doi:doi:10.1088/1748-9326/10/9/094013.

Tokarska, K.B. and N.P. Gillett, 2018: Cumulative carbon emissions budgets consistent with 1.5 °C global warming. *Nature Climate Change*, **8(4)**, 296-299, doi:10.1038/s41558-018-0118-9.

Tol, R.S.J., T.K. Berntsen, B.C. O'Neill, Fuglestvedt, and P.S. Keith, 2012: A unifying framework for metrics for aggregating the climate effect of different emissions. *Environmental Research Letters*, **7(4)**, 44006.

Tschakert, P., B. van Oort, A.L. St. Clair, and A. LaMadrid, 2013: Inequality and transformation analyses: a complementary lens for addressing vulnerability to climate change. *Climate and Development*, **5(4)**, 340-350, doi:10.1080/17565529.2013.828583.

Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8(5)**, e476--n/a, doi:10.1002/wcc.476.

UNDP, 2016: *Human Development Report 2016: Human Development for Everyone*. 286 pp.

UNFCCC, 2016: *Aggregate effect of the intended nationally determined contributions: an update*. FCCC/CP/2016/2, United Nations Framework Convention on Climate Change (UNFCCC), 75 pp.

UNGA, 2015: *Transforming our world: The 2030 agenda for sustainable development*. A/RES/70/1, United Nations General Assembly (UNGA), 35 pp.

United Nations, 2015: *The Millennium Development Goals Report 2015*. 75 pp.

van Oldenborgh, G.J. et al., 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12(12)**, 124009.

van Vuuren, D.P. et al., 2011: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5-31, doi:10.1007/s10584-011-0148-z.

van Vuuren, D.P. et al., 2014: A new scenario framework for Climate Change Research: Scenario matrix architecture. *Climatic Change*, **122(3)**, 373-386, doi:10.1007/s10584-013-0906-1.

van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303-323, doi:10.1016/j.techfore.2015.03.005.

Vautard, R. et al., 2014: The European climate under a 2°C global warming. *Environmental Research Letters*, **9(3)**, doi:10.1088/1748-9326/9/3/034006.

Vincent, K.E., P. Tschakert, J. Barnett, M.G. Rivera-Ferre, and A. Woodward, 2014: Cross-chapter box on gender and climate change. In: *Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 105-107.

von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annual Review of Environment and Resources*, **40(1)**, 363-394, doi:10.1146/annurev-environ-021113-095626.

Vose, R.S. et al., 2012: NOAA's merged land-ocean surface temperature analysis. *Bulletin of the American Meteorological Society*, **93(11)**, 1677-1685, doi:10.1175/BAMS-D-11-00241.1.

Waters, C.N. et al., 2016: The Anthropocene is functionally and stratigraphically distinct from the Holocene. *Science*, **351(6269)**, aad2622-aad2622, doi:10.1126/science.aad2622.

WCED, 1987: *Our Common Future*. World Commission on Environment and Development (WCED), Geneva, Switzerland, 383 pp.

Weber, H., 2017: Politices of 'Leaving no one behind': contesting the 2030 Sustainable development goals. *Globalizations*, **14(3)**, 399-414.

Whitmarsh, L., S. O'Neill, and I. Lorenzoni (eds.), 2011: *Engaging the Public with Climate Change: Behaviour Change and Communication*. Earthscan, London, UK and Washington, DC, USA, 289 pp.

Wigley, T.M.L., 2018: The Paris warming targets: emissions requirements and sea level consequences. *Climatic Change*, **147(1-2)**, 31-45, doi:10.1007/s10584-017-2119-5.

Williams, R.G., V. Roussenov, T.L. Frölicher, and P. Goodwin, 2017: Drivers of Continued Surface Warming After Cessation of Carbon Emissions. *Geophysical Research Letters*, **44(20)**, 10,633-10,642, doi:10.1002/2017GL075080.

Winkler, I.T. and M.L. Satterthwaite, 2017: Leaving no one behind? Persistent inequalities in the SDGs. *The International Journal of Human Rights*, **21(8)**, 1073-1097, doi:10.1080/13642987.2017.1348702.

Wise, R.M. et al., 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, **28**, 325-336, doi:10.1016/j.gloenvcha.2013.12.002.

World Bank, 2013: *Turn Down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience*. 254 pp.

Wright, H., S. Huq, and J. Reeves, 2015: Impact of climate change on least developed countries: are the SDGs possible? IIED Briefing May 2015, 4 pp.

Xu, Y. and V. Ramanathan, 2017: Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proc. Natl. Acad. Sci.* 1-9, doi:10.1073/pnas.1618481114.

Zalasiewicz, J. et al., 2017: Making the case for a formal Anthropocene Epoch: an analysis of ongoing critiques. *Newsletters on Stratigraphy*, **50(2)**, 205-226, doi:10.1127/nos/2017/0385.

Zickfeld, K., A.H. MacDougall, and H. Damon Matthews, 2016: On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions. *Environmental Research Letters*, **11(5)**, doi:10.1088/1748-9326/11/5/055006.

Zickfeld, K., M. Eby, H.D. Matthews, and A.J. Weaver, 2009: Setting cumulative emissions targets to reduce the risk of dangerous climate change.. *Proceedings of the National Academy of Sciences of the United States of America*, **106(38)**, 16129-16134, doi:10.1073/pnas.0805800106.

Zscheischler, J. and S.I. Seneviratne, 2017: Dependence of drivers affects risks associated with compound events. *Science Advances*, **3(6)**, doi:10.1126/sciadv.1700263.

Chapter 1: Framing and Context

Technical Annex 1.A

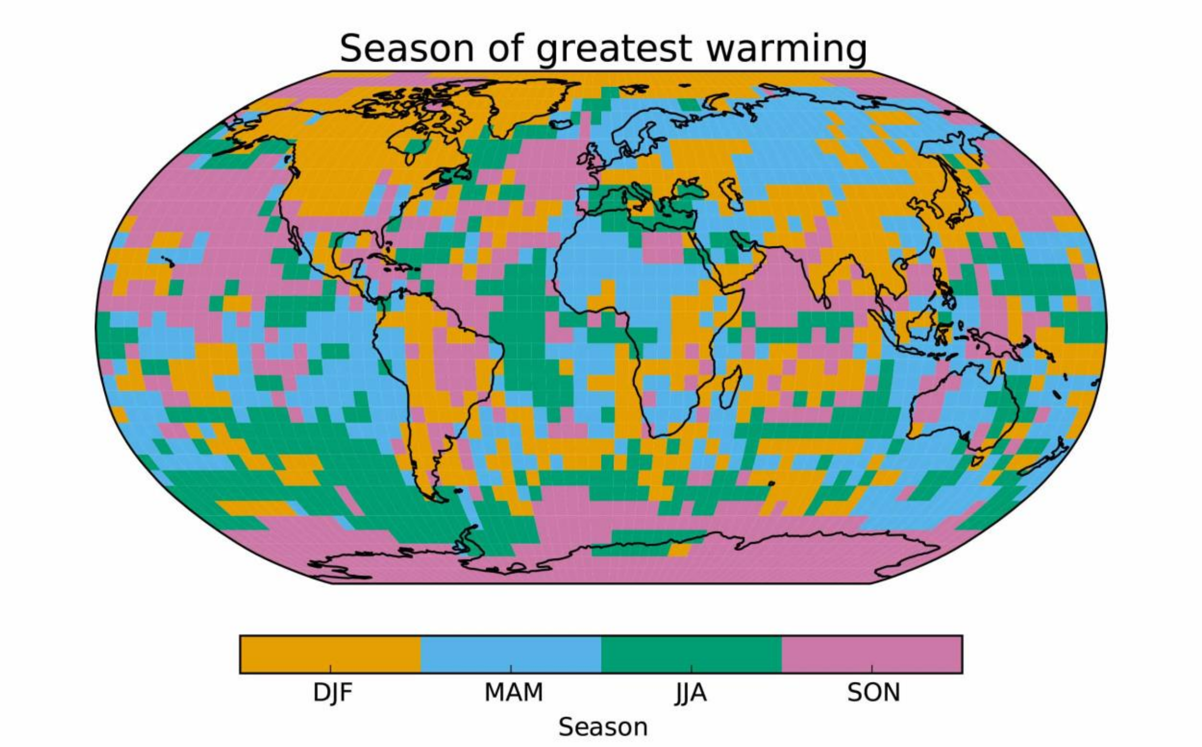
This Annex provides technical details of the calculations behind the figures in the chapter, as well as some supporting figures provided for sensitivity analysis or to provide support to the main assessment.

Table of Content

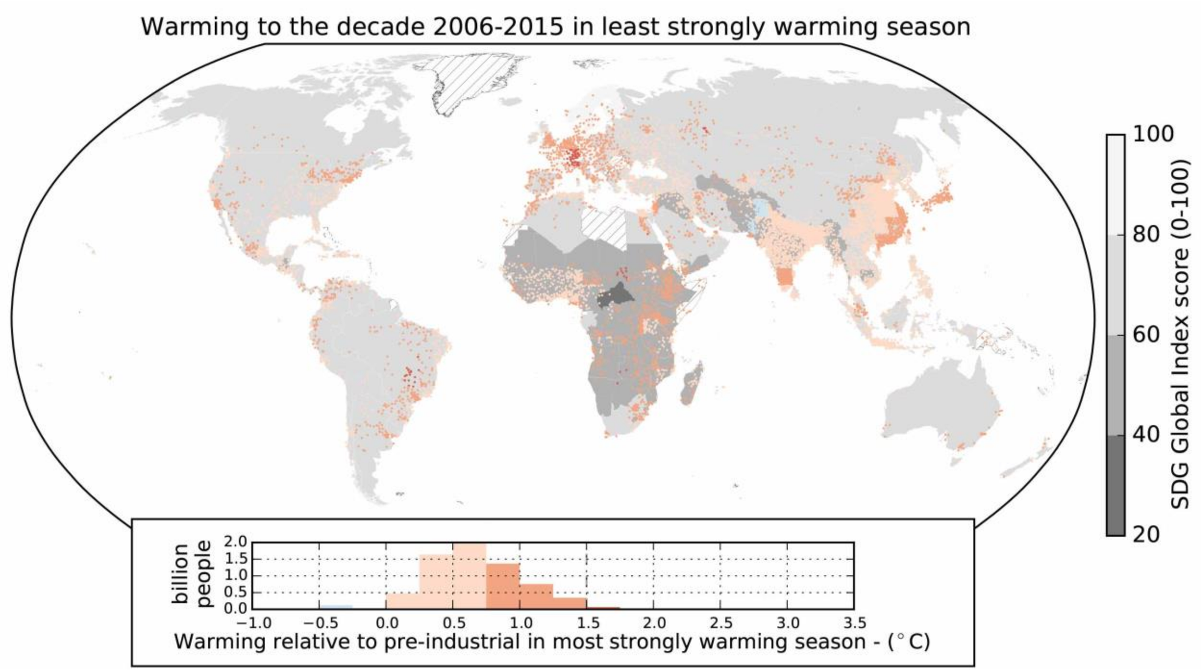
Annex 1.A.1: supporting material for for Figure 1.1

Externally-forced warming is calculated for the Cowtan & Way (Cowtan and Way, 2014) dataset at every location and for each season as in Figure 1.3. The season with the greatest externally-forced warming at every location (averaged over the 2006-2015 period) is selected to give the colour of the dots at that grid box.

Technical Annex 1.A Figure 1 shows the season of maximum warming in each grid-box used in Figure 1.1, while Technical Annex 1.A Figure 2 shows the warming to 2006-2015 in the season that has warmed the least.



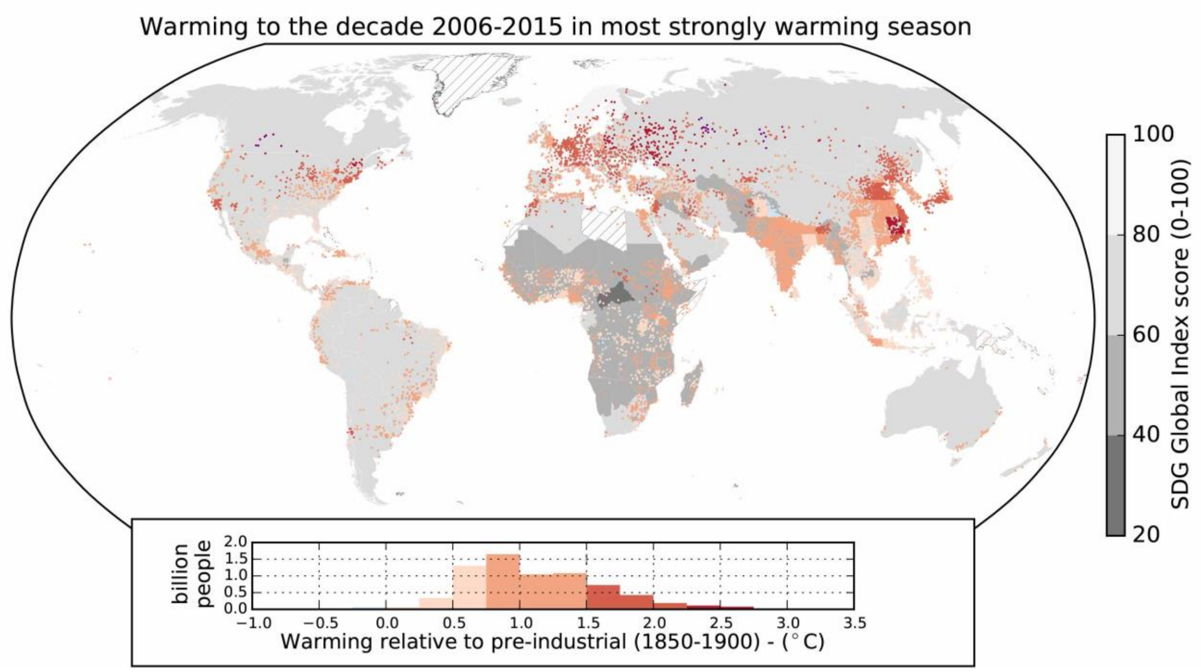
Technical Annex 1.A, Figure 1: Season of greatest human-induced warming over 2006-2015 relative to 1850-1900 for the data shown in Figure 1.1.



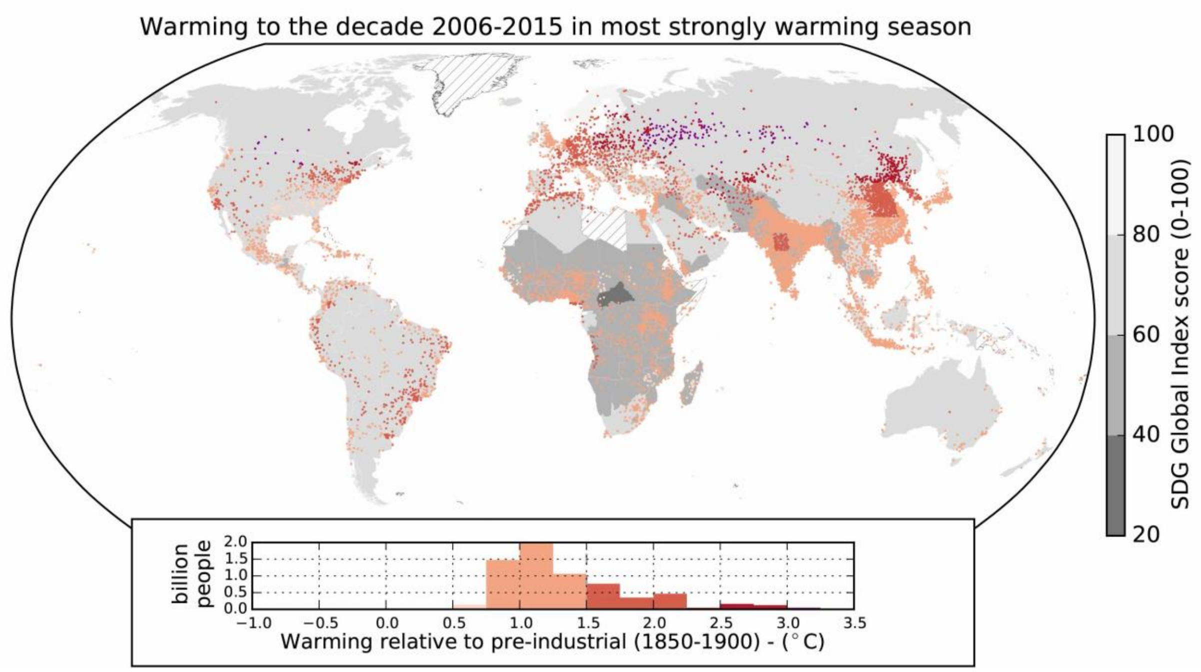
Technical Annex 1.A, Figure 2: As for Figure 1.1 but with scatter points coloured by warming in the season with least warming over the 2006-2015 period.

Population data is taken from Doxsey-Whitfield et al. (2015) for 2010. The number of scatter points shown in each 1°x1° grid box is directly proportional to the population count in the grid-box, with a maximum number of scatter points in a single grid-box associated with the maximum population count in the dataset. For grid-boxes with (non-zero) population counts that are below the population threshold consistent with just a single scatter point (approximately 650,000), the probability that a single scatter point is plotted reduces from unity towards zero with decreasing population in the grid-box to give an accurate visual impression of population distribution.

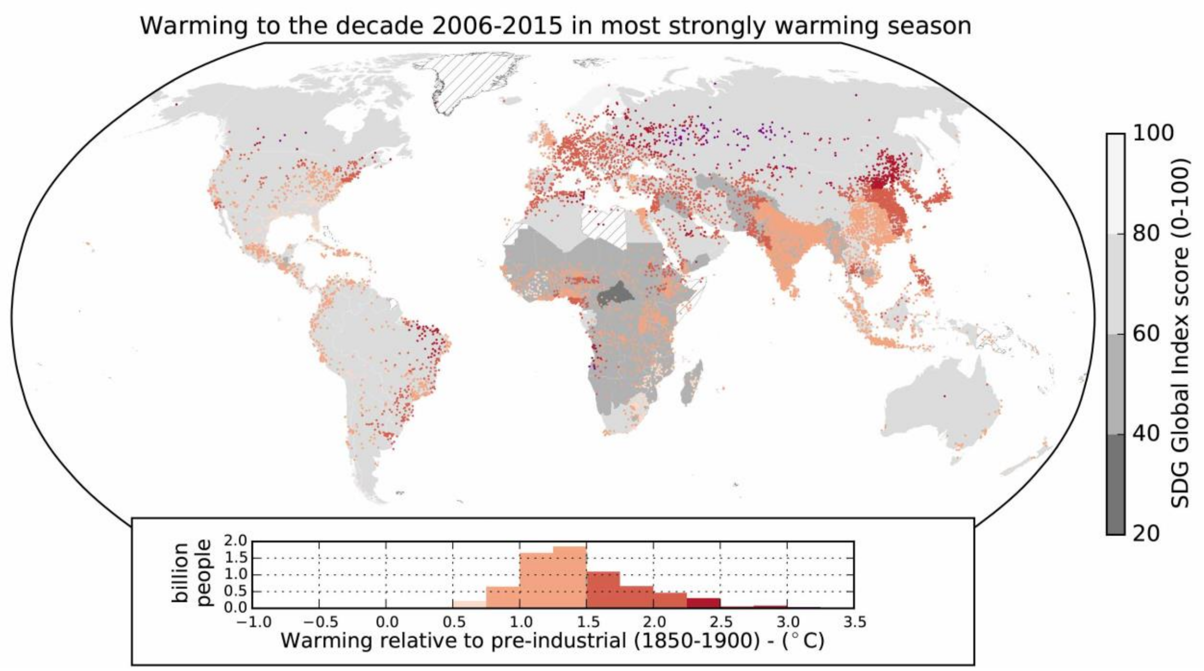
The SDG Global Index Score is a quantitative measure of progress towards the 17 sustainable development goals (Sachs et al., 2017). The goals cross-cut the three dimensions of sustainable development – environmental sustainability, economic growth, and social inclusion. It has a range of 0-100, 100 corresponding to all SDGs being met. Versions of Figure 1.1 using the HadCRUT4, NOAA and GISTEMP temperature datasets are shown in Technical Annex 1.A Figure 3-5 respectively.



Technical Annex 1.A, Figure 3: As for Figure 1.1 but using the HadCRUT4 temperature dataset.



Technical Annex 1.A, Figure 4: As for Figure 1.1 but using the NOAA temperature dataset.



Technical Annex 1.A, Figure 5: As for Figure 1.1 but using the GISTEMP temperature dataset.

Annex 1.A.2: supporting material for Figure 1.2

Observational data used in Chapter figure 1.2 are taken from the Met Office Hadley Centre (http://www.metoffice.gov.uk/hadobs/hadcrut4/), National Oceanic and Atmospheric Administration (NOAA) (https://www.ncdc.noaa.gov/data-access/marineocean-data/noaa-global-surface-temperature-noaaglobaltemp), NASA's Goddard Institute for Space Studies (https://data.giss.nasa.gov/gistemp/) and the Cowtan & Way dataset (http://www-users.york.ac.uk/~kdc3/papers/coverage2013/series.html). The GISTEMP and NOAA observational products (which begin in 1880) are expressed relative to 1850-1900 by assigning these datasets the same anomaly as HadCRUT4 for the mean of the 1880-2017 period. All available data is used, through to the end of 2017, for all datasets. The grey "Observational range" shades between the minimum and maximum monthly-mean anomaly across these four temperature datasets for the month in question.

CMIP5 multi-model means, light blue dashed (full field surface air temperature) and solid (masked and blended as in Cowtan et al. (2015)) are expressed relative to a 1861-1880 base period and then expressed relative to the 1850-1900 reference period using the anomaly between the periods in the HadCRUT4 product (0.02°C). Model data are taken from Richardson et al. (2018). Only RCP8.5 r1i1p1 ensemble members are used with only one ensemble member per model for calculating the mean lines in this figure.

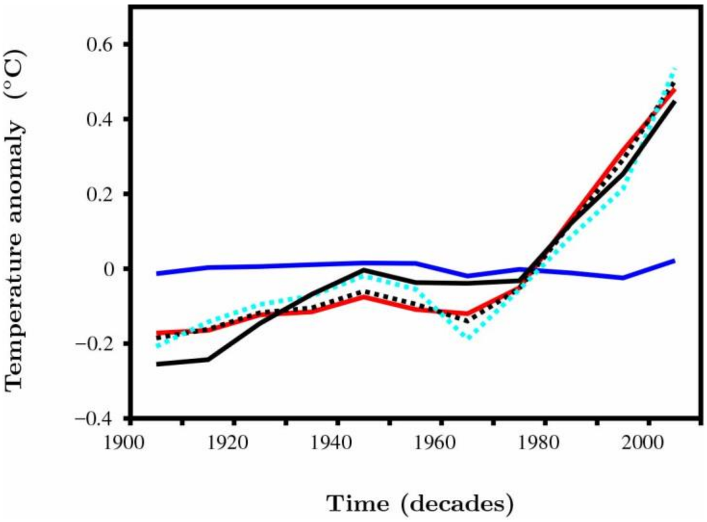
The pink "Holocene" shading is derived from the "Standard5x5Grid" reconstruction of Marcott et al. (2013) (expressed relative to 1850-1900 using the HadCRUT4 anomaly between this reference period and the 1961-90 base period of the data). The vertical extent of the solid shading is determined by the maximum and minimum temperature anomalies in the dataset in the period before 1850. Marcott et al. (2013) report data with a periodicity of 20 years, so the variability shown by the solid pink shading is not directly comparable to the higher frequency variability seen in the observational products which are reported every month), but this Holocene range can be compared to the emerging signal of human-induced warming. Above and below the maximum and minimum temperature anomalies from Marcott et al. (2013) the pink shading fades out to after a magnitude of warming that is equal to the standard deviation of monthly temperature anomalies in the HadCRUT4 dataset over the pre-industrial reference period of 1850-1900, and as such this faded shading does not bound all monthly anomalies in the pre-industrial reference period.

Near term predictions from IPCC-AR5 (Kirtman et al., 2013), for the period 2016-2035 were estimated to be *likely* (>66% probability) between 0.3°C and 0.7°C above the 1986-2005 average, assuming no climatically significant future volcanic eruptions. These are expressed relative to pre-industrial using the updated 0.63°C warming to the 1986-2005 period (Section 1.2.1).

Human-induced temperature change (thick yellow line) and total (human+natural) externally-forced temperature change (thick orange line) are estimated using the method of Haustein et al. (2017) applied to the 4-dataset mean. Best-estimate historical radiative forcings, extended until the end of 2016, are taken from Myhre et al. (2013), incorporating the significant revision to the methane forcing proposed by Etminan et al. (2016). The 2-box thermal impulse-response model used in Myhre et al. (2013), with modified thermal response time-scales to match the multi-model mean from Geoffroy et al. (2013), is used to derive the shape to the global mean temperature response timeseries to total anthropogenic and natural (combined volcanic and solar) forcing. Both of these timeseries are expressed as anomalies relative to their simulated 1850-1900 averages and then used as independent regressors in a multi-variate linear regression to derive scaling factors on the two timeseries that minimise the residual between the combined forced response and the multi-dataset observational mean. The transparent shading around the thick yellow line indicates the *likely* range in attributed human-induced warming conservatively assessed at ±20%. Note that the corresponding *likely* range of ±0.1°C uncertainty in the 0.7°C best-estimate anthropogenic warming trend over the 1951-2010 period assessed in Bindoff et al. (2013) corresponds to a smaller fractional uncertainty (±14%): the broader range reflects greater uncertainty in early-century warming.

The vertical extent of the 1986-2005 cross denotes the 5-95% observational uncertainty range of ±0.06°C (see Table 1.1) while that of the 2006-2015 cross denotes the assessed *likely* uncertainty range of ±0.12°C (Section 1.2.1).

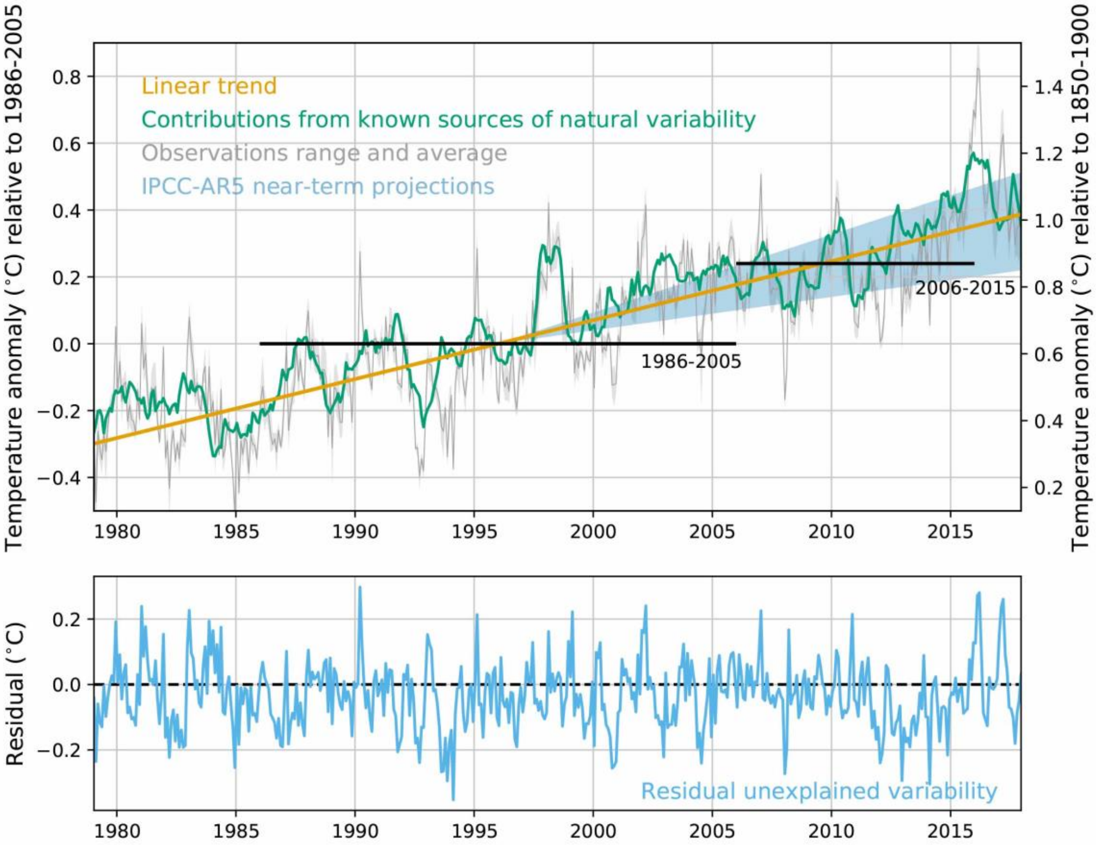
To provide a methodologically independent check on the attribution of human-induced warming since the 19th century (quantitative attribution results quoted in AR5 being primarily focussed on the period 1951-2010), Technical Annex 1.A Figure 6 shows a recalculation of the results of Ribes and Terray (2013), figure 1, applied to the CMIP5 multi-model mean response. Details of the calculation are provided in the original paper. In order to quantify the level of human-induced warming since the late 19th century, observations of GMST are regressed onto the model responses to either natural-only (NAT) or anthropogenic-only (ANT) forcings, consistent with many attribution studies assessed in AR5. Prior to this analysis, model outputs are pre-processed in order to ensure consistency with observations: spatial resolution is lowered to 5°, the spatio-temporal observational mask is applied, and all missing data are set to 0. Global and decadal averages of near-surface temperature are calculated over the 1901-2010 period (11 decades), and translated into anomalies by subtracting the mean over the entire period (1901-2010). Multi-model mean response patterns are calculated over a subset of 7 CMIP5 models providing at least 4 historical simulations and 3 historical NAT-only simulations, all covering the 1901-2010 period. The regression analysis indicates how these multi-model mean responses have to be rescaled in order to best fit observations, accounting for internal variability in both observations and model responses, but neglecting observational uncertainty. Almost no rescaling is needed for ANT (regression coefficient: 1.05 ±0.18), while the NAT simulated response is revised downward (regression coefficient: 0.28±0.49). The resulting estimate of the total externally forced response is very close to observations (Figure 6). The ANT regression coefficient can then be used to assess the human-induced warming over a longer period. Estimated in this way, the human-induced linear warming trend 1880-2012 is found to be 0.86°C±0.14°C.



Technical Annex 1.A, Figure 6: Contributions of natural (NAT) and anthropogenic (ANT) forcings to changes in GMST over the period 1901-2010. Decadal time-series of GMST in HadCRUT4 observations (solid black), from multi-model mean response without any rescaling (dotted cyan), and as reconstructed by the linear regression (dotted black). The estimated contributions of NAT forcings only (solid blue) and anthropogenic forcing only (solid red) correspond to the CMIP5 multi-model mean response to these forcings, after rescaling. All temperatures are anomalies with respect to the 1901-2010 average, after pre-processing (missing data treated as 0). Vertices are plotted at the mid-point of the corresponding decade.

To quantify the potential impact of natural (externally-forced or internally-generated) variability on decadal-mean temperatures in 2006-2015, Technical Annex1.A Figure 7 shows an estimate of the observed warming rate, corrected for the effects of natural variability according to the method of Foster and Rahmstorf, (2011) applied to the average of the four observational datasets used in this report, updated to the end of 2017. The grey line shows the raw monthly GMST observations (with shading showing inter-dataset range), while the green shows the sum of the linear trend plus estimated known sources of variability, such as El Niño events or volcanic eruptions, estimated using an empirical regression model. The orange line shows the linear trend, after correcting for the impact of these known sources of variability, of 0.18°C per decade, while the two black lines show the recent reference periods used in this report. For comparison, the AR5 near-term predicted warming rate of 0.3-0.7°C over 30 years (Kirtman et al, 2013) is shown as the pale blue plume.

The blue line in the lower panel shows residual fluctuations that cannot be attributed to known sources or modes of variability, reflecting internally-generated chaotic weather variability (the difference between grey and green lines in the top panel). The green line is not persistently below the yellow line, nor is the blue line persistently negative, over the period 2006-2015. There is a downward excursion in the residual “unexplained” variability around 2012-13, and a strong ENSO cool phase event in 2011, but even together these depress the decadal average by only a couple of hundredths of a degree.

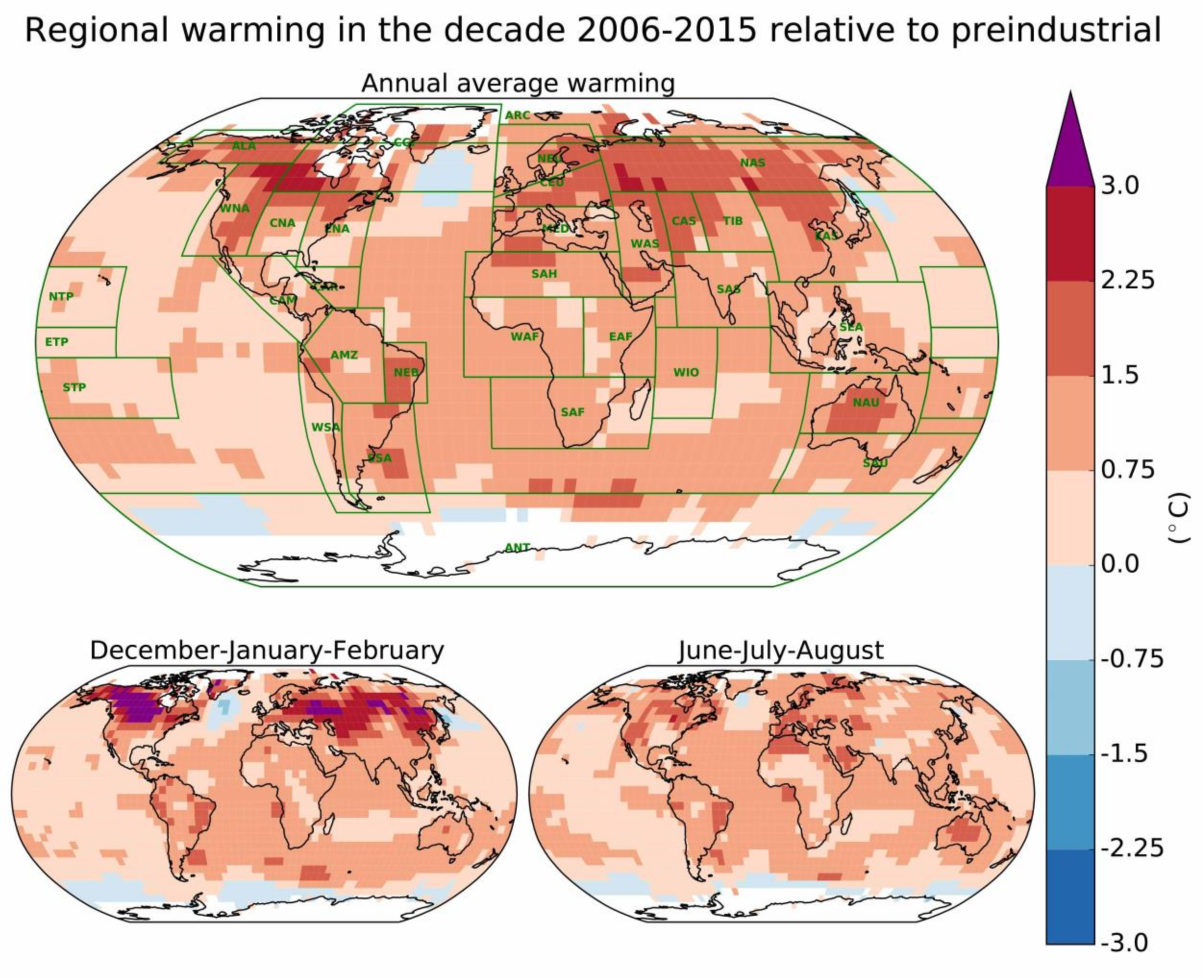


Technical Annex 1.A, Figure 7: Warming and warming rate 1979-2017. The solid grey line shows the average of the four observational datasets used in this assessment report with the observational range shown by grey shading. The yellow line shows the linear trend through the observational data, corrected for the effects of known sources of natural variability (green line). The blue shading indicates that warming rates compatible with the IPCC-AR5 near-term projections. The lower panel shows the residual unexplained variability (difference between grey and green lines in upper panel) after accounting for known sources, including ENSO, solar variability and volcanic activity.

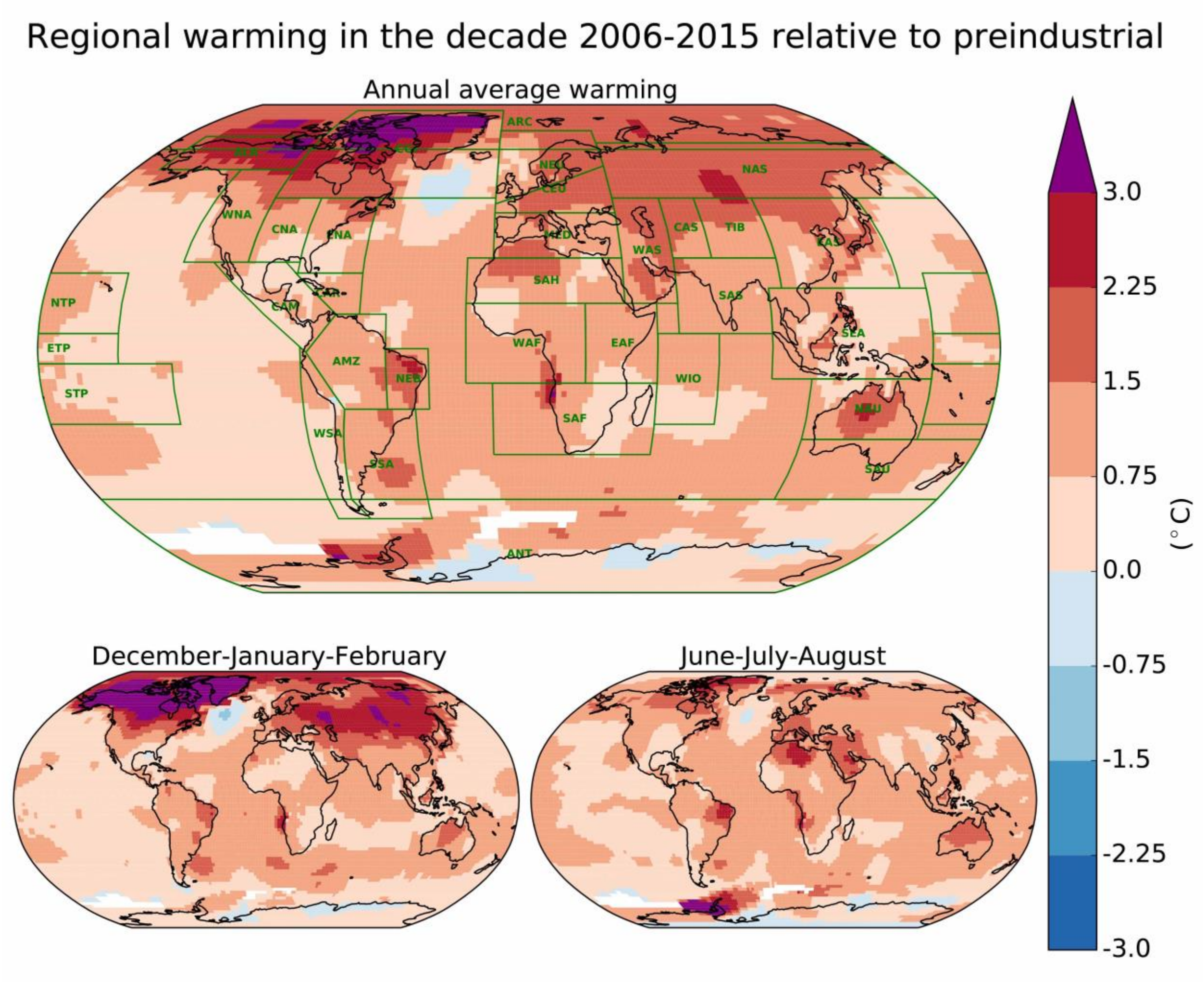
Annex 1.A.3: supporting material for Figure 1.3

Regional warming shown in Figure 1.3 is derived using a similar method to the calculation of externally-forced warming in Figure 1.2. At every grid box location in the native Cowtan & Way resolution, the timeseries of local temperature anomalies in the Cowtan & Way dataset are regressed onto the associated externally-forced warming timeseries, calculated as in Figure 1.1 using all available historical monthly-mean anomalies. The best-fit relationship between these two quantities is then used to estimate the forced warming relative to 1850-1900 at this location. The maps in Figure 1.3 show the average of these estimated local forced warming timeseries over the 2006-2015 period. Trends are only plotted only where over 50% of the entire observational record at this location is available.

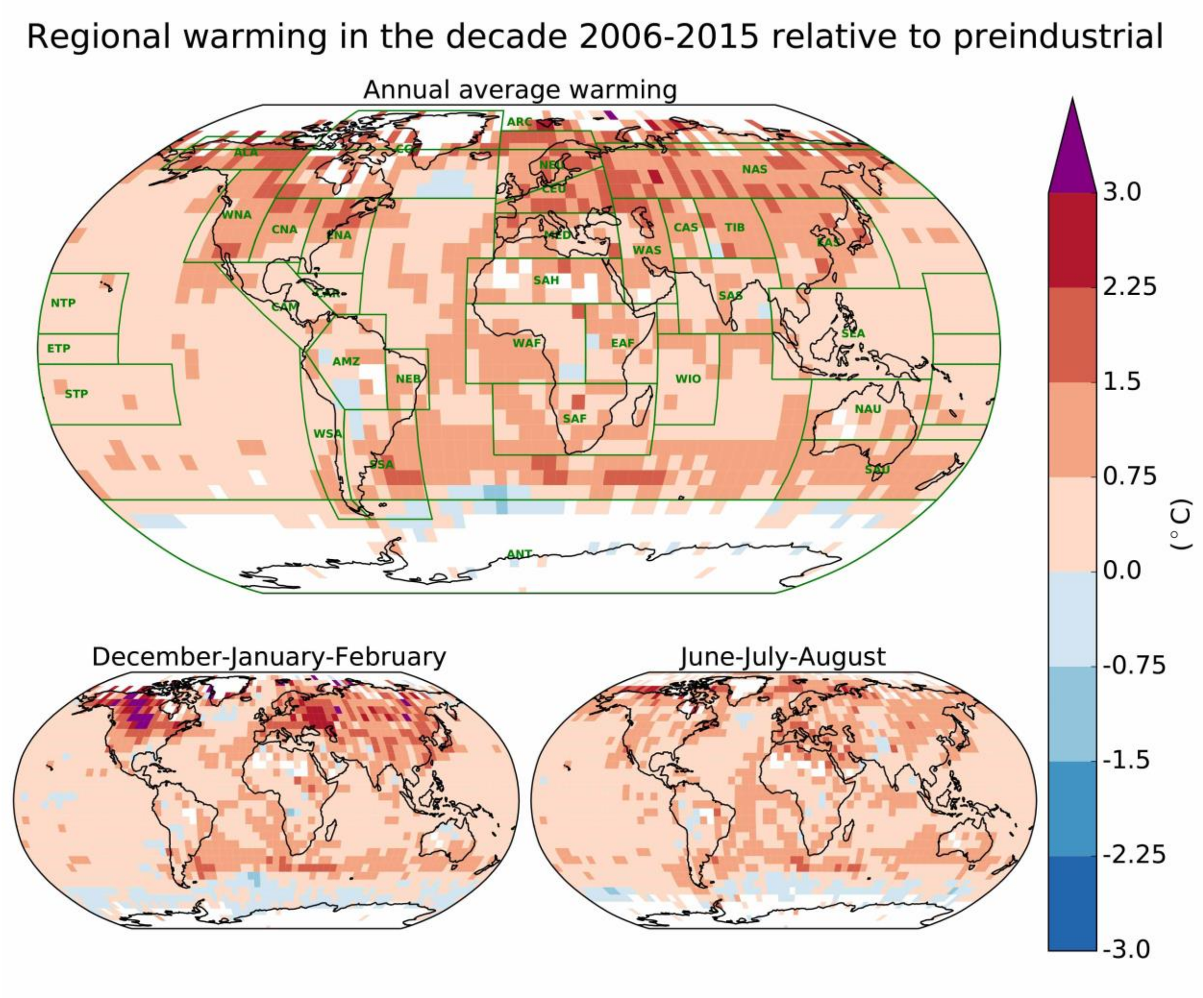
Supplementary maps are included below for the NOAA, GISTEMP and HadCRUT4 observational data. The regression of local temperature anomalies onto the global mean externally-forced warming, allows warming to be expressed relative to 1850-1900 despite many local series in these datasets beginning after 1900, but clearly these inferred century-time-scale warming levels are subject to a lower confidence level than the corresponding global values.



Technical Annex 1.A Figure 8: Externally-forced warming for the average of 2006-2015 relative to 1850-1900 calculated for the NOAA observational dataset as for Figure 1.3.



Technical Annex 1.A, Figure 9: Externally-forced warming for the average of 2006-2015 relative to 1850-1900 calculated for the GISTEMP observational dataset as for Figure 1.3.



Technical Annex 1.A, Figure 10: Externally-forced warming for the average of 2006-2015 relative to 1850-1900 calculated for the HadCRUT4 observational dataset as for Figure 1.3.

Annex 1.A.4: supporting material for Figure 1.4

Idealised temperature pathways computed by specifying the level of human-induced warming in 2017, $T_{2017} = 1$°C, with temperatures from 1850 to 2017 approximated by an exponential rise, with the exponential rate constant, γ, set to give a rate of human-induced warming in 2017 of 0.2°C/decade. Temperatures from 2018-2100 are determined by fitting a smooth 4th-order polynomial through specified warming at particular times after 2017.

Radiative forcing F that would give the temperature profiles is computed using a 2-time-constant climate response function (Myhre et al., 2013b), with Equilibrium Climate Sensitivity (ECS) of 2.7°C and Transient Climate Response (TCR) of 1.6°C and other parameters as given in Millar et al. (2017). Equivalent CO_2 concentrations given by $C = 278 \times \exp(F/5.4)$ ppm.

Cumulative CO_2-forcing-equivalent emissions (Jenkins et al, 2018), or the CO_2 emission pathways that would give the CO_2 concentration pathways compatible with the temperature scenario is computed using an invertible simple carbon cycle model (Myhre et al., 2013b), modified to account for changing CO_2 airborne fraction over the historical period (Millar et al., 2017). These are proportional to CO_2 emissions under the assumption of a constant fractional contribution of non-CO_2

forcers to warming. Indicative cumulative impact variable (e.g. sea level rise) is computed from temperature pathways shown in using semi-empirical model of Kopp et al. (2016).

Annex 1.A.5: supporting material for Figure 1.5

All scenarios in Figure 1.5 start with a 1000 member ensemble of the FAIR model (Smith et al., 2018) driven with emissions from the RCP historical dataset from 1765 to 2000 (Meinshausen et al., 2011), SSP2 from 2005 to 2020 (Fricko et al., 2017), and a linear interpolation between the two inventories for 2000 to 2005. Equilibrium climate sensitivity (ECS) and transient climate response (TCR) parameters are drawn from a joint lognormal distribution informed by CMIP5 models. Uncertainties in present-day non-CO_2 ERF are drawn from the distributions in Myhre et al. (2013) and uncertainties in the carbon cycle response are given a 5 to 95% range of 13% around the best estimate (Millar et al., 2017). All uncertainties except TCR and ECS are assumed to be uncorrelated with each other.

FAIR derives an effective radiative forcing (ERF) time series from emissions, from which temperature change calculated. Greenhouse gas concentrations are first calculated, from which the radiative forcing relationships from Myhre et al. (1998) are used to determine ERF. An increase of ERF of 25% for methane forcing is applied which approximates the updated relationship from Etminan et al. (2016). The Myhre et al. (1998) relationships with a scaling for methane rather than the newer Etminan et al. (2016) relationships are used because the former does not assume any band overlap between CO_2 and N_2O, and isolating CO_2 forcing from N_2O forcing is problematic for certain commitments where CO_2 emissions are set to zero and N_2O forcing is held constant.

Aerosol forcing is based on the Aerocom radiative efficiencies (Myhre et al., 2013a) for ERFari (ERF from aerosol-radiation interactions) and a logarithmic dependence on emissions of black carbon, organic carbon and sulfate for ERFaci (ERF from aerosol-cloud interactions) based on the model of Ghan et al., (2013). Tropospheric ozone forcing is based on Stevenson et al., (2013). Other minor categories of anthropogenic forcing are derived from simple relationships that approximate the evolution of ERF in Annex II of Working Group I of AR5 (Prather et al., 2013) as described in Smith et al., (2018). For forcing categories other than methane (for which a significant revision to be best estimate ERF has occurred since AR5), a time-varying scaling factor is implemented over the historical period, so that for a best estimate forcing, the AR5 ERF time series is replicated. This historical scaling decays linearly between 2000 and 2011 so that in 2011 onwards the FAIR ERF estimate is used for projections. For the 2000-2011 period the impact of the historical scaling is small, because FAIR emissions-forcing relationships are mostly derived from IPCC AR5 best estimates in 2005 or 2011 (Smith et al., 2018).

Two ensembles are produced: a historical (1765 to 2014) ensemble containing all (anthropogenic plus natural) forcing, and a historical+future (1765 to 2100) ensemble containing only anthropogenic forcing for each commitment scenario. In the ensemble where natural forcing is included, solar forcing for the historical period is calculated by using total solar irradiance from the SOLARIS HEPPA v3.2 dataset (Matthes et al., 2017) for 1850-2014 and from Myhre et al. (2013) for 1765-1850: the 1850-1873 mean is subtracted from the time series which is then multiplied by 0.25 (annual illumination factor) times 0.7 (planetary co-albedo) to generate the effective radiative forcing (ERF) timeseries. Volcanic forcing is taken by using stratospheric aerosol optical depths from the CMIP6 historical Easy Volcanic Aerosol dataset (Toohey et al., 2016) prepared for the HadGEM3 CMIP6 historical integrations for 1850-2014. The integrated stratospheric aerosol optical depth at 550 nm (tau) is calculated and converted to ERF by the relationship ERF = -18*tau, based on time slice experiments in the HadGEM3 general circulation model, which agrees well with earlier HadGEM2 and HadCM3 versions of the UK Met Office Hadley Centre model (Gregory et al., 2016). The 1850-2014 mean volcanic ERF of -0.107 is subtracted as an offset to define the mean historical volcanic

ERF as zero. Owing to rapid adjustments to stratospheric aerosol forcing, which are included in the definition of ERF, this less negative value of -18*tau is adopted for volcanic ERF than the RF = -25*tau used in AR5.

The historical all-forcing scenario is then used to constrain parameter sets that satisfy the historical observed temperature trend of 0.90 ± 0.19°C (mean and 5 to 95% range) over the 1880 to 2014 period, using the mean of the HadCRUT4, GISTEMP and NOAA datasets. The trend was derived using an inflation factor for autocorrelation of residuals, and is the same method used to derive linear temperature trends in AR5 (Hartmann et al., 2013). The uncertainty bounds used here are wider than, but consistent with, the 1-sigma range of ±0.12°C assessed for the temperature change in 2006-2015 relative to 1850-1900. The parameter sets that satisfy the historical temperature constraint in the historical ensemble (323 out of 1000) are then selected for the anthropogenic-only ensembles that include commitments.

Each commitment scenario is driven with the following assumptions:

1. Zero CO_2 emissions, constant non-CO2 forcing (blue): FAIR spun up with anthropogenic forcing to 2020. Total non-CO_2 forcing in 2020 is used as the input to the 2021-2100 period with all CO_2 fossil and land use emissions abruptly set to zero.

2. Phase out of CO_2 emissions with 1.5°C commitment (blue dotted): FAIR spun up with anthropogenic forcing to 2020. Total non-CO_2 forcing in 2020 is used as the input to the 2021-2100 periof. Fossil and land-use CO_2 emissions are ramped down to zero at a linear rate over 50 years from 2021 to 2070, consistent with a 1.5°C temperature rise since pre-industrial at the point of zero CO_2 emissions in 2070.

3. Linear continuation of 2010-2020 temperature trend (blue dashed, in bottom panel only).

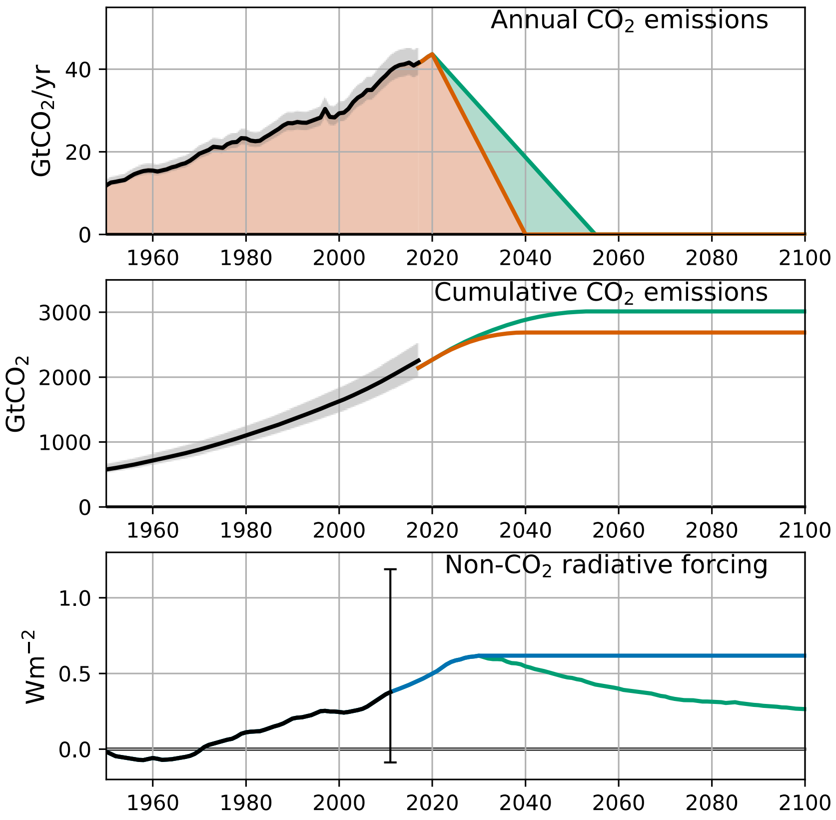
4. Zero GHG emissions, constant aerosol forcing (pink): FAIR spun up with anthropogenic forcing to 2020. All GHG emissions set abruptly to zero in 2021, with aerosol emissions held fixed at their 2020 levels.

5. Zero CO_2 and aerosol emissions, constant non-CO_2 GHG forcing (teal): FAIR spun up with anthropogenic forcing to 2020. Total non-CO_2 GHG forcing, which also includes the proportion of tropospheric ozone forcing attributable to methane emissions, in 2020 is used as the input to the 2021-2100 period. Fossil and land-use CO_2 and aerosol emissions abruptly set to zero in 2021.

6. Zero emissions (yellow): FAIR spun up with anthropogenic forcing to 2020. All emissions set abruptly to zero in 2021.

Annex 1.A.6: supporting material for FAQ 1.2 Figure 1 and Figure SPM1

This section provides supporting material for the figure in FAQ 1.2 and the figure SPM1 in the Summary for Policymakers. Figure 11, top panel, shows time-series of annual CO_2 emissions from the Global Carbon Project (Le Quéré et al, 2018) (black line and grey band, with the width of the band indicating the *likely* range, or one-standard-error, uncertainty in annual emissions), extrapolated to 2020 and then declining in a straight line to reach net zero in either 2055 (green line) or 2040 (brown line).



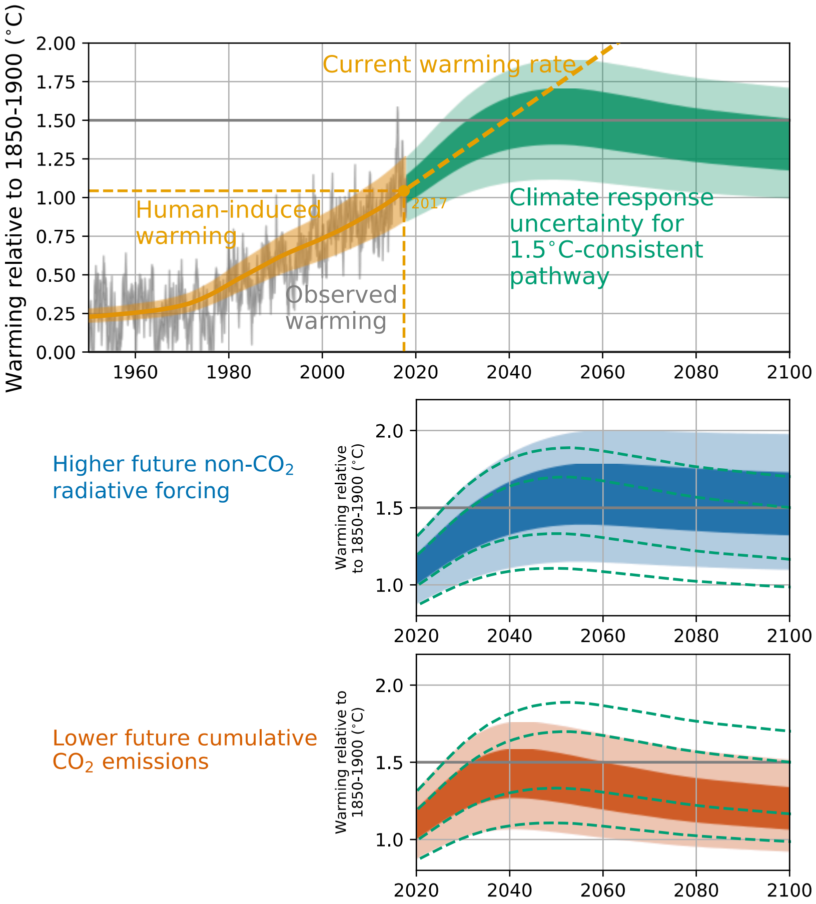
Technical Annex 1.A, Figure 11: Time-series of (top) annual CO_2 emissions, (middle) cumulative CO_2 emissions, and (bottom) non-CO_2 radiative forcing corresponding to observation-based estimates over the historical period and idealised 1.5°C-consistent pathways.

The middle panel in figure 11 shows cumulative (time-integrated) CO_2 emissions, or the areas highlighted as brown+green or brown, respectively, in the top panel. Brown and green lines show cumulative emissions diagnosed from a simple climate-carbon-cycle model (Millar et al, 2017), with historical airborne fraction scaled to reproduce median estimated annual emissions in 2017. Note this does not precisely reproduce median estimated cumulative emissions in 2017, but is well within the range of uncertainty.

The bottom panel in figure 11 shows median non-CO2 effective radiative forcing (ERF) estimates used to drive the model over the historical period, extending forcing components using the RCP8.5 scenario (http://www.pik-potsdam.de/~mmalte/rcps/) between 2011 and 2020, with scaling applied to each full forcing component time-series to match the corresponding AR5 ERF component in 2011. The vertical bar in 2011 shows a simple indication of the *likely* range of non-CO_2 forcing in 2011 obtained simply by subtracting the best-estimate CO_2 forcing from the total anthropogenic forcing uncertainty, assuming the latter is normally distributed: AR5 did not give a full assessment of the distribution of non-CO_2 radiative forcing. It demonstrates there is considerable uncertainty in this quantity, which translates into uncertainty in climate system properties inferred from these data, but has a much smaller impact on estimates of human-induced warming to date, because this is also constrained by temperature observations. The green line shows non-CO_2 forcing in an indicative 1.5°C-consistent pathway consistent with those assessed by Chapter 2, while the blue line shows an idealised case in which non-CO_2 forcing remains constant after 2030.

For all percentiles of the climate response distribution, non-CO_2 forcing timeseries for these idealised scenarios are scaled to allow the corresponding percentiles of the assessed *likely* range of human-induced warming in 2017 to be achieved, assuming the latter is normally distributed. All non-CO_2 forcing components other than aerosols are scaled following their corresponding ranges of uncertainty of values in 2011 given in AR5, with low values of 2011 ERF corresponding to high values of TCR and *vice versa*. This accounts for the anti-correlation between estimated values of the TCR and estimates of current anthropogenic forcing. Then aerosol ERF (the most uncertain component) is scaled to reproduce the correct percentile of human-induced warming in 2011. Values of TCR, ECS and 2011 forcing components are given in Technical Annex 1.A Table 1.

Figure 12 shows timeseries of observed and human-induced warming to 2017 and responses to these idealised future emissions scenarios. Observed and human-induced warming estimates are reproduced exactly as in Figure 1.2, with the orange shaded band showing the assessed uncertainty range of ±20%. The dashed line shows a simple linear extrapolation of the current rate of warming, as calculated over the past 5 years. Responses to idealized future CO_2 emissions and non-CO_2 forcing trajectories are simulated with the FAIR simple climate-carbon-cycle model (Millar et al, 2017b). The four values of the Transient Climate Response (TCR) shown (giving the borders of the green, blue and orange shaded regions) correspond to the 17th, 33rd, 67th and 83rd percentiles of a normal distribution compatible with the *likely* range of TCR as assessed by AR5, combined with the same percentiles of a log-normal distribution for the Equilibrium Climate Sensitivity (ECS) similarly anchored to the AR5 *likely* range for this quantity. Other thermal climate response parameters (short and long adjustment time-scales) are set to match those given in Myhre et al (2013) as used in Millar et al (2017a).



Technical Annex 1.A, Figure 12: Time-series of observed and human-induced warming to 2017 and responses to idealised 1.5°C-consistent pathways of CO_2 and non-CO_2 forcing shown in figure 11.

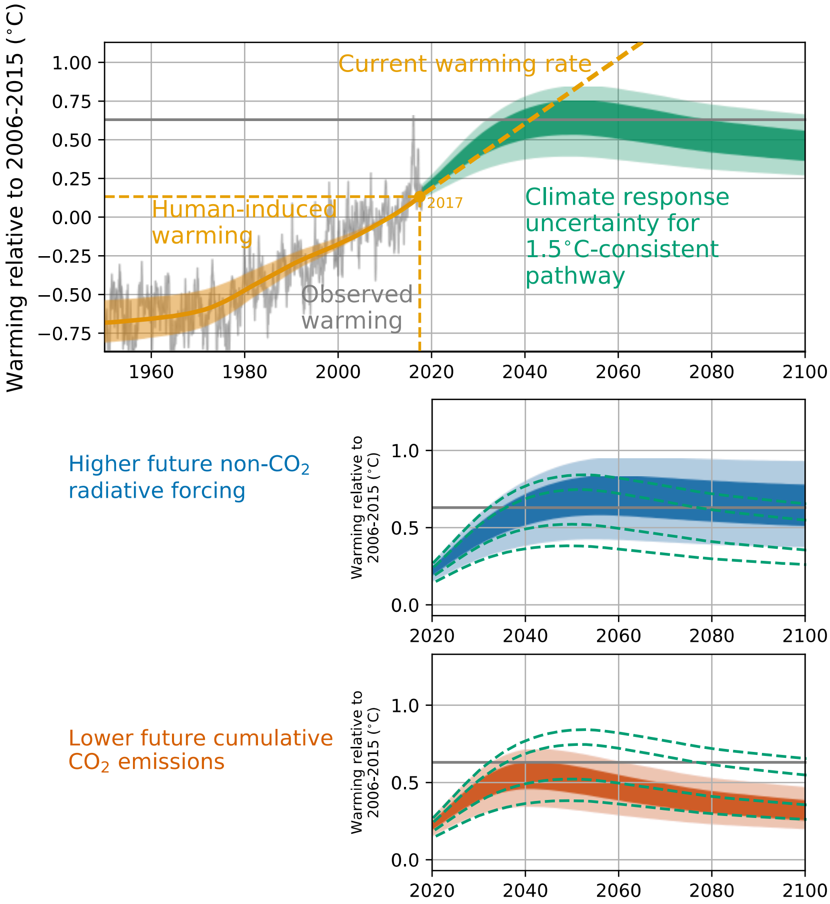
All 1.5°C-consistent scenarios that are also consistent with current emissions and radiative forcing trends show increasing non-CO_2 radiative forcing over the coming decade, as emissions of cooling aerosol precursors are reduced, but there is greater variation between scenarios in non-CO_2 radiative forcing after 2030. The middle panel in figure 12 shows the impact of varying future non-CO_2 radiative forcing (green and blue lines in figure 11, bottom panel), while the green dashed lines show the original percentiles from the top panel. Failure to reduce non-CO_2 forcing after 2030 means that a scenario that would give temperatures *likely* below 1.5°C in 2100 instead give only temperatures *as likely as not* below 1.5°C by 2100. If non-CO_2 forcing were allowed to increase further (as it does in some scenarios due primarily to methane emissions), it would increase 2100 temperatures further.

The bottom panel of figure 12 shows the impact of reducing cumulative CO_2 emissions up to the time they reach net zero by bringing forward the date of net-zero emissions from 2055 to 2040. This reduces future warming, with the impact emerging after 2030, such that the entire *likely* range of future warming is now (on this estimate of the climate response distribution) below 1.5°C in 2100. These changes demonstrate how future warming is determined by cumulative CO_2 emissions up to the time of net-zero and non-CO_2 forcing in the decades immediately prior to that time.

Technical Annex 1.A, Table 1: Climate system properties in the versions of the FAIR model used in figures 12 and 13 of this Technical Annex as well as the FAQ 1.2 figure and figure SPM1. TCR, ECS and total anthropogenic forcing, F_{ant}, in 2011 are set consistent with corresponding distributions in AR5, TCRE is diagnosed from the model while aerosol forcing F_{aer} is adjusted to reproduce the corresponding percentile of human-induced warming in 2017.

Percentile	TCR (°C)	ECS (°C)	TCRE (°C/TtC)	F_{aer} in 2011 (W/m^2)	F_{ant} in 2011 (W/m^2)
17%	1.0	1.5	0.9	-0.67	3.02
33%	1.4	2.0	1.3	-0.95	2.46
50%	1.75	2.6	1.5	-0.99	2.20
67%	2.1	3.3	1.75	-0.95	2.01
83%	2.5	4.5	2.2	-0.84	1.84

Carbon budget calculations in Chapter 2 are based on temperatures relative to 2006-2015, offset by a constant 0.87°C representing the best-estimate observed warming from pre-industrial to that decade. This has little effect on median estimates of future warming, because the median estimated human-induced warming to the decade 2006-2015 was close to the observed warming, but it does affect uncertainties: the uncertainty in 2030 warming relative to 2006-2015 is lower than the uncertainty in 2030 warming relative to pre-industrial because of the additional information provided by the current climate state and trajectory. This additional information is particularly important for the response to rapid mitigation scenarios in which peak warming occurs a small number of decades into the future (Millar et al, 2017a; Leach et al, 2018), highlighting the particular importance of a "seamless" approach to seasonal-to-decadal forecasting (Palmer et al, 2008; Boer et al, 2016) in the context of 1.5°C. The impact of this additional information is illustrated in figure 13, which is constructed identically to figure 12 but shows all time-series expressed as anomalies relative to 2006-2015 rather than 1850-1900. The thick grey line at 0.63°C shows 1.5°C relative to pre-industrial expressed relative to this more recent decade. The central estimate is unaffected, as is the estimate of the time at which temperatures reach 1.5°C if the current rate of warming continues, but uncertainties are reduced. For example, the idealised pathway with CO_2 emissions reaching zero in 2040 is *likely* to limit warming to less than 0.63°C above 2006-2015, even though it just overshoots 1.5°C relative to 1850-1900.



Technical Annex 1.A, Figure 13: As figure 12, but showing time-series of observed and human-induced warming to 2017 and responses to idealised 1.5°C-consistent pathways relative to 2006-2015. Level of warming corresponding to 1.5°C relative to pre-industrial given central estimate of observed warming of 0.87°C from 1850-1900 to 2006-2015 is shown by horizontal line at 0.63°C.

Annex 1.A.7: Recent trends in emissions and radiative forcing

Figure 1.2 shows a small increase in the estimated rate of human–induced warming since 2000, reaching 0.2°C per decade in the past few years. This is attributed (Haustein et al., 2017) to recent changes in a range of climate forcers, reviewed in this section.

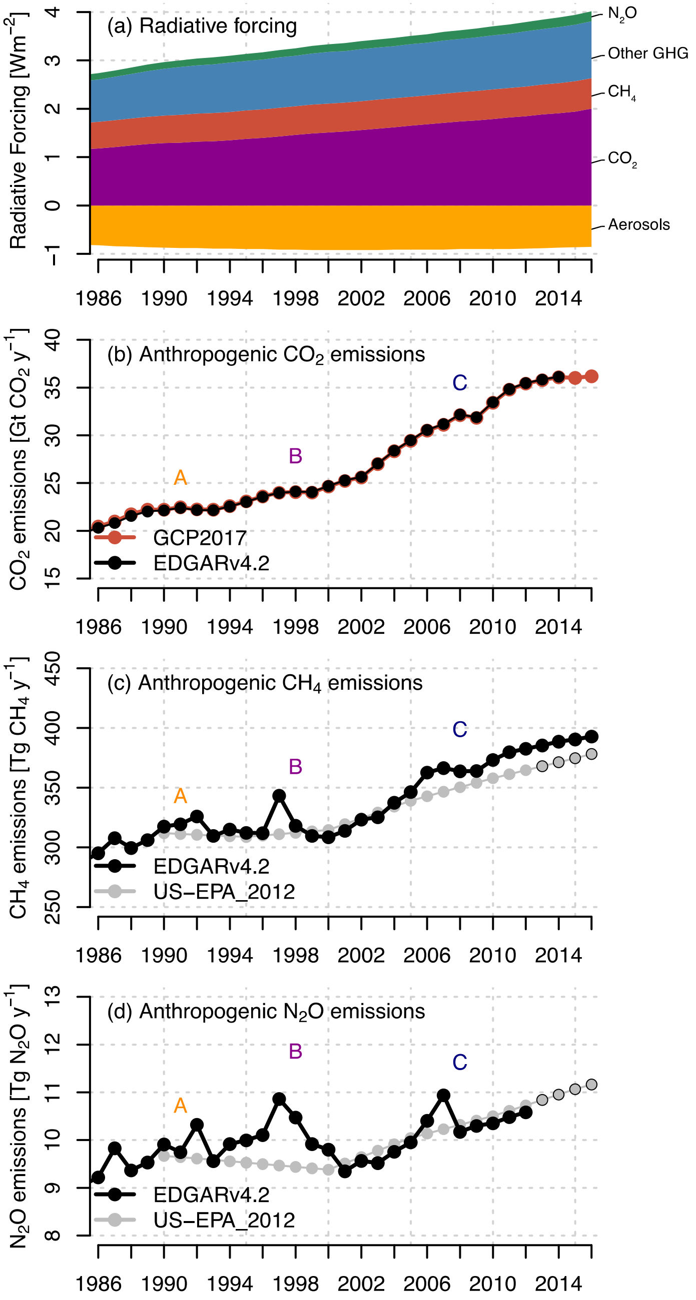
Most studies partition anthropogenic climate forcers into two groups by their lifetime. CO_2 and other long–lived greenhouse gases such as nitrous oxide, sulphur hexafluoride and some halogenated gases contribute to forcing over decades and centuries. Other halogenated gases, ozone precursors and aerosols are defined as short–lived climate forcers (SLCF) due to their residence time of less than several years in the atmosphere. Although methane is either considered as a LLCF or SLCF in published studies or reports (Bowerman et al., 2013; Estrada et al., 2013; Heede, 2014; Jacobson, 2010; Kerr, 2013; Lamarque et al., 2011; Saunois et al., 2016a; WMO, 2015), we assign methane as a SLCF for the purpose of climate assessment, because its lifetime is comparable to or shorter than the thermal adjustment time of the climate system (Smith et al., 2012).

CO_2, methane and nitrous oxide are the most prominent contributors of anthropogenic radiative forcing, contributing 63%, 20% and 6% of the anthropogenic radiative forcing in 2016 respectively, as shown in Figure 14(a). Other long-lived greenhouse gases, including halogenated gases, and SLCFs such as tropospheric ozone are responsible of about 37% of the anthropogenic radiative forcing (figures add up to more than 100% because of the compensating effect of aerosols). Emissions such as black carbon and sulphur dioxide form different types of aerosol particles, which interact with both shortwave and longwave radiation and alter clouds. The resulting net aerosol radiative forcing is spatially inhomogeneous and uncertain. Globally averaged, it is estimated to have reduced the globally averaged anthropogenic forcing by about 27% (figures from Myhre et al. (2013), updated: uncertainties in aerosol forcing in particular are reviewed in AR5, and will be reassessed in AR6. This report continues to work from the AR5 estimates.).

As shown in Figure 14 (b), the growth of CO_2 emissions has slowed since 2013 because of changes in the energy mix moving from coal to natural gas and increased renewable energy generation (Boden et al., 2015). This slowdown in CO_2 emission growth has occurred despite global GDP growth increasing to 3% y^{-1} in 2015, implying a structural shift away from carbon intensive activities (Jackson et al., 2015; Le Quéré et al., 2018). In 2016, however, anthropogenic CO_2 emissions are 36.18 $GtCO_2\,y^{-1}$ and have begun to grow again by 0.4% with respect to 2015 (Le Quéré et al., 2018). Global average concentration in 2016 has reached 402.3 ppm, which represents an increase of about 38.4% from 1850–1900 average (290.7 ppm).

Figure 14 (c) and (d) show that methane and nitrous oxide emissions, unlike $CO_{2,}$ have followed the most emission–intensive pathways assessed in AR5 (Saunois et al., 2016b; Thompson et al., 2014). However, current trends in methane and nitrous oxide emissions are not driven in the same way by human activities. About 60% of methane emissions are attributed to human activities (e.g. ruminants, rice agriculture, fossil fuel exploitation, landfills and biomass burning, Saikawa et al., 2014; Saunois et al., 2016b), while about 40% of nitrous oxide emissions are caused by various industrial processes and agriculture (Bodirsky et al., 2012; Thompson et al., 2014). It is thus more complicated to link rates of emissions to economic trends or energy demands than is the case with CO_2 (Peters et al., 2011).

Estimates of anthropogenic emissions for methane and nitrous oxide are uncertain as shown by the difference between datasets in Figure 1.4 EDGARV4.2 (JRC, 2011) estimates and US–EPA projections give a global amount of methane emission ranging between 392.87 and 378.29 $TgCH_4y^{-1}$ by 2016 which corresponds to a relative increase of 0.6–1% compared to 2015 emissions. However, livestock emissions in these databases are considered to be underestimated (Wolf et al., 2017). Similar uncertainties exist for anthropogenic N_2O emissions for which only US–EPA projections are available. According to US–EPA projections, anthropogenic N_2O emissions reach 11.2 $TgN_2O\ y^{-1}$, representing a relative increase of about 1% compared to 2016. Anthropogenic CH_4 and N_2O emissions also appear to respond to major economic crises.



Technical Annex 1.A, Figure 14: Time series of anthropogenic radiative forcing (a), CO_2, methane (CH_4) and nitrous oxide (N_2O) emissions (b–d) for the period 1986–2016. Anthropogenic radiative forcing data is from Myhre et al., (2013), extended from 2011 until the end of 2017 with greenhouse gas data from Dlugokencky and Tans (2016), updated radiative forcing approximations for greenhouse gases (Etminan et al., 2016) and extended aerosol forcing following (Myhre et al., 2017). Bar graph shows the sum of different forcing agents. Anthropogenic CO_2 emissions are from the Global Carbon Project (GCP2017; Le Quéré et al., 2018), and EDGAR (Joint Research Centre, 2011) datasets. Anthropogenic emissions of CH_4 and N_2O (e) are estimated from EDGAR (JRC, 2011) and the US Environmental Protection Agency (EPA, 1990). Economic crisis (Former Soviet Union, A; Asian financial crisis, B; global financial crisis, C) are reported following the methodology of (Peters et al., 2011).

References

Bindoff, N. L., Stott, P. A., AchutaRao, K. M., Allen, M. R., Gillett, N., Gutzler, D., et al. (2013). “Detection and Attribution of Climate Change: from Global to Regional,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 426–488.

Cowtan, K., Hausfather, Z., Hawkins, E., Jacobs, P., Mann, M. E., Miller, S. K., et al. (2015). Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures. *Geophys. Res. Lett.* 42, 6526–6534. doi:10.1002/2015GL064888.

Cowtan, K., and Way, R. G. (2014). Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Q. J. R. Meteorol. Soc.* 140, 1935–1944. doi:10.1002/qj.2297.

Doxsey-Whitfield, E., MacManus, K., Adamo, S. B., Pistolesi, L., Squires, J., Borkovska, O., et al. (2015). Taking Advantage of the Improved Availability of Census Data: A First Look at the Gridded Population of the World, Version 4. *Pap. Appl. Geogr.* 1, 226–234. doi:10.1080/23754931.2015.1014272.

Etminan, M., Myhre, G., Highwood, E. J., and Shine, K. P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophys. Res. Lett.* 43, 12,614-12,623. doi:10.1002/2016GL071930.

Foster, G., and Rahmstorf, S. (2011). Global temperature evolution 1979–2010. *Environ. Res. Lett.* 6, 044022. doi:10.1088/1748-9326/6/4/044022.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., et al. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Glob. Environ. Chang.* 42, 251–267. doi:10.1016/j.gloenvcha.2016.06.004.

Geoffroy, O., Saint-Martin, D., Olivié, D. J. L., Voldoire, A., Bellon, G., and Tytéca, S. (2013). Transient climate response in a two-layer energy-balance model. Part I: Analytical solution and parameter calibration using CMIP5 AOGCM experiments. *J. Clim.* 26, 1841–1857. doi:10.1175/JCLI-D-12-00195.1.

Ghan, S. J., Smith, S. J., Wang, M., Zhang, K., Pringle, K., Carslaw, K., et al. (2013). A simple model of global aerosol indirect effects. *J. Geophys. Res. Atmos.* 118, 6688–6707. doi:10.1002/jgrd.50567.

Gregory, J. M., Andrews, T., Good, P., Mauritsen, T., and Forster, P. M. (2016). Small global-mean cooling due to volcanic radiative forcing. *Clim. Dyn.* 47, 3979–3991. doi:10.1007/s00382-016-3055-1.

Hartmann, D. J., Klein Tank, A. M. G., Rusticucci, M., Alexander, L. V, Brönnimann, S., Charabi, Y. A.-R., et al. (2013). “Observations: Atmosphere and Surface,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 159–254. doi:10.1017/CBO9781107415324.008.

Haustein, K., Allen, M. R., Forster, P. M., Otto, F. E. L., Mitchell, D. M., Matthews, H. D., et al. (2017). A real-time Global Warming Index. *Sci. Rep.* 7, 15417. doi:10.1038/s41598-017-14828-5.

Kirtman, B., Adedoyin, A., and Bindoff, N. (2013). “Near-term Climate Change: Projections and Predictability,” in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 953–1028. doi:10.1017/CBO9781107415324.023.

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., et al. (2016). Temperature-driven global sea-level variability in the Common Era. *Proc. Natl. Acad. Sci.* 113, 1–8. doi:10.1073/pnas.1517056113.

Marcott, S. A., Shakun, J. D., Clark, P. U., and Mix, A. C. (2013). A reconstruction of regional and global temperature for the past 11,300 years. *Science (80-.).* 339, 1198–201. doi:10.1126/science.1228026.

Matthes, K., Funke, B., Andersson, M. E., Barnard, L., Beer, J., Charbonneau, P., et al. (2017). Solar forcing for CMIP6 (v3.2). *Geosci. Model Dev.* 10, 2247–2302. doi:10.5194/gmd-10-2247-2017.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J., et al. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Clim. Change* 109, 213–241. doi:10.1007/s10584-011-0156-z.

Millar, R. J., Nicholls, Z. R., Friedlingstein, P., and Allen, M. R. (2017). A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmos. Chem. Phys.* 17, 7213–7228. doi:10.5194/acp-17-7213-2017.

Myhre, G., Highwood, E. J., Shine, K. P., and Stordal, F. (1998). New estimates of radiative forcing due to well mixed greenhouse gases. *Geophys. Res. Lett.* 25, 2715–2718. doi:10.1029/98GL01908.

Myhre, G., Samset, B. H., Schulz, M., Balkanski, Y., Bauer, S., Berntsen, T. K., et al. (2013a). Radiative forcing of the direct aerosol effect from AeroCom Phase II simulations. *Atmos. Chem. Phys.* 13, 1853–1877. doi:10.5194/acp-13-1853-2013.

Myhre, G., Shindell, D., Bréon, F., Collins, W., Fuglestvedt, J., Huang, J., et al. (2013b). "Anthropogenic and natural radiative forcing," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press), 658–740. doi:0.1017/CBO9781107415324.018.

Prather, M., Flato, G., Friedlingstein, P., Jones, C., Lamarque, J.-F., Liao, H., et al. (2013). "Annex II: Climate System Scenario Tables," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge, MA, USA and London, England: Cambridge Univeristy Press).

Richardson, M., Cowtan, K., and Millar, R. J. (2018). Global temperature definition affects achievement of long-term climate goals. *Environ. Res. Lett.* 13, 054004.

Sachs, J., Schmidt-Traub, G., Kroll, C., Durand-Delacre, D., and Teksoz, K. (2017). An SDG Index and Dashboards - Global Report. New York, NY, USA.

Smith, C. J., Forster, P. M., Allen, M., Leach, N., Millar, R. J., Passerello, G. A., et al. (2018). FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.* doi:10.5194/gmd-2017-266.

Stevenson, D. S., Young, P. J., Naik, V., Lamarque, J. F., Shindell, D. T., Voulgarakis, A., et al. (2013). Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). *Atmos. Chem. Phys.* 13, 3063–3085. doi:10.5194/acp-13-3063-2013.

Toohey, M., Stevens, B., Schmidt, H., and Timmreck, C. (2016). Easy Volcanic Aerosol (EVA v1.0): an idealized forcing generator for climate simulations. *Geosci. Model Dev.* 9, 4049–4070. doi:10.5194/gmd-9-4049-2016.

Chapter 2: Mitigation pathways compatible with 1.5°C in the context of sustainable development

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Executive Summary

This chapter assesses mitigation pathways consistent with limiting warming to 1.5°C above preindustrial levels. In doing so, it explores the following key questions: What role do CO_2 and non-CO_2 emissions play? {2.2, 2.3, 2.4, 2.6} To what extent do 1.5°C pathways involve overshooting and returning below 1.5°C during the 21st century? {2.2, 2.3} What are the implications for transitions in energy, land use and sustainable development? {2.3, 2.4, 2.5} How do policy frameworks affect the ability to limit warming to 1.5°C? {2.3, 2.5} What are the associated knowledge gaps? {2.6}

The assessed pathways describe integrated, quantitative evolutions of all emissions over the 21st century associated with global energy and land use, and the world economy. The assessment is contingent upon available integrated assessment literature and model assumptions, and is complemented by other studies with different scope, for example those focusing on individual sectors. In recent years, integrated mitigation studies have improved the characterizations of mitigation pathways. However, limitations remain, as climate damages, avoided impacts, or societal co-benefits of the modelled transformations remain largely unaccounted for, while concurrent rapid technological changes, behavioural aspects, and uncertainties about input data present continuous challenges. *(high confidence)* {2.1.3, 2.3, 2.5.1, 2.6, Technical Annex 2}

The chances of limiting warming to 1.5°C and the requirements for urgent action

1.5°C-consistent pathways can be identified under a range of assumptions about economic growth, technology developments and lifestyles. However, lack of global cooperation, lack of governance of the energy and land transformation, and growing resource-intensive consumption are key impediments for achieving 1.5°C-consistent pathways. Governance challenges have been related to scenarios with high inequality and high population growth in the 1.5°C pathway literature. {2.3.1, 2.3.2, 2.5}

Under emissions in line with current pledges under the Paris Agreement (known as Nationally-Determined Contributions or NDCs), global warming is expected to surpass 1.5°C, even if they are supplemented with very challenging increases in the scale and ambition of mitigation after 2030 (*high confidence*). This increased action would need to achieve net zero CO_2 emissions in less than 15 years. Even if this is achieved, temperatures remaining below 1.5°C would depend on the geophysical response being towards the low end of the currently-estimated uncertainty range. Transition challenges as well as identified trade-offs can be reduced if global emissions peak before 2030 and already achieve marked emissions reductions by 2030 compared to today.[1] {2.2, 2.3.5, Cross-Chapter Box 9 in Chapter 4}

Limiting warming to 1.5°C depends on greenhouse gas (GHG) emissions over the next decades, where lower GHG emissions in 2030 lead to a higher chance of peak warming being kept to 1.5°C (*high confidence*). Available pathways that aim for no or limited (0–0.2°C) overshoot of 1.5°C keep GHG emissions in 2030 to 25–30 $GtCO_2e\ yr^{-1}$ in 2030 (interquartile range). This contrasts with median estimates for current NDCs of 50–58 $GtCO_2e\ yr^{-1}$ in 2030. Pathways that aim for limiting warming to 1.5°C by 2100 after a temporary temperature overshoot rely on large-scale deployment of Carbon Dioxide Removal (CDR) measures, which are uncertain and entail clear risks. {2.2, 2.3.3, 2.3.5, 2.5.3, Cross-Chapter Boxes 6 in Chapter 3 and 9 in Chapter 4, 4.3.7}

Limiting warming to 1.5°C implies reaching net zero CO_2 emissions globally around 2050 and concurrent deep reductions in emissions of non-CO_2 forcers, particularly methane (*high confidence*). Such mitigation pathways are characterized by energy-demand reductions, decarbonisation of electricity and other fuels, electrification of energy end use, deep reductions in agricultural emissions, and some form of CDR with carbon storage on land or sequestration in geological reservoirs. Low energy demand and low demand for land- and GHG-intensive consumption goods facilitate limiting warming to as close as possible to 1.5°C. {2.2.2, 2.3.1, 2.3.5, 2.5.1, Cross-Chapter Box 9 in Chapter 4}.

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[1] FOOTNOTE: Kyoto-GHG emissions in this statement are aggregated with GWP-100 values of the IPCC Second Assessment Report.

In comparison to a 2°C limit, required transformations to limit warming to 1.5°C are qualitatively similar but more pronounced and rapid over the next decades (*high confidence*). 1.5°C implies very ambitious, internationally cooperative policy environments that transform both supply and demand *(high confidence)*. {2.3, 2.4, 2.5}

Policies reflecting a high price on emissions are necessary in models to achieve cost-effective 1.5°C-consistent pathways *(high confidence)*. Other things being equal, modelling suggests the price of emissions for limiting warming to 1.5°C being about three four times higher compared to 2°C, with large variations across models and socioeconomic assumptions. A price on carbon can be imposed directly by carbon pricing or implicitly by regulatory policies. Other policy instruments, like technology policies or performance standards, can complement carbon pricing in specific areas. {2.5.1, 2.5.2, 4.4.5}

Limiting warming to 1.5°C requires a marked shift in investment patterns *(limited evidence, high agreement)*. Investments in low-carbon energy technologies and energy efficiency would need to approximately double in the next 20 years, while investment in fossil-fuel extraction and conversion decrease by about a quarter. Uncertainties and strategic mitigation portfolio choices affect the magnitude and focus of required investments. {2.5.2}

Future emissions in 1.5°C-consistent pathways

Mitigation requirements can be quantified using carbon budget approaches that relate cumulative CO_2 emissions to global-mean temperature increase. Robust physical understanding underpins this relationship, but uncertainties become increasingly relevant as a specific temperature limit is approached. These uncertainties relate to the transient climate response to cumulative carbon emissions (TCRE), non-CO_2 emissions, radiative forcing and response, potential additional Earth-system feedbacks (such as permafrost thawing), and historical emissions and temperature. {2.2.2, 2.6.1}

Cumulative CO_2 emissions are kept within a budget by reducing global annual CO_2 emissions to net-zero. This assessment suggests a remaining budget for limiting warming to 1.5°C with a two-thirds chance of about 550 $GtCO_2$, and of about 750 $GtCO_2$ for an even chance (*medium confidence*). The remaining carbon budget is defined here as cumulative CO_2 emissions from the start of 2018 until the time of net-zero global emissions. Remaining budgets applicable to 2100, would approximately be 100 $GtCO_2$ lower than this to account for permafrost thawing and potential methane release from wetlands in the future. These estimates come with an additional geophysical uncertainty of at least ±50%, related to non-CO_2 response and TCRE distribution. In addition, they can vary by ±250 $GtCO_2$ depending on non-CO_2 mitigation strategies as found in available pathways. {2.2.2, 2.6.1}

Staying within a remaining carbon budget of 750 $GtCO_2$ implies that CO_2 emissions reach carbon neutrality in about 35 years, reduced to 25 years for a 550 $GtCO_2$ remaining carbon budget (*high confidence*). The ±50% geophysical uncertainty range surrounding a carbon budget translates into a variation of this timing of carbon neutrality of roughly ±15–20 years. If emissions do not start declining in the next decade, the point of carbon neutrality would need to be reached at least two decades earlier to remain within the same carbon budget. {2.2.2, 2.3.5}

Non-CO_2 emissions contribute to peak warming and thus affect the remaining carbon budget. The evolution of methane and sulphur dioxide emissions strongly influences the chances of limiting warming to 1.5°C. In the near-term, a weakening of aerosol cooling would add to future warming, but can be tempered by reductions in methane emissions *(high confidence)*. Uncertainty in radiative forcing estimates (particularly aerosol) affects carbon budgets and the certainty of pathway categorizations. Some non-CO_2 forcers are emitted alongside CO_2, particularly in the energy and transport sectors, and can be largely addressed through CO_2 mitigation. Others require specific measures, for example to target agricultural N_2O and CH_4, some sources of black carbon, or hydrofluorocarbons *(high confidence)*. In many cases, non-CO_2 emissions reductions are similar in 2°C pathways, indicating reductions near their assumed maximum potential by integrated assessment models. Emissions of N_2O and NH_3 increase in some pathways with strongly increased bioenergy demand. {2.2.2, 2.3.1, 2.4.2, 2.5.3}

The role of Carbon-Dioxide Removal (CDR)

All analysed 1.5°C-consistent pathways use CDR to some extent to neutralize emissions from sources for which no mitigation measures have been identified and, in most cases, also to achieve net-negative emissions that allow temperature to return to 1.5°C following an overshoot (*high confidence*). The longer the delay in reducing CO_2 emissions towards zero, the larger the likelihood of exceeding 1.5°C, and the heavier the implied reliance on net-negative emissions after mid-century to return warming to 1.5°C (*high confidence*). The faster reduction of net CO_2 emissions in 1.5°C- compared to 2°C-consistent pathways is predominantly achieved by measures that result in less CO_2 being produced and emitted, and only to a smaller degree through additional CDR. Limitations on the speed, scale, and societal acceptability of CDR deployment also limit the conceivable extent of temperature overshoot. Limits to our understanding of how the carbon cycle responds to net negative emissions increase the uncertainty about the effectiveness of CDR to decline temperatures after a peak. {2.2, 2.3, 2.6, 4.3.7}

CDR deployed at scale is unproven and reliance on such technology is a major risk in the ability to limit warming to 1.5°C. CDR is needed less in pathways with particularly strong emphasis on energy efficiency and low demand. The scale and type of CDR deployment varies widely across 1.5°C-consistent pathways, with different consequences for achieving sustainable development objectives (*high confidence*). Some pathways rely more on bioenergy with carbon capture and storage (BECCS), while others rely more on afforestation, which are the two CDR methods most often included in integrated pathways. Trade-offs with other sustainability objectives occur predominantly through increased land, energy, water and investment demand. Bioenergy use is substantial in 1.5°C-consistent pathways with or without BECCS due to its multiple roles in decarbonizing energy use. {2.3.1, 2.5.3, 2.6, 4.3.7}

Properties of energy transitions in 1.5°C-consistent pathways

The share of primary energy from renewables increases while coal usage decreases across 1.5°C-consistent pathways *(high confidence)*. By 2050, renewables (including bioenergy, hydro, wind and solar, with direct-equivalence method) supply a share of 49–67% (interquartile range) of primary energy in 1.5°C-consistent pathways; while the share from coal decreases to 1–7% (interquartile range), with a large fraction of this coal use combined with Carbon Capture and Storage (CCS). From 2020 to 2050 the primary energy supplied by oil declines in most pathways (–32 to –74% interquartile range). Natural gas changes by –13% to –60% (interquartile range), but some pathways show a marked increase albeit with widespread deployment of CCS. The overall deployment of CCS varies widely across 1.5°C-consistent pathways with cumulative CO_2 stored through 2050 ranging from zero up to 460 $GtCO_2$ (minimum-maximum range), of which zero up to 190 $GtCO_2$ stored from biomass. Primary energy supplied by bioenergy ranges from 40–310 EJ yr^{-1} in 2050 (minimum-maximum range), and nuclear from 3–120 EJ/yr (minimum-maximum range). These ranges reflect both uncertainties in technological development and strategic mitigation portfolio choices. {2.4.2}

1.5°C-consistent pathways include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end use *(high confidence)*. By 2050, the carbon intensity of electricity decreases to -92 to +11 gCO_2/MJ (minimum-maximum range) from about 140 gCO_2/MJ in 2020, and electricity covers 34–71% (minimum-maximum range) of final energy across 1.5°C-consistent pathways from about 20% in 2020. By 2050, the share of electricity supplied by renewables increases to 36–97% (minimum-maximum range) across 1.5°C-consistent pathways. Pathways with higher chances of holding warming to below 1.5°C generally show a faster decline in the carbon intensity of electricity by 2030 than pathways that temporarily overshoot 1.5°C. {2.4.1, 2.4.2, 2.4.3}

Demand-side mitigation and behavioural changes

Demand-side measures are key elements of 1.5°C-consistent pathways. Lifestyle choices lowering energy demand and the land- and GHG-intensity of food consumption can further support achievement of 1.5°C-consistent pathways (*high confidence*). By 2030 and 2050, all end-use sectors (including building, transport, and industry) show marked energy demand reductions in modelled 1.5°C-consistent pathways, comparable and beyond those projected in 2°C-consistent pathways. Sectorial models support the scale of these reductions. {2.3.4, 2.4.3}

Links between 1.5°C-consistent pathways and sustainable development

Choices about mitigation portfolios for limiting warming to 1.5°C can positively or negatively impact the achievement of other societal objectives, such as sustainable development (*high confidence*). In particular, demand-side and efficiency measures, and lifestyle choices that limit energy, resource, and GHG-intensive food demand support sustainable development *(medium confidence)*. Limiting warming to 1.5°C can be achieved synergistically with poverty alleviation and improved energy security and can provide large public health benefits through improved air quality, preventing millions of premature deaths. However, specific mitigation measures, such as bioenergy, may result in trade-offs that require consideration. {2.5.1, 2.5.2, 2.5.3}

2.1 Introduction to Mitigation Pathways and the Sustainable Development Context

This chapter assesses the literature on mitigation pathways to limit or return global mean warming to 1.5°C (relative to the preindustrial base period 1850–1900). Key questions addressed are: What types of mitigation pathways have been developed that could be consistent with 1.5°C? What changes in emissions, energy and land use do they entail? What do they imply for climate policy and implementation, and what impacts do they have on sustainable development? In terms of feasibility (see Cross-Chapter Box 3 in Chapter 1), this chapter focuses on geophysical dimensions and technological and economic enabling factors, with social and institutional dimensions as well as additional aspects of technical feasibility covered in Chapter 4.

Mitigation pathways are typically designed to reach a pre-defined climate target alone. Minimization of mitigation expenditures, but not climate-related damages or sustainable development impacts, is often the basis for these pathways to the desired climate target (see Cross-Chapter Box 5 in Chapter 2 for additional discussion). However, there are interactions between mitigation and multiple other sustainable development goals (see Sections 1.1 and 5.4) that provide both challenges and opportunities for climate action. Hence there are substantial efforts to evaluate the effects of the various mitigation pathways on sustainable development, focusing in particular on aspects for which Integrated Assessment Models (IAMs) provide relevant information (e.g., land-use changes and biodiversity, food security, and air quality). More broadly, there are efforts to incorporate climate change mitigation as one of multiple objectives that in general reflect societal concerns more completely and could potentially provide benefits at lower costs than simultaneous single objective policies (e.g., Clarke et al., 2014). For example, with carefully selected policies, universal energy access can be achieved while simultaneously reducing air pollution and mitigating climate change (McCollum et al., 2011; Riahi et al., 2012; IEA, 2017d). This chapter thus presents both the pathways and an initial discussion of their context within sustainable development objectives (Section 2.5), with the latter along with equity and ethical issues discussed in more detail in Chapter 5.

As described in Cross-Chapter Box 1 in Chapter 1, scenarios are comprehensive, plausible, integrated descriptions of possible futures based on specified, internally consistent underlying assumptions, with pathways often used to describe the clear temporal evolution of specific scenario aspects or goal-oriented scenarios. We include both these usages of ‘pathways’ here.

2.1.1 Mitigation pathways consistent with 1.5°C

Emissions scenarios need to cover all sectors and regions over the 21st century to be associated with a climate change projection out to 2100. Assumptions regarding future trends in population, consumption of goods and services (including food), economic growth, behaviour, technology, policies and institutions are all required to generate scenarios (Section 2.3.1). These societal choices must then be linked to the drivers of climate change, including emissions of well-mixed greenhouse gases and aerosol and ozone precursors, and land-use and land-cover changes. Deliberate solar radiation modification is not included in these scenarios (see Cross-Chapter Box 10 in Chapter 4).

Plausible developments need to be anticipated in many facets of the key sectors of energy and land use. Within energy, these consider energy resources like biofuels, energy supply and conversion technologies, energy consumption, and supply and end-use efficiency. Within land use, agricultural productivity, food demand, terrestrial carbon management, and biofuel production are all considered. Climate policies are also considered, including carbon pricing and technology policies such as research and development funding and subsidies. The scenarios incorporate regional differentiation in sectoral and policy development. The climate changes resulting from such scenarios are derived using models that typically incorporate physical understanding of the carbon-cycle and climate response derived from complex geophysical models evaluated against observations (Sections 2.2 and 2.6).

The temperature response to a given emission pathway is uncertain and therefore quantified in terms of a probabilistic outcome. Chapter 1 assesses the climate objectives of the Paris agreement in terms of human-induced warming, thus excluding potential impacts of natural forcing such as volcanic eruptions or solar output changes or unforced internal variability. Temperature responses in this chapter are assessed using simple geophysically-based models that evaluate the anthropogenic component of future temperature change and do not incorporate internal natural variations and are thus fit for purpose in the context of this assessment (Section 2.2.1). Hence a scenario that is consistent with 1.5°C may in fact lead to either a higher or lower temperature change, but within quantified and generally well-understood bounds (see also Section 1.2.3). Consistency with avoiding a human-induced temperature change limit must therefore also be defined probabilistically, with likelihood values selected based on risk avoidance preferences. Responses beyond global mean temperature are not typically evaluated in such models and are assessed in Chapter 3.

2.1.2 The Use of Scenarios

Variations in scenario assumptions and design define to a large degree which questions can be addressed with a specific scenario set, for example, the exploration of implications of delayed climate mitigation action. In this assessment, the following classes of 1.5°C – and 2°C – consistent scenarios are of particular interest to the topics addressed in this chapter: (a) scenarios with the same climate target over the 21st century but varying socio-economic assumptions (Sections 2.3 and 2.4); (b) pairs of scenarios with similar socio-economic assumptions but with forcing targets aimed at 1.5°C and 2°C (Section 2.3); (c) scenarios that follow the Nationally Determined Contributions or NDCs[2] until 2030 with much more stringent mitigation action thereafter (Section 2.3.5).

Characteristics of these pathways such as emissions reduction rates, time of peaking, and low-carbon energy deployment rates can be assessed as being consistent with 1.5°C. However, they cannot be assessed as ‘requirements’ for 1.5°C, unless a targeted analysis is available that specifically asked whether there could be pathways without the characteristics in question. AR5 already assessed such targeted analyses, for example asking which technologies are important to keep open the possibility to limit warming to 2°C (Clarke et al., 2014). By now, several such targeted analyses are also available for questions related to 1.5°C (Luderer et al., 2013; Rogelj et al., 2013b; Bauer et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). This assessment distinguishes between consistent and the much stronger concept of required characteristics of 1.5°C pathways wherever possible.

Ultimately, society will adjust as new information becomes available and technical learning progresses, and these adjustments can be in either direction. Earlier scenario studies have shown, however, that deeper emissions reductions in the near term hedge against the uncertainty of both climate response and future technology availability (Luderer et al., 2013; Rogelj et al., 2013b; Clarke et al., 2014). Not knowing what adaptations might be put in place in the future, and due to limited studies, this chapter examines prospective rather than iteratively adaptive mitigation pathways (Cross-Chapter Box 1 in Chapter 1). Societal choices illustrated by scenarios may also influence what futures are envisioned as possible or desirable and hence whether those come into being (Beck and Mahony, 2017).

2.1.3 New scenario information since AR5

In this chapter, we extend the AR5 mitigation pathway assessment based on new scenario literature. Updates in understanding of climate sensitivity, transient climate response, radiative forcing, and the cumulative carbon budget consistent with 1.5°C are discussed in Sections 2.2.

Mitigation pathways developed with detailed process-based IAMs covering all sectors and regions over the 21st century describe an internally consistent and calibrated (to historical trends) way to get from current developments to meeting long-term climate targets like 1.5°C (Clarke et al., 2014). The overwhelming majority of available 1.5°C pathways were generated by such IAMs and these can be directly linked to climate outcomes and their consistency with the 1.5°C goal evaluated. The AR5 similarly relied upon such studies, which were mainly discussed in Chapter 6 of Working Group III (WGIII) (Clarke et al., 2014).

Since the AR5, several new integrated multi-model studies have appeared in the literature that explore

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[2] FOOTNOTE: Current pledges include those from the US although they have stated their intention to withdraw in the future.

specific characteristics of scenarios more stringent than the lowest scenario category assessed in AR5 that was assessed to limit warming below 2°C with greater that 66% likelihood (Rogelj et al., 2015b, 2018; Akimoto et al., 2017; Su et al., 2017; Liu et al., 2017; Marcucci et al., 2017; Bauer et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Kriegler et al., 2018b; Luderer et al., 2018). Those scenarios explore 1.5°C-consistent pathways from multiple perspectives (see Annex 2.A.3), examining sensitivity to assumptions regarding:

- socio-economic drivers and developments including energy and food demand as, for example, characterized by the shared socio-economic pathways (SSPs; Cross-Chapter Box 1 in Chapter 1)
- near-term climate policies describing different levels of strengthening the NDCs
- the use of bioenergy and availability and desirability of carbon-dioxide-removal (CDR) technologies

A large number of these scenarios were collected in a scenario database established for the assessment of this Special Report (Annex 2.A.3). Mitigation pathways were classified by four factors: consistency with a temperature limit (as defined by Chapter 1), whether they temporarily overshoot that limit, the extent of this potential overshoot, and the likelihood of falling within these bounds. Specifically, they were put into classes that either kept surface temperatures below a given threshold throughout the 21st century or returned to a value below 1.5°C at some point before 2100 after temporarily exceeding that level earlier, referred to as an overshoot (OS). Both groups were further separated based on the probability of being below the threshold and the degree of overshoot, respectively (Table 2.1). Pathways are uniquely classified, with 1.5°C-related classes given higher priority than 2°C classes in cases where a pathway would be applicable to either class.

The probability assessment used in the scenario classification are based on simulations using two reduced complexity carbon-cycle, atmospheric composition and climate models: the ‘Model for the Assessment of Greenhouse Gas Induced Climate Change’ (MAGICC) (Meinshausen et al., 2011a), and the ‘Finite Amplitude Impulse Response’ (FAIRv1.3) model (Smith et al., 2018). For the purpose of this report, and to facilitate comparison with AR5, the range of the key carbon-cycle and climate parameters for MAGICC and its setup are identical to those used in AR5 WGIII (Clarke et al., 2014). For each mitigation pathway, MAGICC and FAIR simulations provide probabilistic estimates of atmospheric concentrations, radiative forcing and global temperature outcomes until 2100. However, the classification uses MAGICC probabilities directly for traceability with AR5 and since this model is more established in the literature. Nevertheless, the overall uncertainty assessment is based on results from both models, which are considered in the context of the latest radiative forcing estimates and observed temperatures (Etminan et al., 2016; Smith et al., 2018) (Section 2.2 and Annex 2.A.1). The comparison of these lines of evidence shows *high agreement* in the relative temperature response of pathways, with *medium agreement* on the precise absolute magnitude of warming, introducing a level of imprecision in these attributes. Consideration of the combined evidence here leads to *medium confidence* in the overall geophysical characteristics of the pathways reported here.

Table 2.1: Classification of pathways this chapter draws upon along with the number of available pathways in each class. The definition of each class is based on probabilities derived from the MAGICC model in a setup identical to AR5 WGIII (Clarke et al., 2014), as detailed in Annex 2.A.4.

Pathway Group	***Pathway Class***	***Pathway selection criteria and description***	***Number of scenarios***	***Number of scenarios***
1.5°C or 1.5°C-consistent	*Below-1.5°C*	*Pathways limiting peak warming to below 1.5°C during the entire 21st century with 50-66% likelihood**	*9*	*90*
	1.5°C-low-OS	*Pathways limiting median warming to below 1.5°C in 2100 and with a 50-67% probability of temporarily overshooting that level earlier, generally implying less than 0.1°C higher peak warming than Below-1.5°C pathways*	*44*	
	1.5°C-high-OS	*Pathways limiting median warming to below 1.5°C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1–0.4°C higher peak warming than Below-1.5°C pathways*	*37*	
2°C or 2°C-consistent	*Lower-2°C*	*Pathways limiting peak warming to below 2°C during the entire 21st century with greater than 66% likelihood*	*74*	*132*
	Higher-2°C	*Pathways assessed to keep peak warming to below 2°C during the entire 21st century with 50-66% likelihood*	*58*	

** No pathways were available that achieve a greater than 66% probability of limiting warming below 1.5°C during the entire 21st century based on the MAGICC model projections.*

In addition to the characteristics of the above-mentioned classes, four illustrative pathway archetypes have been selected and are used throughout this chapter to highlight specific features of and variations across 1.5°C pathways. These are chosen in particular to illustrate the spectrum of CO_2 emissions reduction patterns consistent with 1.5°C, ranging from very rapid and deep near-term decreases facilitated by efficiency and demand-side measures that lead to limited CDR requirements to relatively slower but still rapid emissions reductions that lead to a temperature overshoot and necessitate large CDR deployment later in the century (Section 2.3).

2.1.4 Utility of integrated assessment models (IAMs) in the context of this report

IAMs lie at the basis of the assessment of mitigation pathways in this chapter as much of the quantitative global scenario literature is derived with such models. IAMs combine insights from various disciplines in a single framework resulting in a dynamic description of the coupled energy-economy-land-climate system that cover the largest sources of anthropogenic greenhouse gas (GHG) emissions from different sectors. Many of the IAMs that contributed mitigation scenarios to this assessment include a process-based description of the land system in addition to the energy system (e.g., Popp et al., 2017), and several have been extended to cover air pollutants (Rao et al., 2017) and water use (Hejazi et al., 2014; Fricko et al., 2016; Mouratiadou et al., 2016). Such integrated pathways hence allow the exploration of the whole-system transformation, as well as the interactions, synergies, and trade-offs between sectors, and increasing with questions beyond climate mitigation (von Stechow et al., 2015). The models do not, however, fully account for all constraints that could affect realization of pathways (see Chapter 4).

Section 2.3 assesses the overall characteristics of 1.5°C pathways based on fully integrated pathways, while Sections 2.4 and 2.5 describe underlying sectorial transformations, including insights from sector-specific assessment models and pathways that are not derived from IAMs. Such models provide detail in their domain of application and make exogenous assumptions about cross-sectoral or global factors. They often focus on a specific sector, such as the energy (Bruckner et al., 2014; IEA, 2017a; Jacobson, 2017; OECD/IEA and IRENA, 2017), buildings (Lucon et al., 2014) or transport (Sims et al., 2014) sector, or a specific country or region (Giannakidis et al., 2018). Sector-specific pathways are assessed in relation to integrated pathways because they cannot be directly linked to 1.5°C by themselves if they do not extend to 2100 or do not include all GHGs or aerosols from all sectors.

AR5 found sectorial 2°C decarbonisation strategies from IAMs to be consistent with sector-specific studies (Clarke et al., 2014). A growing body of literature on 100%-renewable energy scenarios has emerged (e.g., see Creutzig et al., 2017; Jacobson et al., 2017), which goes beyond the wide range of IAM projections of renewable energy shares in 1.5°C and 2°C pathways. While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, leading to higher renewable energy deployments in many cases (Luderer et al., 2017; Pietzcker et al., 2017), none of the IAM projections identify 100% renewable energy solutions for the global energy system as part of cost-effective mitigation pathways (Section 2.4.2). Bottom-up studies find higher mitigation potentials in the industry, buildings, and transport sector in 2030 than realized in selected 2°C pathways from IAMs (UNEP 2017), indicating the possibility to strengthen sectorial decarbonisation strategies until 2030 beyond the integrated 1.5°C pathways assessed in this chapter (Luderer et al., 2018).

Detailed process-based IAMs are a diverse set of models ranging from partial equilibrium energy-land models to computable general equilibrium models of the global economy, from myopic to perfect foresight models, and from models with to models without endogenous technological change (Annex 2.A.2). The IAMs used in this chapter have limited to no coverage of climate impacts. They typically use GHG pricing mechanisms to induce emissions reductions and associated changes in energy and land uses consistent with the imposed climate goal. The scenarios generated by these models are defined by the choice of climate goals and assumptions about near-term climate policy developments. They are also shaped by assumptions about mitigation potentials and technologies as well as baseline developments such as, for example, those represented by different Shared Socioeconomic Pathways (SSPs), especially those pertaining to energy and food demand (Riahi et al., 2017). See Section 2.3.1 for discussion of these assumptions. Since the AR5, the scenario literature has greatly expanded the exploration of these dimensions. This includes low demand scenarios (Grubler et al., 2018; van Vuuren et al., 2018), scenarios taking into account a larger set of sustainable development goals (Bertram et al., 2018), scenarios with restricted availability of CDR technologies (Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b; van Vuuren et al., 2018), scenarios with near-term action dominated by regulatory policies (Kriegler et al., 2018b) and scenario variations across the Shared Socioeconomic Pathways (Riahi et al., 2017; Rogelj et al., 2018). IAM results depend upon multiple underlying assumptions, for example the extent to which global markets and economies are assumed to operate frictionless and policies are cost-optimised, assumptions about technological progress and availability and costs of mitigation and CDR measures, assumptions about underlying socio-economic developments and future energy, food and materials demand, and assumptions about the geographic and temporal pattern of future regulatory and carbon pricing policies (see Annex 2.A.2 for additional discussion on IAMs and their limitations).

2.2 Geophysical relationships and constraints

Emissions pathways can be characterised by various geophysical characteristics such as radiative forcing (Masui et al., 2011; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011b), atmospheric concentrations (van Vuuren et al., 2007, 2011a; Clarke et al., 2014) or associated temperature outcomes (Meinshausen et al., 2009; Rogelj et al., 2011; Luderer et al., 2013). These attributes can be used to derive geophysical relationships for specific pathway classes, such as cumulative CO_2 emissions compatible with a specific level of warming also known as 'carbon budgets' (Meinshausen et al., 2009; Rogelj et al., 2011; Stocker et al., 2013; Friedlingstein et al., 2014a), the consistent contributions of non-CO_2 GHGs and aerosols to the remaining carbon budget (Bowerman et al., 2011; Rogelj et al., 2015a, 2016b) or to temperature outcomes (Lamarque et al., 2011; Bowerman et al., 2013; Rogelj et al., 2014b). This section assesses geophysical relationships for both CO_2 and non-CO_2 emissions.

2.2.1 Geophysical characteristics of mitigation pathways

This section employs the pathway classification introduced in Section 2.1, with geophysical characteristics derived from simulations with the MAGICC reduced-complexity carbon-cycle and climate model and supported by simulations with the FAIR reduced-complexity model (Section 2.1). Within a specific category and between models, there remains a large degree of variance. Most pathways exhibit a temperature overshoot which has been highlighted in several studies focusing on stringent mitigation pathways (Huntingford and Lowe, 2007; Wigley et al., 2007; Nohara et al., 2015; Rogelj et al., 2015d; Zickfeld and Herrington, 2015; Schleussner et al., 2016; Xu and Ramanathan, 2017). Only very few of the scenarios collected in the database for this report hold the average future warming projected by MAGICC below 1.5°C during the entire 21st century (Table 2.1, Figure 2.1). Most 1.5°C-consistent pathways available in the database overshoot 1.5°C around mid-century before peaking and then reducing temperatures so as to return below that level in 2100. However, because of numerous geophysical uncertainties and model dependencies (Section 2.2.1.1, Annex 2.A.1), absolute temperature characteristics of the various pathway categories are more difficult to distinguish than relative features (Figure 2.1, Annex 2.A.1) and actual probabilities of overshoot are imprecise. However, all lines of evidence available for temperature projections indicate a probability greater than 50% of overshooting 1.5°C by mid-century in all but the most stringent pathways currently available (Annex 2.A.1, 2.A.4).

Most 1.5°C-consistent pathways exhibit a peak in temperature by mid-century whereas 2°C-consistent pathways generally peak after 2050 (Annex 2.A.4). The peak in median temperature in the various pathway categories occurs about ten years before reaching net zero CO_2 emissions due to strongly reduced annual CO_2 emissions and deep reductions in CH_4 emissions (Section 2.3.3). The two reduced-complexity climate models used in this assessment suggest that virtually all available 1.5°C-consistent pathways peak and decline global-mean temperature rise, but with varying rates of temperature decline after the peak (Figure 2.1). The estimated decadal rates of temperature change by the end of the century are smaller than the amplitude of the climate variability as assessed in AR5 (1σ of about ±0.1°C), which hence complicates the detection of a global peak and decline of warming in observations on timescales of on to two decades (Bindoff et al., 2013). In comparison, many pathways limiting warming to 2°C or higher by 2100 still have noticeable increasing trends at the end of the century, and thus imply continued warming.

By 2100, the difference between 1.5°C- and 2°C-consistent pathways becomes clearer compared to mid-century, and not only for the temperature response (Figure 2.1) but also for atmospheric CO_2 concentrations. In 2100, the median CO_2 concentration in 1.5°C-consistent pathways is below 2016 levels (Le Quéré et al., 2018), whereas it remains higher by about 5-10% compared to 2016 in the 2°C-consistent pathways.

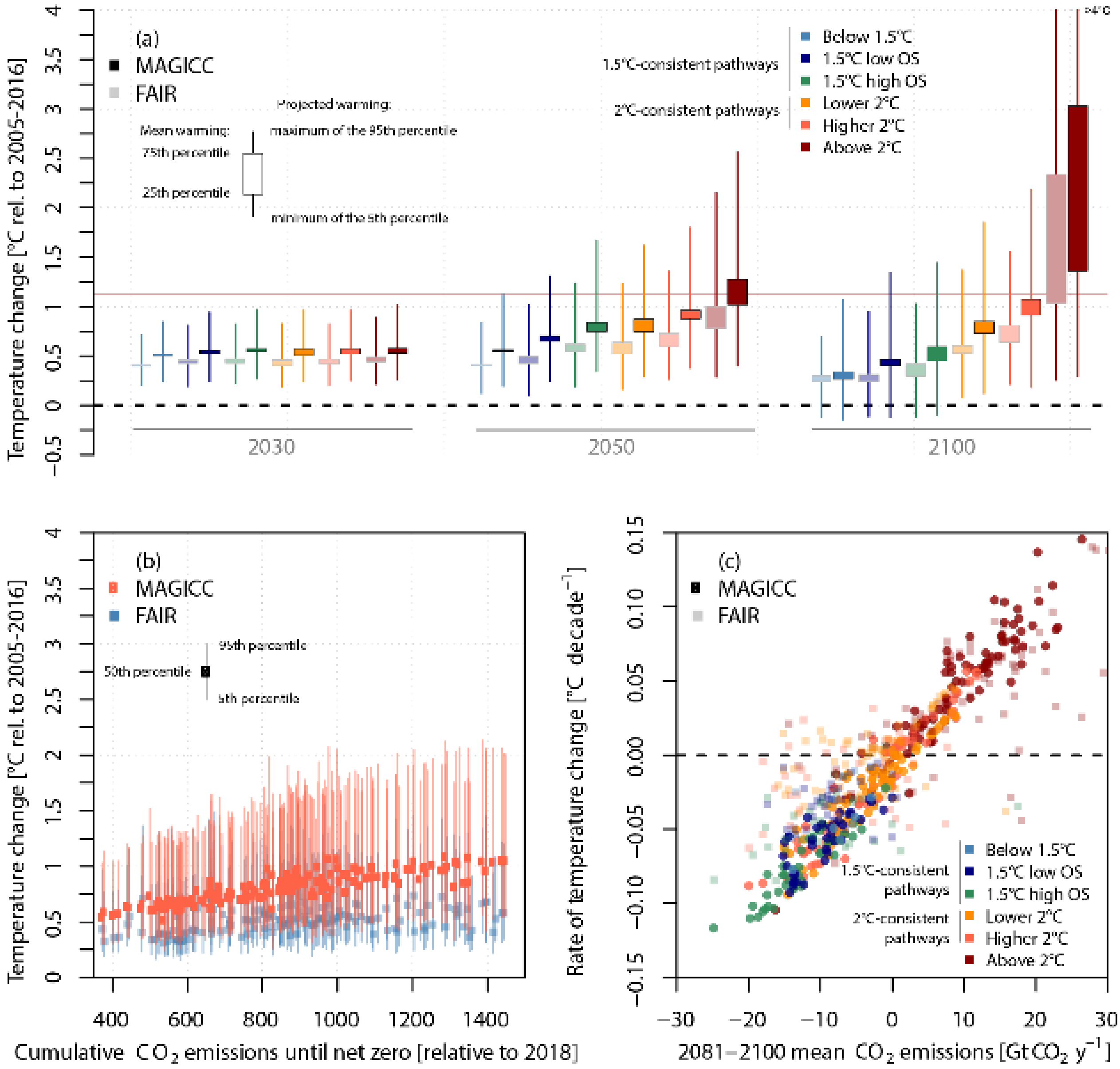

Figure 2.1: **Pathways classification overview.** (a) Average global-mean temperature increase relative to 2010 as projected by FAIR and MAGICC in 2030, 2050 and 2100; (b) response of peak warming to cumulative CO_2 emissions until net zero by MAGICC (red) and FAIR (blue); (c) decadal rate of average global-mean temperature change from 2081 to 2100 as a function of the annual CO_2 emissions averaged over the same period as given by FAIR (transparent squares) and MAGICC (filled circles). In panel (a), horizontal lines at 0.63°C and 1.13°C are indicative of the 1.5°C and 2°C warming thresholds with the respect to 1850–1900, taking into account the assessed historical warming of 0.87°C ±0.12°C between the 1850–1900 and 2006–2015 periods (Section 1.2.1). In panel (a), vertical lines illustrate both the physical and the scenario uncertainty as captured by MAGICC and FAIR and show the minimal warming of the 5th percentile of projected warming and the maximal warming of the 95th percentile of projected warming per scenario class. Boxes show the interquartile range of mean warming across scenarios, and thus represent scenario uncertainty only.

2.2.1.1 Geophysical uncertainties: non-CO2 forcing agents

Impacts of non-CO_2 climate forcers on temperature outcomes are particularly important when evaluating stringent mitigation pathways (Weyant et al., 2006; Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Samset et al., 2018). However, many uncertainties affect the role of non-CO_2 climate forcers in stringent mitigation pathways.

A first uncertainty arises from the magnitude of the radiative forcing attributed to non-CO_2 climate forcers. Figure 2.2 illustrates how, for one representative 1.5°C-consistent pathway (SSP2-1.9) (Fricko et al., 2017; Rogelj et al., 2018), the effective radiative forcings as estimated by MAGICC and FAIR can differ (see Annex 2.A.1 for further details). This large spread in non-CO_2 effective radiative forcings leads to considerable uncertainty in the predicted temperature response. This uncertainty ultimately affects the assessed temperature outcomes for pathway classes used in this chapter (Section 2.1) and also affects the carbon budget (Section 2.2.2). Figure 2.2 highlights the important role of methane emissions reduction in this scenario in agreement with the recent literature focussing on stringent mitigation pathways (Shindell et al., 2012; Rogelj et al., 2014b, 2015a; Stohl et al., 2015; Collins et al., 2018).

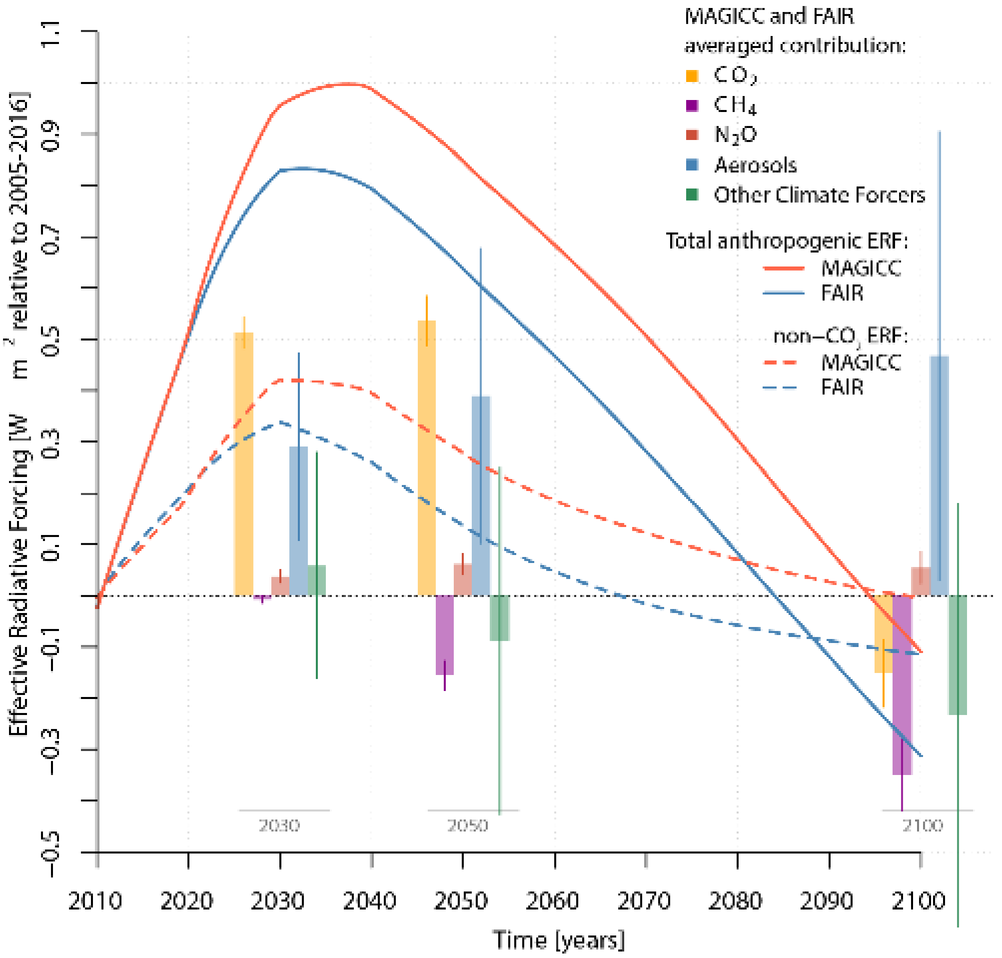

Figure 2.2: Changes and uncertainties in effective radiative forcings (ERF) for one 1.5°C-consistent pathway (SSP2-19) as estimated by MAGICC and FAIR. Solid and dashed lines are indicative of the effective radiative forcing for CO_2 and non-CO_2 agents as represented by MAGICC (red) and FAIR (blue) relative to 2010, respectively. Vertical bars show the mean radiative forcing as predicted by MAGICC and FAIR of relevant non-CO_2 agents for year 2030, 2050 and 2100. The vertical lines give the uncertainty (1σ) of the ERFs for the represented species.

For mitigation pathways that aim at halting and reversing radiative forcing increase during this century, the aerosol radiative forcing is a considerable source of uncertainty (Figure 2.2) (Samset et al., 2018; Smith et al., 2018). Indeed, reductions in SO_2 (and NO_x) emissions largely associated with fossil-fuel burning are expected to reduce the cooling effects of both aerosol radiative interactions and aerosol cloud interactions, leading to warming (Myhre et al., 2013; Samset et al., 2018). A multi-model analysis (Myhre et al., 2017) and a study based on observational constraints (Malavelle et al., 2017) largely support the AR5 best estimate and uncertainty range of aerosol forcing. The partitioning of total aerosol radiative forcing between aerosol precursor emissions is important (Ghan et al., 2013; Jones et al., 2018; Smith et al., 2018) as this affects the estimate of the mitigation potential from different sectors that have aerosol precursor emission sources. The total aerosol effective radiative forcing change in stringent mitigation pathways is expected to be dominated by the effects from the phase-out of SO_2, although the magnitude of this aerosol-warming effect depends on how much of the present-day aerosol cooling is attributable to SO_2, particularly the cooling associated with aerosol-cloud interaction (Figure 2.2). Regional differences in the linearity of aerosol-cloud interaction (Carslaw et al., 2013; Kretzschmar et al., 2017) make it difficult to separate the role of individual precursors. Precursors that are not fully mitigated will continue to affect the Earth system. If, for example, the role of nitrate aerosol cooling is at the strongest end of the assessed IPCC AR5 uncertainty range, future temperature increases may be more modest if ammonia emissions continue to rise (Hauglustaine et al., 2014).

Figure 2.2 shows that there are substantial differences in the evolution of estimated effective radiative forcing of non-CO_2 forcers between MAGICC and FAIR. These forcing differences result in MAGICC simulating a larger warming trend in the near term compared to both the FAIR model and the recent observed trends of 0.2°C per decade reported in Chapter 1 (Figure 2.1, Annex 2.A.1, Section 1.2.1.3). The aerosol effective forcing is stronger in MAGICC compared to either FAIR or the AR5 best estimate, though it is still well within the AR5 uncertainty range (Annex 2.A.1.1). A recent revision (Etminan et al., 2016) increases the methane forcing by 25%. This revision is used in the FAIR but not in the AR5 setup of MAGICC that is applied here. Other structural differences exist in how the two models relate emissions to concentrations that contribute to differences in forcing (see Annex 2.A.1.1).

Non-CO_2 climate forcers exhibit a greater geographical variation in radiative forcings than CO_2, which lead to important uncertainties in the temperature response (Myhre et al., 2013). This uncertainty increases the relative uncertainty of the temperature pathways associated with low emission scenarios compared to high emission scenarios (Clarke et al., 2014). It is also important to note that geographical patterns of temperature change and other climate responses, especially those related to precipitation, depend significantly on the forcing mechanism (Myhre et al., 2013; Shindell et al., 2015; Marvel et al., 2016; Samset et al., 2016) (see also Section 3.6.2.2).

2.2.1.2 Geophysical uncertainties: climate and Earth-system feedbacks

Climate sensitivity uncertainty impacts future projections as well as carbon-budget estimates (Schneider et al., 2017). AR5 assessed the equilibrium climate sensitivity (ECS) to be *likely* in the 1.5–4.5°C range, *extremely unlikely* less than 1°C and *very unlikely* greater than 6°C. The lower bound of this estimate is lower than the range of CMIP5 models (Collins et al., 2013). The evidence for the 1.5°C lower bound on ECS in AR5 was based on analysis of energy-budget changes over the historical period. Work since AR5 has suggested that the climate sensitivity inferred from such changes has been lower than the 2xCO_2 climate sensitivity for known reasons (Forster, 2016; Gregory and Andrews, 2016; Rugenstein et al., 2016; Armour, 2017; Ceppi and Gregory, 2017; Knutti et al., 2017; Proistosescu and Huybers, 2017). Both a revised interpretation of historical estimates and other lines of evidence based on analysis of climate models with the best representation of today's climate (Sherwood et al., 2014; Zhai et al., 2015; Tan et al., 2016; Brown and Caldeira, 2017; Knutti et al., 2017) suggest that the lower bound of ECS could be revised upwards which would decrease the chances of limiting warming below 1.5°C in assessed pathways. However, such a reassessment has been challenged (Lewis and Curry, 2018), albeit from a single line of evidence. Nevertheless, it is premature to make a major revision to the lower bound. The evidence for a possible revision of the upper bound on ECS is less clear with cases argued from different lines of evidence for both decreasing (Lewis and Curry, 2015, 2018; Cox et al., 2018) and increasing (Brown and Caldeira, 2017) the bound presented in the literature. The tools used in this chapter employ ECS ranges consistent with the AR5 assessment. The MAGICC ECS distribution has not been selected to explicitly reflect this but is nevertheless consistent (Rogelj et al., 2014a). The FAIR model used here to estimate carbon budgets explicitly constructs log-normal distributions of ECS and transient climate response based on a multi parameter fit to the AR5 assessed ranges of climate sensitivity and individual historic effective radiative forcings (Smith et al., 2018) (Annex 2.A.1.1).

Several feedbacks of the Earth system, involving the carbon cycle, non-CO_2 GHGs and/or aerosols, may also impact the future dynamics of the coupled carbon-climate system's response to anthropogenic emissions. These feedbacks are caused by the effects of nutrient limitation (Duce et al., 2008; Mahowald et al., 2017), ozone exposure (de Vries et al., 2017), fire emissions (Narayan et al., 2007) and changes associated with natural aerosols (Cadule et al., 2009; Scott et al., 2017). Among these Earth-system feedbacks, the importance of the permafrost feedback's influence has been highlighted in recent studies. Combined evidence from both models (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) and field studies (like Schädel et al., 2014; Schuur et al., 2015) shows *high agreement* that permafrost thawing will release both CO_2 and CH_4 as the Earth warms, amplifying global warming. This thawing could also release N_2O (Voigt et al., 2017a, 2017b). Field, laboratory and modelling studies estimate that the vulnerable fraction in permafrost is about 5–15% of the permafrost soil carbon (~5300–5600 $GtCO_2$ in Schuur et al., 2015) and that carbon emissions are expected to occur beyond 2100 because of system inertia and the large proportion of slowly decomposing carbon in permafrost (Schädel et al., 2014). Published model studies suggest that a large part of the carbon release to the atmosphere is in the form of CO_2 (Schädel et al., 2016), while the amount of CH_4 released by permafrost thawing is estimated to be much smaller than that CO_2. Cumulative CH_4 release by 2100 under RCP2.6 ranges from 0.13 to 0.45 Gt of methane (Burke et al., 2012; Schneider von Deimling et al., 2012, 2015) with fluxes being the highest in the middle of the century because of maximum thermokarst lake extent by mid-century (Schneider von Deimling et al., 2015).

The reduced complexity climate models employed in this assessment do not take into account permafrost or non-CO_2 Earth-system feedbacks, although the MAGICC model has a permafrost module that can be enabled. Taking the current climate and Earth-system feedbacks understanding together, there is a possibility that these models would underestimate the longer-term future temperature response to stringent emission pathways (Section 2.2.2).

2.2.2 The remaining 1.5°C carbon budget

2.2.2.1 Carbon budget estimates

Since the AR5, several approaches have been proposed to estimate carbon budgets compatible with 1.5°C or 2°C. Most of these approaches indirectly rely on the approximate linear relationship between peak global-mean temperature and cumulative emissions of carbon (the transient climate response to cumulative emissions of carbon, TCRE (Collins et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b) whereas others base their estimates on equilibrium climate sensitivity (Schneider et al., 2017). The AR5 employed two approaches to determine carbon budgets. Working Group I (WGI) computed carbon budgets from 2011 onwards for various levels of warming relative to the 1861–1880 period using RCP8.5 (Meinshausen et al., 2011b; Stocker et al., 2013) whereas WGIII estimated their budgets from a set of available pathways that were assessed to have a >50% probability to exceed 1.5°C by mid-century, and return to 1.5°C or below in 2100 with greater than 66% probability (Clarke et al., 2014). These differences made AR5 WGI and WGIII carbon budgets difficult to compare as they are calculated over different time periods, derived from a different sets of multi-gas and aerosol emission scenarios and use different concepts of carbon budgets (exceedance for WGI, avoidance for WGIII) (Rogelj et al., 2016b; Matthews et al., 2017).

Carbon budgets can be derived from CO_2-only experiments as well as from multi-gas and aerosol scenarios. Some published estimates of carbon budgets compatible with 1.5°C or 2°C refer to budgets for CO_2-induced warming only, and hence do not take into account the contribution of non-CO_2 climate forcers (Allen et al., 2009; Matthews et al., 2009; Zickfeld et al., 2009; IPCC, 2013a). However, because the projected changes in non-CO_2 climate forcers tend to amplify future warming, CO_2-only carbon budgets overestimate the total net cumulative carbon emissions compatible with 1.5°C or 2°C (Friedlingstein et al., 2014a; Rogelj et al., 2016b; Matthews et al., 2017; Mengis et al., 2018; Tokarska et al., 2018).

Since the AR5, many estimates of the remaining carbon budget for 1.5°C have been published (Friedlingstein et al., 2014a; MacDougall et al., 2015; Peters, 2016; Rogelj et al., 2016b; Matthews et al., 2017; Millar et al., 2017; Goodwin et al., 2018b; Kriegler et al., 2018a; Lowe and Bernie, 2018; Mengis et al., 2018; Millar and Friedlingstein, 2018; Rogelj et al., 2018; Schurer et al., 2018; Séférian et al., 2018;

Tokarska et al., 2018; Tokarska and Gillett, 2018). These estimates cover a wide range as a result of differences in the models used, and of methodological choices, as well as physical uncertainties. Some estimates are exclusively model-based while others are based on observations or on a combination of both. Remaining carbon budgets limiting warming below 1.5°C or 2°C that are derived from Earth-system models of intermediate complexity (MacDougall et al., 2015; Goodwin et al., 2018a), IAMs (Luderer et al., 2018; Rogelj et al., 2018), or based on Earth-system model results (Lowe and Bernie, 2018; Séférian et al., 2018; Tokarska and Gillett, 2018) give remaining carbon budgets of the same order of magnitude than the IPCC AR5 Synthesis Report (SYR) estimates (IPCC, 2014a). This is unsurprising as similar sets of models were used for the AR5 (IPCC, 2013b). The range of variation across models stems mainly from either the inclusion or exclusion of specific Earth-system feedbacks (MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018) or different budget definitions (Rogelj et al., 2018).

In contrast to the model-only estimates discussed above and employed in the AR5, this report additionally uses observations to inform its evaluation of the remaining carbon budget. Table 2.2 shows that the assessed range of remaining carbon budgets consistent with 1.5°C or 2°C is larger than the AR5 SYR estimate and is part way towards estimates constrained by recent observations (Millar et al., 2017; Goodwin et al., 2018a; Tokarska and Gillett, 2018). Figure 2.3 illustrates that the change since AR5 is, in very large part, due to the application of a more recent observed baseline to the historic temperature change and cumulative emissions; here adopting the baseline period of 2006-2015 (see Section 1.2.1). AR5 SYR Figures SPM.10 and 2.3 already illustrated the discrepancy between models and observations, but did not apply this as a correction to the carbon budget because they were being used to illustrate the overall linear relationship between warming and cumulative carbon emissions in the CMIP5 models since 1870, and were not specifically designed to quantify residual carbon budgets relative to the present for ambitious temperature goals. The AR5 SYR estimate was also dependent on a subset of Earth-system models illustrated in Figure 2.3 of this report. Although, as outlined below and in Table 2.2, considerably uncertainties remain, there is *high agreement* across various lines of evidence assessed in this report that the remaining carbon budget for 1.5°C or 2°C would be larger than the estimates at the time of the AR5. However, the overall remaining budget for 2100 is assessed to be smaller than that derived from the recent observational-informed estimates, as Earth-system feedbacks such as permafrost thawing reduce the budget applicable to centennial scales (see Section 2.2.2.2).

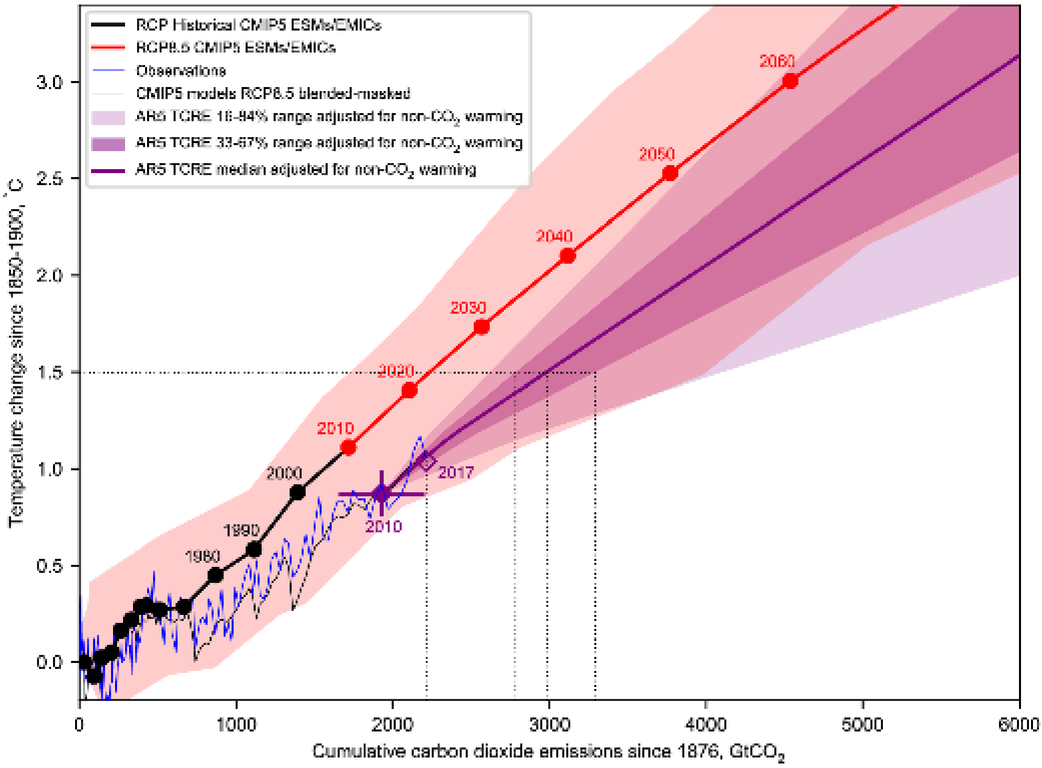

Figure 2.3: Temperature changes from 1850-1900 versus cumulative CO$_2$ emissions since 1st January 1876. Solid lines with dots reproduce the temperature response to cumulative CO$_2$ emissions plus non-CO$_2$ forcers as assessed in Figure SPM10 of WGI AR5, except that points marked with years relate to a

particular year, unlike in WGI AR5 Fig. SPM10 where each point relates to the mean over the previous decade. The AR5 data was derived from available Earth-system models and Earth-system models of Intermediate Complexity for the historic observations (black) and RCP 8.5 scenario (red) and the red shaded plume shows the uncertainty range across the models as presented in the AR5. The purple shaded plume and the line are indicative of the temperature response to cumulative CO_2 emissions and non-CO_2 warming adopted in this report. The non-CO_2 warming contribution is averaged from the MAGICC and FAIR models and the purple shaded range assumes the AR5 WGI TCRE distribution (Annex 2.A.1.2). The 2010 observations of temperature anomaly (0.87°C based on 2006-2015 mean compared to 1850-1900, Section 1.2.1) and cumulative carbon dioxide emissions from 1876 to the end of 2010 of 1,930 $GtCO_2$ (Le Quéré et al., 2018) is shown as a filled purple diamond. 2017 values based on the latest cumulative carbon emissions up to the end of 2017 of 2,220 $GtCO_2$ (Version 1.3 accessed 22 May 2018) and a temperature anomaly of 1.04°C based on an assumed temperature increase of 0.2°C per decade is shown as a hollow purple diamond. The thin blue line shows annual observations, with CO_2 emissions from (Le Quéré et al., 2018) and temperatures from the average of datasets in Chapter 1, Figure 1.2. The thin black line shows the CMIP5 models blended-masked estimates with CO_2 emissions also from (Le Quéré et al., 2018). Dotted black lines illustrate the remaining carbon budget estimates for 1.5°C given in Table 2.2. Note these remaining budgets exclude possible Earth-system feedbacks that could reduce the budget, such as CO_2 and CH_4 release from permafrost thawing and tropical wetlands (see Section 2.2.2.2).

2.2.2.2 CO_2 and non-CO_2 contributions to the remaining carbon budget

A remaining carbon budget can be estimated from calculating the amount of CO_2 emissions consistent, given a certain value of TCRE, with an allowable additional amount of warming. Here, the allowable warming is the 1.5°C warming threshold minus the current warming taken as the 2006-2015 average, with a further amount removed to account for the estimated non-CO_2 temperature contribution to the remaining warming (Peters, 2016; Rogelj et al., 2016b). This assessment uses the TCRE range from AR5 WGI (Collins et al., 2013) supported by estimates of non-CO_2 contributions that are based on published methods and integrated pathways (Friedlingstein et al., 2014a; Allen et al., 2016, 2018; Peters, 2016; Smith et al., 2018). Table 2.2 and Figure 2.3 show the assessed remaining carbon budgets and key uncertainties for a set of additional warming levels relative to the 2006–2015 period (see Annex 2.A.1.2 for details). With an assessed historical warming of 0.87°C ±0.12°C from 1850–1900 to 2006–2015 (Section 1.2.1), 0.63°C of additional warming would be approximately consistent with a global-mean temperature increase of 1.5°C relative to preindustrial levels. For this level of additional warming, remaining carbon budgets have been estimated (Table 2.2, Annex 2.A.1.2).

The remaining carbon budget calculation presented in the Table 2.2 and illustrated in Figure 2.3 does not consider additional Earth-system feedbacks such as permafrost thawing. These are uncertain but estimated to reduce the remaining carbon budget by an order of magnitude of about 100 $GtCO_2$. Accounting for such feedbacks would make the carbon budget more applicable for 2100 temperature targets, but would also increase uncertainty (Table 2.2 and see below). Excluding such feedbacks, the assessed range for the remaining carbon budget is estimated to be 1100, 750, and 550 $GtCO_2$ (rounded to the nearest 50 $GtCO_2$) for the 33rd, 50th and, 67th percentile of TCRE, respectively, with a median non-CO_2 warming contribution and starting from 1 January 2018 onward. Note that future research and ongoing observations over the next years will provide a better indication as to how the 2006–2015 base period compares with the long-term trends and might bias the budget estimates. Similarly, improved understanding in Earth-system feedbacks would result in a better quantification of their impacts on remaining carbon budgets for 1.5°C and 2°C.

After TCRE uncertainty, a major additional source of uncertainty is the magnitude of non-CO_2 forcing and its contribution to the temperature change between the present day and the time of peak warming. Integrated emissions pathways can be used to ensure consistency between CO_2 and non-CO_2 emissions (Bowerman et al., 2013; Collins et al., 2013; Clarke et al., 2014; Rogelj et al., 2014b, 2015a; Tokarska et al., 2018). Friedlingstein et al. (2014a) used pathways with limited to no climate mitigation to find a variation due to non-CO_2 contributions of about ±33% for a 2°C carbon budget. Rogelj et al. (2016b) showed no particular bias in non-CO_2 radiative forcing or warming at the time of exceedance of 2°C or at peak warming between scenarios with increasing emissions and strongly mitigated scenarios (consistent with Stocker et al., 2013). However, clear differences of the non-CO_2 warming contribution at the time of deriving a 2°C-consistent carbon budget were reported for the four RCPs. Although the spread in non-CO_2 forcing across scenarios can be smaller in absolute terms at lower levels of cumulative emissions, it can be larger in relative terms compared to the remaining carbon budget (Stocker et al., 2013; Friedlingstein et al., 2014a; Rogelj et al., 2016b). Tokarska and Gillett (2018) find no statistically significant differences in 1.5°C-consistent cumulative emissions budgets when calculated for different RCPs from consistent sets of CMIP5 simulations.

The mitigation pathways assessed in this report indicate that emissions of non-CO_2 forcers contribute an average additional warming of around 0.15°C relative to 2006–2015 at the time of net zero CO_2 emissions, reducing the remaining carbon budget by roughly 320 $GtCO_2$. This arises from a weakening of aerosol cooling and continued emissions of non-CO_2 GHGs (Sections 2.2.1, 2.3.3). This non-CO_2 contribution at the time of net zero CO_2 emissions varies by about ±0.1°C across scenarios resulting in a carbon budget uncertainty of about ±250 $GtCO_2$ and takes into account marked reductions in methane emissions (Section 2.3.3). In case these would not be achieved, remaining carbon budgets are further reduced. Uncertainties in the non-CO_2 forcing and temperature response are asymmetric and can influence the remaining carbon budget by -400 to +200 $GtCO_2$ with the uncertainty in aerosol radiative forcing being the largest contributing factor (Table 2.2). The MAGICC and FAIR models in their respective parameter setups and model versions used to assess the non-CO_2 warming contribution give noticeable different non-CO_2 effective radiative forcing and warming for the same scenarios while both being within plausible ranges of future response (Fig. 2.2 and Annex 2.A.1–2). For this assessment, it is premature to assess the accuracy of their results, so it is assumed that both are equally representative of possible futures. Their non-CO_2 warming estimates are therefore averaged for the carbon budget assessment and their differences used to guide the uncertainty assessment of the role of non-CO_2 forcers. Nevertheless, the findings are robust enough to give *high confidence* that the changing emissions non-CO_2 forcers (particularly the reduction in cooling aerosol precursors) cause additional near-term warming and reduce the remaining carbon budget compared to the CO_2 only budget.

TCRE uncertainty directly impacts carbon budget estimates (Peters, 2016; Matthews et al., 2017; Millar and Friedlingstein, 2018). Based on multiple lines of evidence, AR5 WGI assessed a *likely* range for TCRE of 0.2–0.7°C per 1000 $GtCO_2$ (Collins et al., 2013). The TCRE of the CMIP5 Earth-system models ranges from 0.23 to 0.66°C per 1000 $GtCO_2$ (Gillett et al., 2013). At the same time, studies using observational constraints find best estimates of TCRE of 0.35–0.41°C per 1000 $GtCO_2$ (Matthews et al., 2009; Gillett et al., 2013; Tachiiri et al., 2015; Millar and Friedlingstein, 2018). This assessment continues to use the assessed AR5 TCRE range under the working assumption that TCRE is normally distributed (Stocker et al., 2013). Observation-based estimates have reported log-normal distributions of TCRE (Millar and Friedlingstein, 2018). Assuming a log-normal instead of normal distribution of the assessed AR5 TCRE range would result in about a 200 $GtCO_2$ increase for the median budget estimates but only about half at the 67th percentile, while historical temperature uncertainty and uncertainty in recent emissions contribute ±150 and ±50 $GtCO_2$ to the uncertainty, respectively (Table 2.2).

Calculating carbon budgets from the TCRE requires the assumption that the instantaneous warming in response to cumulative CO_2 emissions equals the long-term warming or, equivalently, that the residual warming after CO_2 emissions cease is negligible. The magnitude of this residual warming, referred to as the zero-emission commitment, ranges from slightly negative (i.e., a slight cooling) to slightly positive for CO_2 emissions up to present-day (Section 1.2.4) (Lowe et al., 2009; Frölicher and Joos, 2010; Gillett et al., 2011; Matthews and Zickfeld, 2012). The delayed temperature change from a pulse CO_2 emission introduces uncertainties in emission budgets, which have not been quantified in the literature for budgets consistent with limiting warming to 1.5°C. As a consequence, this uncertainty does not affect our carbon budget estimates directly but it is included as an additional factor in the assessed Earth-system feedback uncertainty (as detailed below) of roughly 100 $GtCO_2$ on decadal timescales presented in Table 2.2.

Remaining carbon budgets are further influenced by Earth-system feedbacks not accounted for in CMIP5 models, such as the permafrost carbon feedback (Friedlingstein et al., 2014b; MacDougall et al., 2015; Burke et al., 2017; Lowe and Bernie, 2018), and their influence on the TCRE. Lowe and Bernie (2018) used a simple climate sensitivity scaling approach to estimate that Earth-system feedbacks (such as CO_2 released by permafrost thawing or methane released by wetlands) could reduce carbon budgets for 1.5°C and 2°C by roughly 100 $GtCO_2$ on centennial time scales. Their findings are based on older previous Earth-system feedbacks understanding (Arneth et al., 2010). This estimate is broadly supported by more recent analysis of individual feedbacks. Schädel et al. (2014) suggest an upper bound of 24.4 PgC (90 $GtCO_2$) emitted from carbon release from permafrost over the next forty years for a RCP4.5 scenario. Burke et al. (2017) use a single model to estimate permafrost emissions between 0.3 and 0.6 $GtCO_2$ y^{-1} from the point of 1.5°C stabilization, which would reduce the budget by around 20 $GtCO_2$ by 2100. Comyn-Platt et al. (2018) include methane emissions from permafrost and suggest the 1.5°C remaining carbon budget is reduced by 180 $GtCO_2$. Additionally, Mahowald et al. (2017) find there is possibility of 0.5–1.5 $GtCO_2$ y^{-1} being released from aerosol-biogeochemistry changes if aerosol emissions cease. In summary, these additional Earth system feedbacks taken together are assessed to reduce the remaining carbon budget applicable to 2100 by an order of magnitude of 100 $GtCO_2$, compared to the budgets based on the assumption of a constant TCRE presented in Table 2.2 (*limited evidence, medium agreement*), leading to overall *medium confidence* in their assessed impact.

The uncertainties presented in Table 2.2 cannot be formally combined, but current understanding of the assessed geophysical uncertainties suggests at least a ±50% possible variation for remaining carbon budgets for 1.5°C-consistent pathways. When put in the context of year-2017 CO_2 emissions (about 41 $GtCO_2$ yr^{-1}) (Le Quéré et al., 2018), a remaining carbon budget of 750 $GtCO_2$ (550 $GtCO_2$) suggests meeting net zero global CO_2 emissions in about 35 years (25 years) following a linear decline starting from 2018 (rounded to the nearest five years), with a variation of ±15–20 years due to the above mentioned geophysical uncertainties (*high confidence*).

The remaining carbon budgets assessed in this section are consistent with limiting peak warming to the indicated levels of additional warming. However, if these budgets are exceeded and the use of CDR (see Sections 2.3 and 2.4) is envisaged to return cumulative CO_2 emissions to within the carbon budget at a later point in time, additional uncertainties apply because the TCRE is different under increasing and decreasing atmospheric CO_2 concentrations due to ocean thermal and carbon-cycle inertia (Herrington and Zickfeld, 2014; Krasting et al., 2014; Zickfeld et al., 2016). This asymmetrical behaviour makes carbon budgets path-dependent in case of a budget and/or temperature overshoot (MacDougall et al., 2015). Although potentially large for scenarios with large overshoot (MacDougall et al., 2015), this path-dependence of carbon budgets has not been well quantified for 1.5°C- and 2°C-consistent scenarios and as such remains an important knowledge gap. This assessment does not explicitly account for path dependence but takes it into consideration for its overall confidence assessment.

This assessment finds a larger remaining budget from the 2006-2015 base period than the 1.5°C and 2°C remaining budgets inferred from AR5 from the start of 2011, approximately 1000 $GtCO_2$ for the 2°C (66% of model simulations) and approximately 400 $GtCO_2$ for the 1.5°C budget (66% of model simulations). In contrast, this assessment finds approximately 1600 $GtCO_2$ for the 2°C (66th TCRE percentile) and approximately 860 $GtCO_2$ for the 1.5°C budget (66th TCRE percentile) from 2011. However, these budgets are not directly equivalent as AR5 reported budgets for fractions of CMIP5 simulations and other lines of evidence, while this report uses the assessed range of TCRE and an assessment of the non-CO_2 contribution at net zero CO_2 emissions to provide remaining carbon budget estimates at various percentiles of TCRE. Furthermore, AR5 did not specify remaining budgets to carbon neutrality as we do here, but budgets until the time the temperature limit of interest was reached, assuming negligible zero emission commitment and taking into account the non-CO_2 forcing at that point in time.

In summary, although robust physical understanding underpins the carbon budget concept, relative uncertainties become larger as a specific temperature limit is approached. For the budget, applicable to the mid-century, the main uncertainties relate to the TCRE, non-CO_2 emissions, radiative forcing and response. For 2100, uncertain Earth-system feedbacks such as permafrost thawing would further reduce the available budget. The remaining budget is also conditional upon the choice of baseline, which is affected by uncertainties in both historical emissions, and in deriving the estimate of globally averaged human-induced warming. As a result, only *medium confidence* can be assigned to the assessed remaining budget values for 1.5°C and 2.0°C and their uncertainty.

Table 2.2: The assessed remaining carbon budget and its uncertainties. Shaded grey horizontal bands illustrate the uncertainty in historical temperature increase from the 1850-1900 base period until the 2006-2015 period, which impacts the additional warming until a specific temperature limit like 1.5°C or 2°C relative to the 1850-1900 period.

Additional warming since 2006-2015 [°C]*(1)	**Approximate warming since 1850-1900 [°C]*(1)**	**Remaining carbon budget (excluding additional Earth-system feedbacks*(5)) [GtCO$_2$ from 1.1.2018]*(2)**			**Key uncertainties and variations*(4)**					
		Percentiles of TCRE*(3)			**Additional Earth-system feedbacks*(5)**	**Non-CO$_2$ scenario variation*(6)**	**Non-CO$_2$ forcing and response uncertainty**	**TCRE distribution uncertainty*(7)**	**Historical temperature uncertainty*(1)**	**Recent emissions uncertainty*(8)**
		33rd	*50th*	*67th*	*[GtCO$_2$]*	*[GtCO$_2$]*	*[GtCO$_2$]*	*[GtCO$_2$]*	*[GtCO$_2$]*	*[GtCO$_2$]*
0.3		290	160	80	Budgets on the left are reduced by about 100 GtCO$_2$ If evaluated to 2100 and potentially more on centennial time scales	+-250	-400 to +200	+100 to +200	+-250	+-20
0.4		530	350	230						
0.5		770	530	380						
0.6		1010	710	530						
0.63	**~1.5°C**	**1080**	**770**	**570**						
0.7		1240	900	680						
0.8		1480	1080	830						
0.9		1720	1260	980						
1		1960	1450	1130						
1.1		2200	1630	1280						
1.13	**~2.°C**	**2270**	**1690**	**1320**						
1.2		2440	1820	1430						

*(1) Chapter 1 has assessed historical warming between the 1850-1900 and 2006-2015 periods to be 0.87°C with a +/- 0.12°C *likely* (1-σ) range
*(2) Historical CO$_2$ emissions since the middle of the 1850-1900 historical base period (1 January 1876) are estimated at 1930 GtCO$_2$ (1630-2230 GtCO$_2$, 1-σ range) until end 2010. Since 1 January 2011, an additional 290 GtCO$_2$ (270-310 GtCO$_2$, 1-σ range) has been emitted until the end of 2017 (Le Quéré et al., 2018, Version 1.3 - accessed 22 May 2018).
*(3) TCRE: transient climate response to cumulative emissions of carbon, assessed by AR5 to fall *likely* between 0.8-2.5°C / 1000 PgC (Collins et al., 2013), considering a normal distribution consistent with AR5 (Stocker et al., 2013). Values are rounded to the nearest 10 GtCO$_2$ in the table and to the nearest 50 GtCO$_2$ in the text.
*(4) Focussing on the impact of various key uncertainties on median budgets for 0.63°C of additional warming.
*(5) Earth system feedbacks include CO$_2$ released by permafrost thawing or methane released by wetlands, see main text.
*(6) Variations due to different scenario assumptions related to the future evolution of non-CO$_2$ emissions.
*(7) The distribution of TCRE is not precisely defined. Here the influence of assuming a log-normal instead of a normal distribution shown.
*(8) Historical emissions uncertainty reflects the uncertainty in historical emissions since 1 January 2011.

2.3 Overview of 1.5°C mitigation pathways

Limiting global mean temperature increase at any level requires global CO_2 emissions to become net zero at some point in the future (Zickfeld et al., 2009; Collins et al., 2013). At the same time, limiting the residual warming of short-lived non-CO_2 emissions, can be achieved by reducing their annual emissions as far as possible (Section 2.2, Cross-Chapter Box 2 in Chapter 1). This will require large-scale transformations of the global energy-agriculture-land-economy system, affecting the way in which energy is produced, agricultural systems are organised, and food, energy and materials are consumed (Clarke et al., 2014). This section assesses key properties of pathways consistent with limiting global mean temperature to 1.5°C relative to pre-industrial levels, including their underlying assumptions and variations.

Since the AR5, an extensive body of literature has appeared on integrated pathways consistent with 1.5°C (Rogelj et al., 2015b; Akimoto et al., 2017; Liu et al., 2017; Löffler et al., 2017; Marcucci et al., 2017; Su et al., 2017; Bauer et al., 2018; Bertram et al., 2018; Grubler et al., 2018; Kriegler et al., 2018b; Luderer et al., 2018; Rogelj et al., 2018; Strefler et al., 2018a; van Vuuren et al., 2018; Vrontisi et al., 2018; Zhang et al., 2018) (Section 2.1). These pathways have global coverage and represent all GHG-emitting sectors and their interactions. Such integrated pathways allow the exploration of the whole-system transformation, and hence provide the context in which the detailed sectorial transformations assessed in Section 2.4 of this chapter are taking place.

The overwhelming majority of published integrated pathways have been developed by global IAMs that represent key societal systems and their interactions, like the energy system, agriculture and land use, and the economy (see Section 6.2 in Clarke et al., 2014). Very often these models also include interactions with a representation of the geophysical system, for example, by including spatially explicit land models or carbon-cycle and climate models. The complex features of these subsystems are approximated and simplified in these models. IAMs are briefly introduced in Section 2.1 and important knowledge gaps identified in Section 2.6. An overview to the use, scope and limitations of IAMs is provided in Annex 2.A.2.

The pathway literature is assessed in two ways in this section. First, various insights on specific questions reported by studies can be assessed to identify robust or divergent findings. Second, the combined body of scenarios can be assessed to identify salient features of pathways in line with a specific climate goal across a wide range of models. The latter can be achieved by assessing pathways available in the database to this assessment (Section 2.1, Annex 2.A.2–4). The ensemble of scenarios available to this assessment is an ensemble of opportunity: it is a collection of scenarios from a diverse set of studies that was not developed with a common set of questions and a statistical analysis of outcomes in mind. This means that ranges can be useful to identify robust and sensitive features across available scenarios and contributing modelling frameworks, but do not lend themselves to a statistical interpretation. To understand the reasons underlying the ranges, an assessment of the underlying scenarios and studies is required. To this end, this section highlights illustrative pathway archetypes that help to clarify the variation in assessed ranges for 1.5°C-consistent pathways.

2.3.1 Range of assumptions underlying 1.5°C pathways

Earlier assessments have highlighted that there is no single pathway to achieve a specific climate objective (e.g., Clarke et al., 2014). Pathways depend on the underlying development processes, and societal choices, which affect the drivers of projected future baseline emissions. Furthermore, societal choices also affect climate change solutions in pathways, like the technologies that are deployed, the scale at which they are deployed, or whether solutions are globally coordinated. A key finding is that 1.5°C-consistent pathways could be identified under a considerable range of assumptions in model studies despite the tightness of the 1.5°C emissions budget (Figures 2.4, 2.5) (Rogelj et al., 2018).

The AR5 provided an overview of how differences in model structure and assumptions can influence the outcome of transformation pathways (Section 6.2 in Clarke et al., 2014, as well as Table A.II.14 in Krey et al., 2014b) and this was further explored by the modelling community in recent years with regard to, e.g., socio-economic drivers (Kriegler et al., 2016; Marangoni et al., 2017; Riahi et al., 2017), technology assumptions (Bosetti et al., 2015; Creutzig et al., 2017; Pietzcker et al., 2017), and behavioural factors (van

Sluisveld et al., 2016; McCollum et al., 2017).

2.3.1.1 Socio-economic drivers and the demand for energy and land in 1.5°C-consistent pathways

There is deep uncertainty about the ways humankind will use energy and land in the 21st century. These ways are intricately linked to future population levels, secular trends in economic growth and income convergence, behavioural change and technological progress. These dimensions have been recently explored in the context of the Shared Socioeconomic Pathways (SSP) (Kriegler et al., 2012; O'Neill et al., 2014) which provide narratives (O'Neill et al., 2017) and quantifications (Crespo Cuaresma, 2017; Dellink et al., 2017; KC and Lutz, 2017; Leimbach et al., 2017; Riahi et al., 2017) of different future worlds in which scenario dimensions are varied to explore differential challenges to adaptation and mitigation (Cross-Chapter Box 1 in Chapter 1). This framework is increasingly adopted by IAMs to systematically explore the impact of socio-economic assumptions on mitigation pathways (Riahi et al., 2017), including 1.5°C-consistent pathways (Rogelj et al., 2018). The narratives describe five worlds (SSP1–5) with different socio-economic predispositions to mitigate and adapt to climate change (Table 2.3). As a result, population and economic growth projections can vary strongly across integrated scenarios, including available 1.5°C-consistent pathways (Fig. 2.4). For example, based on alternative future fertility, mortality, migration and educational assumptions, population projections vary between 8.5-10.0 billion people by 2050, and 6.9–12.6 billion people by 2100 across the SSPs. An important factor for these differences is future female educational attainment, with higher attainment leading to lower fertility rates and therewith decreased population growth up to a level of 1 billion people by 2050 (Lutz and KC, 2011; Snopkowski et al., 2016; KC and Lutz, 2017). Consistent with population development, GDP per capita also varies strongly in SSP baselines varying about 20 to more than 50 thousand USD_{2010} per capita in 2050 (in power purchasing parity values, PPP), in part driven by assumptions on human development, technological progress and development convergence between and within regions (Crespo Cuaresma, 2017; Dellink et al., 2017; Leimbach et al., 2017). Importantly, none of the GDP projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Hsiang et al., 2017).

Baseline projections for energy-related GHG emissions are sensitive to economic growth assumptions, while baseline projections for land-use emissions are more directly affected by population growth (assuming unchanged land productivity and per capita demand for agricultural products) (Kriegler et al., 2016). SSP-based modelling studies of mitigation pathways have identified high challenges to mitigation for worlds with a focus on domestic issues and regional security combined with high population growth (SSP3), and for worlds with rapidly growing resource and fossil-fuel intensive consumption (SSP5) (Riahi et al., 2017). No model could identify a 2°C-consistent pathway for SSP3, and high mitigation costs were found for SSP5. This picture translates to 1.5°C-consistent pathways that have to remain within even tighter emissions constraints (Rogelj et al., 2018). No model found a 1.5°C-consistent pathway for SSP3 and some models could not identify 1.5°C-consistent pathways for SSP5 (2 of 4 models, compared to 1 of 4 models for 2°C-consistent pathways). The modelling analysis also found that the effective control of land-use emissions becomes even more critical in 1.5°C-consistent pathways. Due to high inequality levels in SSP4, land use can be less well managed. This caused 2 of 3 models to no longer find an SSP4-based 1.5°C-consistent pathway even though they identified SSP4-based 2°C-consistent pathways at relatively moderate mitigation costs (Riahi et al., 2017). Rogelj et al. (2018) further reported that all six participating models identified 1.5°C-consistent pathways in a sustainability oriented world (SSP1) and four of six models found 1.5°C-consistent pathways for middle-of-the-road developments (SSP2). These results show that 1.5°C-consistent pathways can be identified under a broad range of assumptions, but that lack of global cooperation (SSP3), high inequality (SSP4) and/or high population growth (SSP3) that limit the ability to control land use emissions, and rapidly growing resource-intensive consumption (SSP5) are key impediments.

Table 2.3: Key characteristics of the five Shared Socio-economic Pathways (O'Neill et al., 2017).

Socio-economic challenges to mitigation	**Socio-economic challenges to adaptation**		
	Low	**Medium**	**High**
High	**SSP5: Fossil-fuelled development** • low population • very high economic growth per capita • high human development • high technological progress • ample fossil fuel resources • resource intensive lifestyles • high energy and food demand per capita • convergence and global cooperation		**SSP3: Regional rivalry** • high population • low economic growth per capita • low human development • low technological progress • resource intensive lifestyles • resource constrained energy and food demand per capita • focus on regional food and energy security • regionalization and lack of global cooperation
Medium		**SSP2: Middle of the road** • medium population • medium and uneven economic growth • medium and uneven human development • medium and uneven technological progress • resource intensive lifestyles • medium and uneven energy and food demand per capita • limited global cooperation and convergence	
Low	**SSP1: Sustainable development** • low population • high economic growth per capita • high human development • high technological progress • environmentally oriented technological and behavioural change • resource efficient lifestyles • low energy and food demand per capita • convergence and global cooperation		**SSP4: Inequality** • Medium to high population • Unequal low to medium economic growth per capita • Unequal low to medium human development • unequal technological progress: high in globalized high tech sectors, slow in domestic sectors • unequal lifestyles and energy / food consumption: resource intensity depending on income • Globally connected elite, disconnected domestic work forces

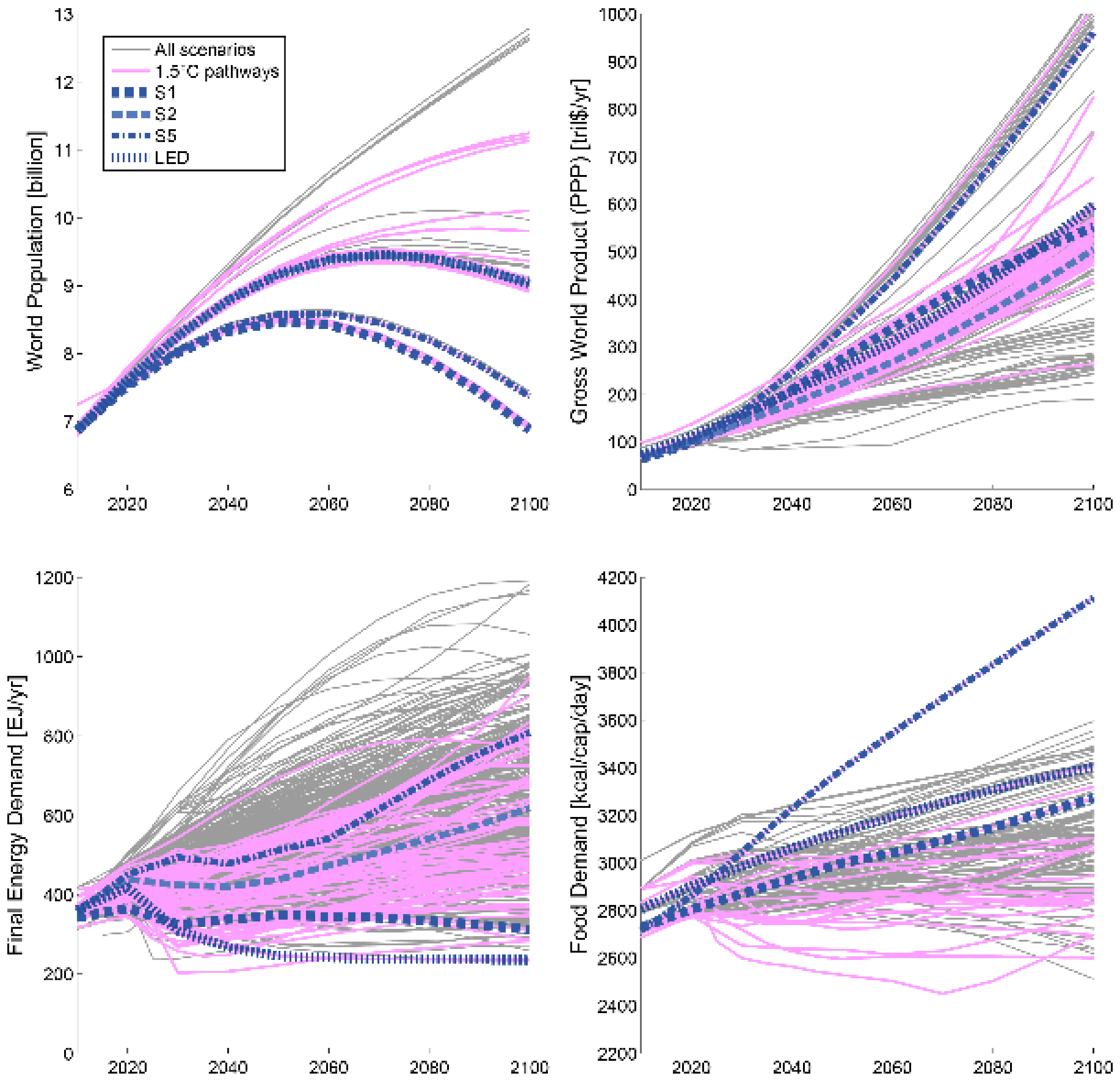

Figure 2.4: Range of assumptions about socio-economic drivers and projections for energy and food demand in the pathways available to this assessment. 1.5°C-consistent pathways are pink, other pathways grey. Trajectories for the illustrative 1.5°C-consistent archetypes used in this Chapter (*S1*, *S2*, *S3*, *LED*) are highlighted. Population assumptions in *S2* and *LED* are identical.

Figure 2.4 compares the range of underlying socio-economic developments as well as energy and food demand in available 1.5°C-consistent pathways with the full set of published scenarios that were submitted to this assessment. While 1.5°C-consistent pathways broadly cover the full range of population and economic growth developments (except of the high population development in SSP3-based scenarios), they tend to cluster on the lower end for energy and food demand. They still encompass, however, a wide range of developments from decreasing to increasing demand levels relative to today. For the purpose of this assessment, a set of four illustrative 1.5°C-consistent pathway archetypes were selected to show the variety of underlying assumptions and characteristics (Fig. 2.4). They comprise three 1.5°C-consistent pathways based on the SSPs (Rogelj et al., 2018): a sustainability oriented scenario (*S1* based on SSP1) developed with the AIM model (Fujimori, 2017), a fossil-fuel intensive and high energy demand scenario (*S5*, based on SSP5) developed with the REMIND-MAgPIE model (Kriegler et al., 2017), and a middle-of-the-road scenario (*S2*, based on SSP2) developed with the MESSAGE-GLOBIOM model (Fricko et al., 2017). In addition, we include a scenario with low energy demand (*LED*) (Grubler et al., 2018), which reflects recent literature with a stronger focus on demand-side measures (Liu et al., 2017; Bertram et al., 2018; Grubler et al., 2018; van Vuuren et al., 2018).

2.3.1.2 Mitigation options in 1.5°C-consistent pathways

In the context of 1.5°C-consistent pathways, the portfolio of mitigation options available to the model becomes an increasingly important factor. IAMs include a wide variety of mitigation options, as well as measures that achieve CDR from the atmosphere (Krey et al., 2014a, 2014b) (see Section 4.3 for a broad assessment of available mitigation measures). For the purpose of this assessment, we elicited technology availability in models that submitted scenarios to the database as summarized in Annex 2.A.2, where a detailed picture of the technology variety underlying available 1.5°C-consistent pathways is provided. Modelling choices on whether a particular mitigation measure is included are influenced by an assessment of its global mitigation potential, the availability of data and literature describing its techno-economic characteristics and future prospects, and computational challenge to represent the measure, e.g., in terms of required spatio-temporal and process detail.

This elicitation (Annex 2.A.2) confirms that IAMs cover most supply-side mitigation options on the process level, while many demand-side options are treated as part of underlying assumptions, which can be varied (Clarke et al., 2014). In recent years, there has been increasing attention on improving the modelling of integrating variable renewable energy into the power system (Creutzig et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017) and of behavioural change and other factors influencing future demand for energy and food (van Sluisveld et al., 2016; McCollum et al., 2017; Weindl et al., 2017), including in the context of 1.5°C-consistent pathways (Grubler et al., 2018; van Vuuren et al., 2018). The literature on the many diverse CDR options only recently started to develop strongly (Minx et al., 2017) (see Section 4.3.7 for a detailed assessment), and hence these options are only partially included in IAM analyses. IAMs mostly incorporate afforestation and bioenergy with carbon capture and storage (BECCS) and only in few cases also include direct air capture with CCS (DACCS) (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b).

Several studies have either directly or indirectly explored the dependence of 1.5°C-consistent pathways on specific (sets of) mitigation and CDR technologies (Liu et al., 2017; Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018b; Rogelj et al., 2018; Strefler et al., 2018b; van Vuuren et al., 2018). However, there are a few potentially disruptive technologies that are typically not yet well covered in IAMs and that have the potential to alter the shape of mitigation pathways beyond the ranges in the IAM-based literature. Those are also included in Annex 2.A.2. The configuration of carbon-neutral energy systems projected in mitigation pathways can vary widely, but they all share a substantial reliance on bioenergy under the assumption of effective land-use emissions control. There are other configurations with less reliance on bioenergy that are not yet comprehensively covered by global mitigation pathway modelling. One approach is to dramatically reduce and electrify energy demand for transportation and manufacturing to levels that make residual non-electric fuel use negligible or replaceable by limited amounts of electrolytic hydrogen. Such an approach is presented in a first-of-its kind low energy demand scenario (Grubler et al., 2018) which is part of this assessment. Other approaches rely less on energy demand reductions, but employ cheap renewable electricity to push the boundaries of electrification in the industry and transport sectors (Breyer et al., 2017; Jacobson, 2017). In addition, these approaches deploy renewable-based Power-2-X (read: Power to “x”) technologies to substitute residual fossil-fuel use (Brynolf et al., 2018). An important element of carbon-neutral Power-2-X applications is the combination of hydrogen generated from renewable electricity and CO_2 captured from the atmosphere (Zeman and Keith, 2008). Alternatively, algae are considered as a bioenergy source with more limited implications for land use and agricultural systems than energy crops (Williams and Laurens, 2010; Walsh et al., 2016; Greene et al., 2017).

Furthermore, a range of measures could radically reduce agricultural and land-use emissions and are not yet well-covered in IAM modelling. This includes plant-based proteins (Joshi and Kumar, 2015) and cultured meat (Post, 2012) with the potential to substitute for livestock products at much lower GHG footprints (Tuomisto and Teixeira de Mattos, 2011). Large-scale use of synthetic or algae-based proteins for animal feed could free pasture land for other uses (Madeira et al., 2017; Pikaar et al., 2018). Novel technologies such as methanogen inhibitors and vaccines (Wedlock et al., 2013; Hristov et al., 2015; Herrero et al., 2016; Subharat et al., 2016) as well as synthetic and biological nitrification inhibitors (Subbarao et al., 2013; Jie Di and Cameron, 2016) could substantially reduce future non-CO_2 emissions from agriculture if commercialised successfully. Enhancing carbon sequestration in soils (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017) can provide the dual benefit of CDR and improved soil quality. A range of conservation, restoration and land management options can also increase terrestrial carbon uptake (Griscom et al., 2017). In addition, the literature discusses CDR measures to permanently sequester atmospheric carbon in rocks (mineralisation and enhanced weathering, see Section 4.3.7) as well as carbon capture and usage in long-lived products like plastics and carbon fibres (Mazzotti et al., 2005; Hartmann et al., 2013). Progress in the understanding of the technical viability, economics, and sustainability of these ways to achieve and maintain carbon neutral energy and land use can affect the characteristics, costs and feasibility of 1.5°C-consistent pathways significantly.

2.3.1.3 Policy assumptions in 1.5°C-consistent pathways

Besides assumptions related to socio-economic drivers and mitigation technology, scenarios are also subject to assumptions about the mitigation policies that can be put in place. Mitigation policies can either be applied immediately in scenarios or follow staged or delayed approaches. Policies can span many sectors (e.g., economy-wide carbon pricing), or policies can be applicable to specific sectors only (like the energy sector) with other sectors (e.g., the agricultural or the land-use sector) treated differently. These variations can have an important impact on the ability of models to generate scenarios compatible with stringent climate targets like 1.5°C (Luderer et al., 2013; Rogelj et al., 2013; Bertram et al., 2015b; Kriegler et al., 2018b; Michaelowa et al., 2018). In the scenario ensemble available to this assessment, several variations of near-term mitigation policy implementation can be found: immediate and cross-sectorial global cooperation from 2020 onward towards a global climate objective, a phase-in of globally coordinated mitigation policy from 2020 to 2040, and a more short-term oriented and regionally diverse global mitigation policy, following NDCs until 2030 (Kriegler et al., 2018b; Luderer et al., 2018; McCollum et al., 2018; Rogelj et al., 2018; Strefler et al., 2018b). For example, above-mentioned SSP quantifications assume regionally scattered mitigation policies until 2020, and vary in global convergence thereafter (Kriegler et al., 2014a; Riahi et al., 2017). The impact of near-term policy choices on 1.5°C-consistent pathways is discussed in Section 2.3.5. The literature has also explored 1.5°C-consistent pathways building on a portfolio of policy approaches until 2030, including the combination of regulatory policies and carbon pricing (Kriegler et al., 2018b) and a variety of ancillary policies to safeguard other sustainable development goals (Bertram et al., 2018; van Vuuren et al., 2018). A further discussion of policy implications of 1.5°C-consistent pathways is provided in Section 2.5.1, while a general discussion of policies and options to strengthen action are subject of Section 4.4.

2.3.2 Key characteristics of 1.5°C-consistent pathways

1.5°C-consistent pathways are characterised by a rapid phase out of CO_2 emissions and deep emissions reductions in other GHGs and climate forcers (Section 2.2.2 and 2.3.3). This is achieved by broad transformations in the energy, industry, transport, buildings, Agriculture, Forestry and Other Land-Use (AFOLU) sectors (Section 2.4) (Liu et al., 2017; Bauer et al., 2018; Grubler et al., 2018; Holz et al., 2018b; Kriegler et al., 2018a; Luderer et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018; Zhang et al., 2018). Here we assess 1.5°C-consistent pathways with and without overshoot during the 21st century. One study also explores pathways overshooting 1.5°C for longer than the 21st century (Akimoto et al., 2017), but these are not considered 1.5°C-consistent pathways in this report (Section 1.1.3). This subsection summarizes robust and varying properties of 1.5°C-consistent pathways regarding system transformations, emission reductions and overshoot. It aims to provide an introduction to the detailed assessment of the emissions evolution (Section 2.3.3), CDR deployment (Section 2.3.4), energy (Section 2.4.1, 2.4.2), industry (2.4.3.1), buildings (2.4.3.2), transport (2.4.3.3) and land-use transformations (Section 2.4.4) in 1.5°C-consistent pathways. Throughout Sections 2.3 and 2.4, pathway properties are highlighted with four 1.5°C-consistent pathway archetypes (*S1*, *S2*, *S5*, *LED*) covering a wide range of different socio-economic and technology assumptions (Fig. 2.5, Section 2.3.1).

2.3.2.1 Variation in system transformations underlying 1.5°C-consistent pathways

Be it for the energy, transport, buildings, industry, or AFOLU sector, the literature shows that multiple options and choices are available in each of these sectors to pursue stringent emissions reductions (Section

2.3.1.2, Annex 2.A.2, Section 4.3). Because the overall emissions total under a pathway is limited by a geophysical carbon budget (Section 2.2.2), choices in one sector affect the efforts that are required from others (Clarke et al., 2014). A robust feature of 1.5°C-consistent pathways, as highlighted by the set of pathway archetypes in Figure 2.5, is a virtually full decarbonisation of the power sector around mid-century, a feature shared with 2°C-consistent pathways. The additional emissions reductions in 1.5°C-consistent compared to 2°C-consistent pathways come predominantly from the transport and industry sectors (Luderer et al., 2018). Emissions can be apportioned differently across sectors, for example, by focussing on reducing the overall amount of CO_2 produced in the energy end use sectors, and using limited contributions of CDR by the AFOLU sector (afforestation and reforestation, *S1* and *LED* pathways in Figure 2.5) (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018), or by being more lenient about the amount of CO_2 that continues to be produced in the above-mentioned end-use sectors (both by 2030 and mid-century) and strongly relying on technological CDR options like BECCS (*S2* and *S5* pathways in Figure 2.5) (Luderer et al., 2018; Rogelj et al., 2018). Major drivers of these differences are assumptions about energy and food demand and the stringency of near term climate policy (see the difference between early action in the scenarios *S1*, *LED* and more moderate action until 2030 in the scenarios *S2*, *S5*). Furthermore, the carbon budget in each of these pathways depends also on the non-CO_2 mitigation measures implemented in each of them, particularly for agricultural emissions (Sections 2.2.2, 2.3.3) (Gernaat et al., 2015). Those pathways differ not only in terms of their deployment of mitigation and CDR measures (Sections 2.3.4 and 2.4), but also in terms of the temperature overshoot they imply (Figure 2.1). Furthermore, they have very different implications for the achievement of sustainable development objectives, as further discussed in Section 2.5.3.

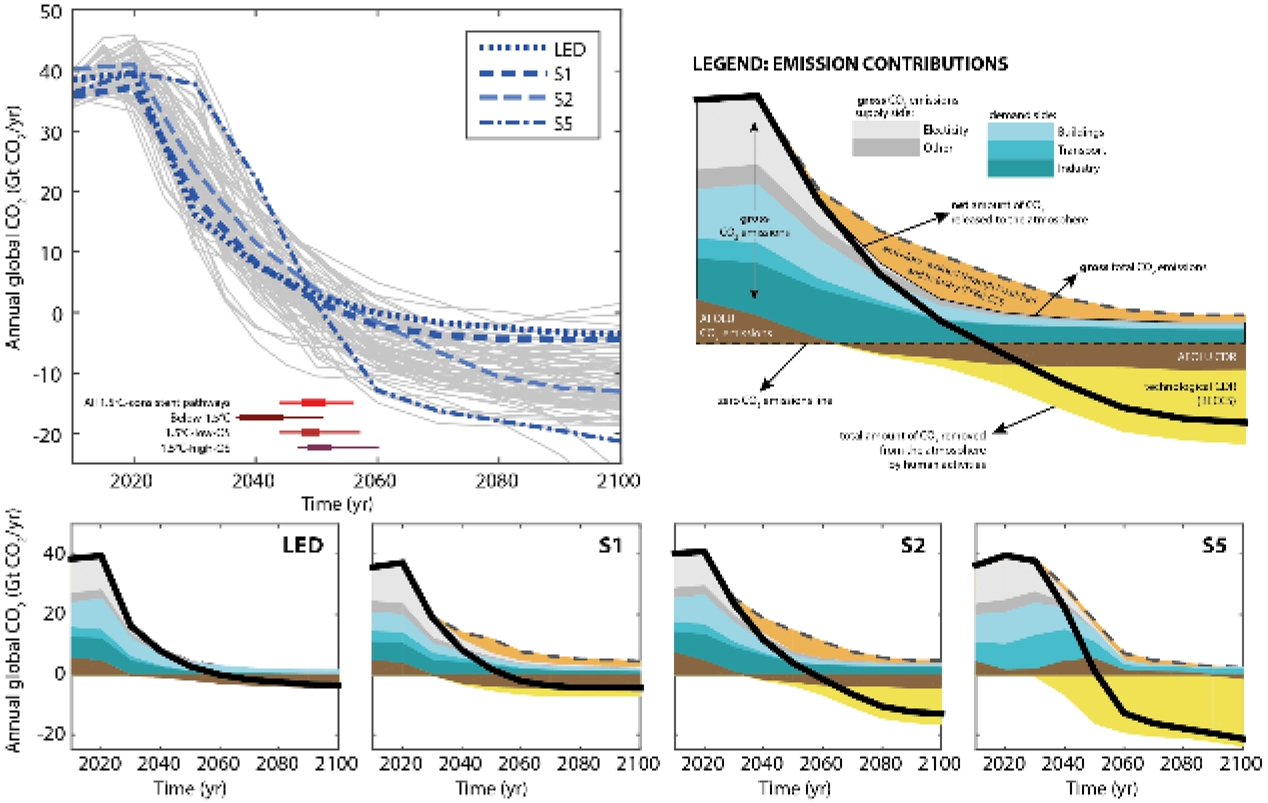

Figure 2.5: **Evolution and break down of global anthropogenic CO_2 emissions until 2100.** The top-left panel shows global net CO_2 emissions in Below-1.5°C, 1.5°C-low-OS, and 1.5°C-high-OS pathways, with the four illustrative 1.5°C-consistent pathway archetypes of this chapter highlighted. Ranges at the bottom of the top-left panel show the 10th–90th percentile range (thin line) and interquartile range (thick line) of the time that global CO_2 emissions reach net zero per pathway class, and for all pathways classes combined. The top-right panel provides a schematic legend explaining all CO_2 emissions contributions to global CO_2 emissions. The bottom row shows how various CO_2 contributions are deployed and used in the four illustrative pathway archetypes (*S1*, *S2*, *S5*, and *LED*) used in this chapter. Note that the S5 scenario reports the building and industry sector emissions jointly. Green-blue areas hence show emissions from the transport, and building & industry demand sectors, respectively.

2.3.2.2 Pathways keeping warming below 1.5°C or temporarily overshooting it

This subsection explores the conditions that would need to be fulfilled to stay below 1.5°C warming without overshoot. As discussed in Section 2.2.2, to keep warming below 1.5°C with a two-in-three (one-in-two) chance, the cumulative amount of CO_2 emissions from 2018 onwards need to remain below a carbon budget of 550 (750) $GtCO_2$, further reduced by 100 $GtCO_2$ when accounting for additional Earth-system feedbacks until 2100. Based on the current state of knowledge, exceeding this remaining carbon budget at some point in time would give a one-in-three (one-in-two) chance that the 1.5°C limit is overshot (Table 2.2). For comparison, around 290 ±20 (1-sigma range) $GtCO_2$ have been emitted in the years 2011-2017 with annual CO_2 emissions in 2017 slightly above 40 $GtCO_2\,yr^{-1}$ (Jackson et al., 2017; Le Quéré et al., 2018). Committed fossil-fuel emissions from existing fossil-fuel infrastructure as of 2010 have been estimated at around 500 ±200 $GtCO_2$ (with ca. 200 $GtCO_2$ already emitted until 2017) (Davis and Caldeira, 2010). Coal-fired power plants contribute the largest part. Committed emissions from existing coal-fired power plants built until the end of 2016 are estimated to add up to roughly 200 $GtCO_2$ and a further 100–150 $GtCO_2$ from coal-fired power plants are under construction or planned (González-Eguino et al., 2017; Edenhofer et al., 2018). However, there has been a marked slowdown of planned coal-power projects in recent years, and some estimates indicate that the committed emissions from coal plants that are under construction or planned have halved since 2015 (Shearer et al., 2018). Despite these uncertainties, the committed fossil-fuel emissions are assessed to already amount to more than half (a third) of the remaining carbon budget.

An important question is to what extent the nationally determined contributions (NDCs) under the Paris Agreement are aligned with the remaining carbon budget. It was estimated that the NDCs, if successfully implemented, imply a total of 400–560 $GtCO_2$ emissions over the 2018–2030 period (considering both conditional and unconditional NDCs) (Rogelj et al., 2016a). Thus, following an NDC trajectory would exhaust already 70–100% (50–75%) of the remaining two-in-three (one-in-two) 1.5°C carbon budget (unadjusted for additional Earth-system feedbacks) by 2030. This would leave only about 0–8 (9–18) years to bring down global emissions from NDC levels of around 40 $GtCO_2\,yr^{-1}$ in 2030 (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero (further discussion in Section 2.3.5).

Most 1.5°C-consistent pathways show more stringent emissions reductions by 2030 than implied by the NDCs (Section 2.3.5) The lower end of those pathways reach down to below 20 $GtCO_2\,yr^{-1}$ in 2030 (Section 2.3.3, Table 2.4), less than half of what is implied by the NDCs. Whether such pathway will be able to limit warming to 1.5°C without overshoot will depend on whether cumulative net CO_2 emissions over the 21st century can be kept below the remaining carbon budget at any time. Net global CO_2 emissions are derived from the gross amount of CO_2 that humans annually emit into the atmosphere reduced by the amount of anthropogenic CDR in each year. New research has looked more closely at the amount and the drivers of gross CO_2 emissions from fossil-fuel combustion and industrial processes (FFI) in deep mitigation pathways (Luderer et al., 2018), and found that the larger part of remaining CO_2 emissions come from direct fossil-fuel use in the transport and industry sectors, while residual energy supply sector emissions (mostly from the power sector) are limited by a rapid approach to net zero CO_2 emissions until mid-century. The 1.5°C-consistent pathways from the literature that were reported in the scenario database project remaining FFI CO_2 emissions of 620–1410 $GtCO_2$ over the period 2018–2100 (5th–95th percentile range; median: 970 $GtCO_2$). Kriegler et al. (2018a) conducted a sensitivity analysis that explores the four central options for reducing fossil-fuel emissions: lowering energy demand, electrifying energy services, decarbonizing the power sector and decarbonizing non-electric fuel use in energy end-use sectors. By exploring these options to their extremes, they found a lowest value of 500 $GtCO_2$ (2018–2100) gross fossil-fuel CO_2 emissions for the hypothetical case of aligning the strongest assumptions for all four mitigation options. The two lines of evidence and the fact that available 1.5°C pathways cover a wide range of assumptions (Section 2.3.1) give a robust indication of a lower limit of ca. 500 $GtCO_2$ remaining fossil-fuel and industry CO_2 emissions in the 21st century.

To compare these numbers with the remaining carbon budget, Land-Use Change (LUC) CO_2 emissions need to be taken into account. In many of the 1.5°C-consistent pathways LUC CO_2 emissions reach zero at or before mid-century and then turn to negative values (Table 2.4). This means human changes to the land lead to atmospheric carbon being stored in plants and soils. This needs to be distinguished from the natural CO_2

uptake by land which is not accounted for in the anthropogenic LUC CO_2 emissions reported in the pathways. Given the difference in estimating the 'anthropogenic' sink between countries and the global integrated assessment and carbon modelling community (Grassi et al., 2017), the LUC CO_2 estimates included here are not necessarily directly comparable with countries' estimates at global level. The cumulated amount of LUC CO_2 emissions until the time they reach zero combine with the fossil-fuel and industry CO_2 emissions to a total amount of gross emissions of 670–1430 $GtCO_2$ for the period 2018–2100 (5th–95th percentile; median 1040 $GtCO_2$). The lower end of the range is similar to what emerges from a scenario of transformative change that halves CO_2 emissions every decade from 2020 to 2050 (Rockström et al., 2017). All these estimates are above the remaining carbon budget for a two-in-three chance of limiting warming below 1.5°C without overshoot, including the low end of the hypothetical sensitivity analysis of Kriegler et al. (2018a), who assumes 75 $GtCO_2$ LUC emissions adding to a total of 575 $GtCO_2$ gross CO_2 emissions. As only limited, highly idealized cases have been identified that keep gross CO_2 emissions within the 1.5°C carbon budget and based on current understanding of the geophysical response and its uncertainties, the available evidence indicates that avoiding overshoot will require some type of CDR in a broad sense, e.g., via negative LUC CO_2 emissions. (*medium confidence*) (Table 2.2).

Net CO_2 emissions can fall below gross CO_2 emissions, if CDR is brought into the mix. Studies have looked at mitigation and CDR in combination to identify strategies for limiting warming to 1.5°C (Sanderson et al., 2016; Ricke et al., 2017). CDR and/or negative LUC CO_2 emissions are deployed by all 1.5°C-consistent pathways available to this assessment, but the scale of deployment and choice of CDR measure varies widely (Section 2.3.4). Furthermore, no CDR technology has been deployed at scale yet, and all come with concerns about their potential (Fuss et al., 2018), feasibility (Nemet et al., 2018) and/or sustainability (Smith et al., 2015; Fuss et al., 2018) (see Sections 2.3.4, 4.3.2 and 4.3.7 and Cross-Chapter Box 7 in Chapter3 for further discussion). CDR can have two very different functions in 1.5°C-consistent pathways. If deployed in the first half of the century, before net zero CO_2 emissions are reached, it neutralizes some of the remaining CO_2 emissions year by year and thus slows the accumulation of CO_2 in the atmosphere. In this first function it can be used to remain within the carbon budget and avoid overshoot. If CDR is deployed in the second half of the century after carbon neutrality has been established, it can still be used to neutralize some residual emissions from other sectors, but also to create net negative emissions that actively draw down the cumulative amount of CO_2 emissions to return below a 1.5°C warming level. In the second function, CDR enables temporary overshoot. The literature points to strong limitations to upscaling CDR (limiting its first abovementioned function) and to sustainability constraints (limiting both abovementioned functions) (Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018). Large uncertainty hence exists about what amount of CDR could actually be available before mid-century. Kriegler et al. (2018a) explore a case limiting CDR to 100 $GtCO_2$ until 2050, and the 1.5°C-consistent pathways available in the report's database project 40–260 $GtCO_2$ CDR until the point of carbon neutrality (5^{th} to 95^{th} percentile; median 120 $GtCO_2$). Because gross CO_2 emissions in most cases exceed the remaining carbon budget by several hundred $GtCO_2$ and given the limits to CDR deployment until 2050, most of the 1.5°C-consistent pathways available to this assessment are overshoot pathways. However, the scenario database also contains nine non-overshoot pathways that remain below 1.5°C throughout the 21st century and that are assessed in the chapter.

2.3.3 Emissions evolution in 1.5°C pathways

This section assesses the salient temporal evolutions of climate forcers over the 21st century. It uses the classification of 1.5°C-consisten pathways presented in Section 2.1, which includes a Below-1.5°C class, as well as other classes with varying levels of projected overshoot (1.5°C-low-OS and 1.5°C-high-OS). First, aggregate-GHG benchmarks for 2030 are assessed. Subsequent sections assess long-lived climate forcers (LLCF) and short-lived climate forcers (SLCF) separately because they contribute in different ways to near-term, peak and long-term warming (Section 2.2, Cross-Chapter Box 2 in Chapter 1).

Estimates of aggregated GHG emissions in line with specific policy choices are often compared to near-term benchmark values from mitigation pathways to explore their consistency with long-term climate goals (Clarke et al., 2014; UNEP, 2016, 2017; UNFCCC, 2016). Benchmark emissions or estimates of peak years derived from IAMs provide guidelines or milestones that are consistent with achieving a given temperature level. While they do not set mitigation requirements in a strict sense, exceeding these levels in a given year almost invariably increases the mitigation challenges afterwards by increasing the rates of change and increasing the reliance on speculative technologies, including the possibility that its implementation becomes unachievable (Luderer et al., 2013; Rogelj et al., 2013b; Clarke et al., 2014; Fawcett et al., 2015; Riahi et al., 2015; Kriegler et al., 2018b) (see Cross-Chapter Box 3 in Chapter 1 for a discussion of feasibility concepts). These trade-offs are particularly pronounced in 1.5°C-consistent pathways and are discussed in Section 2.3.5. This section assesses Kyoto-GHG emissions in 2030 expressed in CO_2 equivalent (CO_2e) emissions using 100-year global warming potentials[3].

Appropriate benchmark values of aggregated GHG emissions depend on a variety of factors. First and foremost, they are determined by the desired likelihood to keep warming below 1.5°C and the extent to which projected temporary overshoot is to be avoided (Sections 2.2, 2.3.2, and 2.3.5). For instance, median aggregated 2030 GHG emissions are about 10 $GtCO_2e\ yr^{-1}$ lower in 1.5°C-low-OS compared to 1.5°C-high-OS pathways, with respective interquartile ranges of 26–31 and 36–49 $GtCO_2e\ yr^{-1}$ (Table 2.4). These ranges correspond to 25–30 and 35–48 $GtCO_2e\ yr^{-1}$ in 2030, respectively, when aggregated with 100-year Global Warming Potentials from the IPCC Second Assessment Report. The limited evidence available for pathways aiming to limit warming below 1.5°C without overshoot or with limited amounts of CDR (Grubler et al., 2018; Holz et al., 2018b; van Vuuren et al., 2018) indicates that under these conditions consistent emissions in 2030 would fall at the lower end and below the abovementioned ranges. Ranges for the 1.5°C-low-OS and Lower-2°C classes only overlap outside their interquartile ranges highlighting the more accelerated reductions in 1.5°C-consistent compared to 2°C-consistent pathways.

Appropriate benchmark values also depend on the acceptable or desired portfolio of mitigation measures, representing clearly identified trade-offs and choices (Sections 2.3.4, 2.4, and 2.5.3) (Luderer et al., 2013; Rogelj et al., 2013a; Clarke et al., 2014; Krey et al., 2014a; Strefler et al., 2018b). For example, lower 2030 GHG emissions correlate with a lower dependence on the future availability and desirability of CDR (Strefler et al., 2018b). Explicit choices or anticipation that CDR options are only deployed to a limited degree during the 21st century imply lower benchmarks over the coming decades that are achieved through lower CO_2 emissions. The pathway archetypes used in the chapter illustrate this further (Figure 2.6). Under middle-of-the-road assumptions of technological and socioeconomic development, pathway *S2* suggests emission benchmarks of 34, 12 and -8 $GtCO_2e\ yr^{-1}$ in the years 2030, 2050, and 2100, respectively. In contrast, a pathway that further limits overshoot and aims at eliminating the reliance on negative emissions technologies like BECCS as well as CCS (here labelled as the *LED* pathway) shows deeper emissions reductions in 2030 to limit the cumulative amount of CO_2 until net zero global CO_2 emissions (carbon neutrality). The *LED* pathway here suggest emission benchmarks of 25, 9 and 2 $GtCO_2e\ yr^{-1}$ in the years 2030, 2050, and 2100, respectively. However, a pathway that allows and plans for the successful large-scale deployment of BECCS by and beyond 2050 (*S5*) shows a shift in the opposite direction. The variation within and between the abovementioned ranges of 2030 GHG benchmarks hence depends strongly on societal choices and preferences related to the acceptability and availability of certain technologies.

Overall these variations do not strongly affect estimates of the 1.5°C-consistent timing of global peaking of GHG emissions. Both Below-1.5°C and 1.5°C-low-OS pathways show minimum-maximum ranges in 2030 that do not overlap with 2020 ranges, indicating the global GHG emissions peaked before 2030 in these pathways. Also 2020 and 2030 GHG emissions in 1.5°C-high-OS pathways only overlap outside their interquartile ranges.

Kyoto-GHG emission reductions are achieved by reductions in CO_2 and non-CO_2 GHGs. The AR5 identified two primary factors that influence the depth and timing of reductions in non-CO_2 Kyoto-GHG emissions: (1) the abatement potential and costs of reducing the emissions of these gases and (2) the strategies that allow making trade-offs between them (Clarke et al., 2014). Many studies indicate low-cost near-term mitigation options in some sectors for non-CO_2 gases compared to supply-side measures for CO_2 mitigation (Clarke et al., 2014). A large share of this potential is hence already exploited in mitigation pathways in line with 2°C. At the same time, by mid-century and beyond, estimates of further reductions of non-CO_2 Kyoto-GHGs, in

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[3] FOOTNOTE: In this chapter GWP-100 values from the IPCC Fourth Assessement Report are used because emissions of fluorinated gases in the integrated pathways have been reported in this metric to the database. At a global scale, switching between GWP-100 values of the Second, Fourth or Fifth IPCC Assessment Reports could result in variations in aggregated Kyoto-GHG emissions of about ±5% in 2030 (UNFCCC, 2016).

particular CH_4 and N_2O, are hampered by the absence of mitigation options in the current generation of IAMs which are hence not able to reduce residual emissions of sources linked to livestock production and fertilizer use (Clarke et al., 2014; Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Annex 2.A.2). Therefore, while net CO_2 emissions are projected to be markedly lower in 1.5°C-consistent compared to 2°C-consistent pathways, this is much less the case for methane (CH_4) and nitrous-oxide (N_2O) (Figures 2.6–2.7). This results in reductions of CO_2 being projected to take up the largest share of emissions reductions when moving between 1.5°C-consistent and 2°C-consistent pathways (Rogelj et al., 2015b, 2018; Luderer et al., 2018). If additional non-CO_2 mitigation measures are identified and adequately included in IAMs, they are expected to further contribute to mitigation efforts by lowering the floor of residual non-CO_2 emissions. However, the magnitude of these potential contributions has not been assessed as part of this report.

The interplay between residual CO_2 and non-CO_2 emissions, as well as CDR results in different times at which global GHG emissions reach net zero levels in 1.5°C-consistent pathways. Interquartile ranges of the years in which 1.5°C-low-OS and 1.5°C-high-OS reach net zero GHG emissions range from 2060 to 2080 (Table 2.4). A seesaw characteristic can be found between near-term emissions reductions and the timing of net zero GHG emissions as a result of the reliance on net negative emissions of pathways with limited emissions reductions in the next one to two decades (see earlier). Most 1.5°C-high-OS pathways lead to net zero GHG emissions in approximately the third quarter of this century, because all of them rely on significant amounts of annual net negative emissions in the second half of the century to decline temperatures after overshoot (Table 2.4). However, emissions in pathways that aim at limiting overshoot as much as possible or more slowly decline temperatures after their peak reach this point slightly later or at times never. Early emissions reductions in this case result in a lower requirement for net negative emissions. Estimates of 2030 GHG emissions in line with the current NDCs overlap with the highest quartile of 1.5°C-high-OS pathways (Cross-Chapter Box 9 in Chapter 4).

2.3.3.1 Emissions of long-lived climate forcers

Climate effects of long-lived climate forcers (LLCFs) are dominated by CO_2, with smaller contributions of N_2O and some fluorinated gases (Myhre et al., 2013; Blanco et al., 2014). Overall net CO_2 emissions in pathways are the result of a combination of various anthropogenic contributions (Figure 2.5) (Clarke et al., 2014): (a) CO_2 produced by fossil-fuel combustion and industrial processes, (b) CO_2 emissions or removals from the Agriculture, Forestry and Other Land Use (AFOLU) sector, (c) CO_2 capture and sequestration (CCS) from fossil fuels or industrial activities before it is released to the atmosphere, (d) CO_2 removal by technological means, which in current pathways is mainly achieved by BECCS although other options could be conceivable (see Section 4.3.7). Pathways apply these four contributions in different configurations (Figure 2.5) depending on societal choices and preferences related to the acceptability and availability of certain technologies, the timing and stringency of near-term climate policy, and the ability to limit the demand that drives baseline emissions (Marangoni et al., 2017; Riahi et al., 2017; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018), and come with very different implication for sustainable development (Section 2.5.3).

All 1.5°C-consistent pathways see global CO_2 emissions embark on a steady decline to reach (near) net zero levels around 2050, with 1.5°C-low-OS pathways reaching net zero CO_2 emissions around 2045–2055 (Table 2.4; Figure 2.5). Near-term differences between the various pathway classes are apparent, however. For instance, Below-1.5°C and 1.5°C-low-OS pathways show a clear shift towards lower CO_2 emissions in 2030 relative to other 1.5°C and 2°C pathway classes, although in all 1.5°C-consistent classes reductions are clear (Figure 2.6). These lower near-term emissions levels are a direct consequence of the former two pathway classes limiting cumulative CO_2 emissions until carbon neutrality to aim for a higher probability that peak warming is limited to 1.5°C (Section 2.2.2 and 2.3.2.2). In some cases, 1.5°C-low-OS pathways achieve net zero CO_2 emissions one or two decades later, contingent on 2030 CO_2 emissions in the lower quartile of the literature range, i.e. below about 18 $GtCO_2\ yr^{-1}$. Median year-2030 global CO_2 emissions are of the order of 5–10 $GtCO_2\ yr^{-1}$ lower in Below-1.5°C compared to 1.5°C-low-OS pathways, which are in turn lower than 1.5°C-high-OS pathways (Table 2.4). 1.5°C-high-OS pathways show broadly similar emissions levels than the 2°C-consistent pathways in 2030.

The development of CO_2 emissions in the second half of the century in 1.5°C pathways is characterised by the need to stay or return within a carbon budget. Figure 2.6 shows net CO_2 and N_2O emissions from various sources in 2050 and 2100 in 1.5°C-consistent pathways in the literature. Virtually all 1.5°C pathways obtain net negative CO_2 emissions at some point during the 21st century but the extent to which net negative emissions are relied upon varies substantially (Figure 2.6, Table 2.4). This net withdrawal of CO_2 from the atmosphere compensates for residual long-lived non-CO_2 GHG emissions that also accumulate in the atmosphere (like N_2O) or to cancel some of the build-up of CO_2 due to earlier emissions to achieve increasingly higher likelihoods that warming stays or returns below 1.5°C (see Section 2.3.4 for a discussion of various uses of CDR). Even non-overshoot pathways that aim at achieving temperature stabilisation would hence deploy a certain amount of net negative emissions to offset any accumulating long-lived non-CO_2 GHGs. 1.5°C overshoot pathways display significantly larger amounts of annual net negative emissions in the second half of the century. The larger the overshoot the more net negative emissions are required to return temperatures to 1.5°C by the end of the century (Table 2.4, Figure 2.1).

N_2O emissions decline to a much lesser extent than CO_2 in currently available 1.5°C-consistent pathways (Figure 2.6). Current IAMs have limited emissions reduction potentials (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Annex 2.A.2), reflecting the difficulty of eliminating N_2O emission from agriculture (Bodirsky et al., 2014). Moreover, the reliance of some pathways on significant amounts of bioenergy after mid-century (Section 2.4.2) coupled to a substantial use of nitrogen fertilizer (Popp et al., 2017) also makes reducing N_2O emissions harder (for example, see pathway *S5* in Figure 2.6). As a result, sizeable residual N_2O emissions are currently projected to continue throughout the century, and measures to effectively mitigate them will be of continued relevance for 1.5°C societies. Finally, the reduction of nitrogen use and N_2O emissions from agriculture is already a present-day concern due to unsustainable levels of nitrogen pollution (Bodirsky et al., 2012). Section 2.4.4 provides a further assessment of the agricultural non-CO_2 emissions reduction potential.

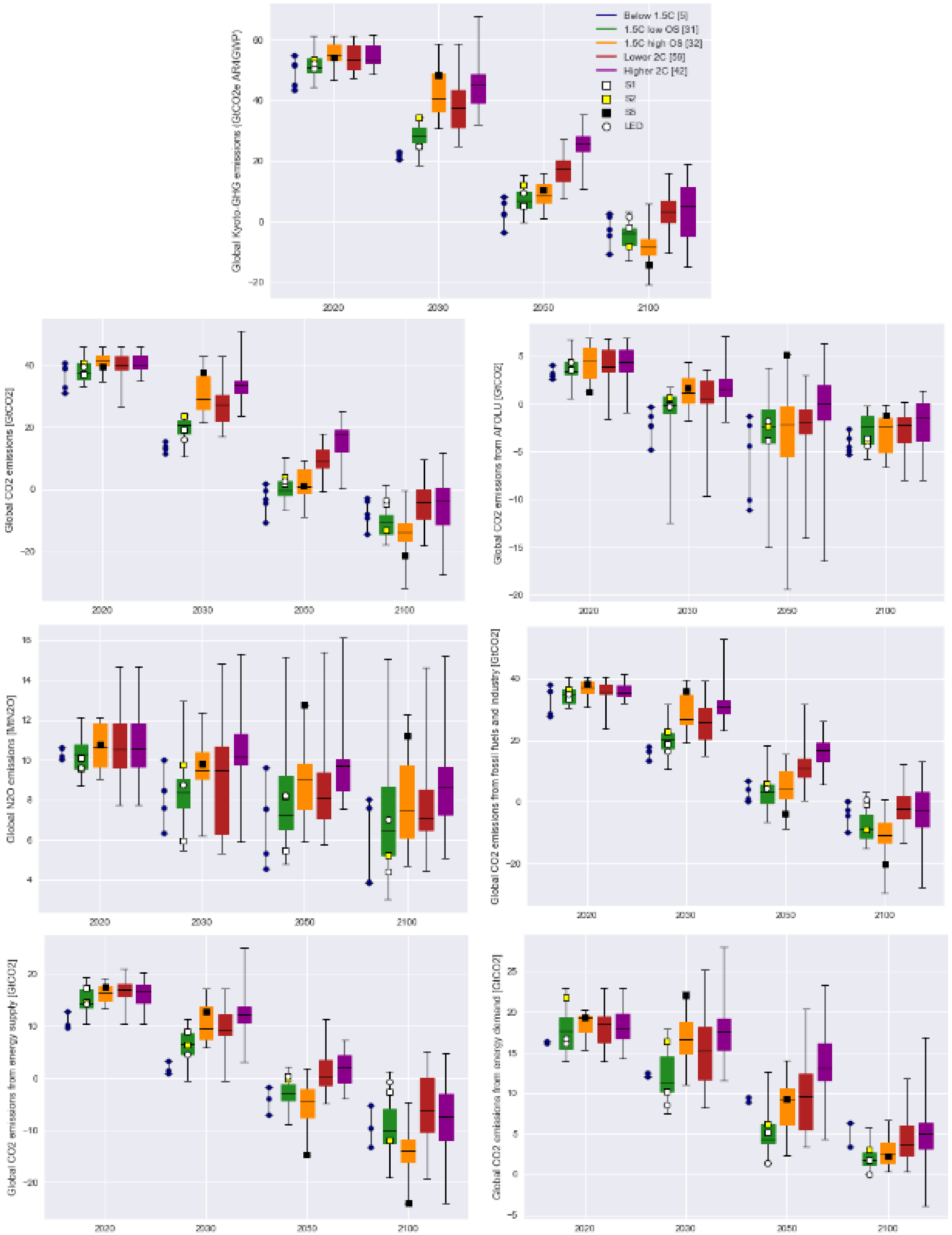

Figure 2.6: **Annual global emissions characteristics for 2020, 2030, 2050, 2100.** Data are shown for Kyoto-GHG emissions (top panel), and total CO_2 emissions, CO_2 emissions from the AFOLU sector, global N_2O emissions, and CO_2 emissions from fossil-fuel use and industrial processes. The latter is also split into emissions from the energy supply sector (electricity sector and refineries), and direct emissions from fossil-fuel use in energy demand sectors (industry, buildings, transport) (bottom row). Horizontal black lines show the median, boxes show the interquartile range, and whiskers the minimum-maximum range. Icons indicate the four pathway archetypes used in this chapter. In case less than 7 data points are available in a class, the minimum-maximum range and single data points are shown. Kyoto-GHG, emissions in the top panel are aggregated with AR4 GWP-100 and contain CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. NF_3 is typically not reported by IAMs. Scenarios with year-2010 Kyoto-GHG emissions outside

the range assessed by IPCC AR5 WGIII assessed are excluded (IPCC, 2014b)..

2.3.3.2 Emissions of short-lived climate forcers and fluorinated gases

SLCFs include shorter-lived GHGs like CH_4 and some HFCs, as well as particles (aerosols), their precursors and ozone precursors. SLCFs are strongly mitigated in 1.5°C pathways as is the case for 2°C pathways (Figure 2.7). SLCF emissions ranges of 1.5°C and 2°C pathway classes strongly overlap, indicating that the main incremental mitigation contribution between 1.5°C and 2°C pathways comes from CO_2 (Luderer et al., 2018; Rogelj et al., 2018). CO_2 and SLCF emissions reductions are connected in situations where SLCF and CO_2 are co-emitted by the same process, for example, with coal-fired power plants (Shindell and Faluvegi, 2010) or within the transport sector (Fuglestvedt et al., 2010). Many CO_2-targeted mitigation measures in industry, transport and agriculture (Sections 2.4.3–4) hence also reduce non-CO_2 forcing (Rogelj et al., 2014b; Shindell et al., 2016).

Despite having a strong warming effect (Myhre et al., 2013; Etminan et al., 2016), current 1.5°C-consistent pathways still project significant emissions of CH_4 by 2050, indicating that only limited mitigation options are included and identified in IAM analyses (Gernaat et al., 2015) (Sections 2.3.1.2, 2.4.4, Table 2.A.2). The AFOLU sector contributes an important share of the residual CH_4 emissions until mid-century, with its relative share increasing from slightly below 50% in 2010 to roughly around 55–70% in 2030, and 60–80% in 2050 in 1.5°C-consistent pathways (interquartile range across 1.5°C-consistent pathways for projections). Many of the proposed measures to target CH_4 (Shindell et al., 2012; Stohl et al., 2015) are included in 1.5°C-consistent pathways (Figure 2.7), though not all (Sections 2.3.1.2, 2.4.4, Table 2.A.2). A detailed assessment of measures to further reduce AFOLU CH_4 emissions has not been conducted.

Overall reductions of SLCFs can have effects of either sign on temperature depending on the balance between cooling and warming agents. The reduction in SO_2 emissions is the dominant single effect as it weakens the negative total aerosol forcing. This means that reducing all SLCF emissions to zero would result in a short-term warming, although this warming is unlikely to be more than 0.5°C (Section 2.2 and Figure 1.5 (Samset et al., 2018)). Because of this effect, suggestions have been proposed that target the warming agents only (referred to as short-lived climate pollutants or SLCPs instead of the more general short-lived climate forcers; e.g., Shindell et al., 2012) though aerosols are often emitted in varying mixtures of warming and cooling species (Bond et al., 2013). Black Carbon (BC) emissions reach similar levels across 1.5°C-consistent and 2°C-consistent pathways available in the literature, with interquartile ranges of emissions reductions across pathways of 16–34% and 48–58% in 2030 and 2050, respectively, relative to 2010 (Figure 2.7). Recent studies have identified further reduction potentials for the near term, with global reductions of about 80% being suggested (Stohl et al., 2015; Klimont et al., 2017). Because the dominant sources of certain aerosol mixtures are emitted during the combustion of fossil fuels, the rapid phase-out of unabated fossil-fuels to avoid CO_2 emissions would also result in removal of these either warming or cooling SLCF air-pollutant species. Furthermore, they are also reduced by efforts to reduce particulate air pollution. For example, year-2050 SO_2 emissions, precursor of sulphate aerosol, in 1.5°C-consistent pathways are about 75–85% lower than their 2010 levels. Some caveats apply, for example, if residential biomass use would be encouraged in industrialised countries in stringent mitigation pathways without appropriate pollution control measures, aerosol concentrations could also increase (Sand et al., 2015; Stohl et al., 2015).

Table 2.4: Emissions in 2030, 2050 and 2100 in 1.5°C and 2°C scenario classes and absolute annual rates of change between 2010–2030, 2020–2030 and 2030–2050, respectively. Values show: median (25th and 75th percentile), across available scenarios. If less than seven scenarios are available (*), the minimum-maximum range is given instead. For the timing of global zero of total net CO_2 and Kyoto-GHG emissions, the interquartile range is given. Kyoto-GHG emissions are aggregated with GWP-100 values from IPCC AR4. 2010 emissions for total net CO_2, CO_2 from fossil-fuel use & industry, and AFOLU CO_2 are estimated at 38.5, 33.4, and 5 $GtCO_2$/yr, respectively (Le Quéré et al., 2018). A difference is reported in estimating the "anthropogenic" sink by countries or the global carbon modelling community (Grassi et al., 2017), and AFOLU CO_2 estimates reported here are thus not necessarily comparable with countries' estimates. Scenarios with year-2010 Kyoto-GHG emissions outside the range assessed by IPCC AR5 WGIII are excluded (IPCC, 2014b).

	type					Absolute annual change (GtCO2/yr)			Timing of global zero
name	category	count	2030	2050	2100	2010-2030	2020-2030	2030-2050	year
Total CO_2 (net)	Below-1.5°C	5	13 (11 15)	-3 (-11 2)	-8 (-14 -3)	-1.2 (-1.3 -1.0)	-2.5 (-2.8 -1.8)	-0.8 (-1.2 -0.7)	(2037 2054)
	1.5°C-low-OS	37	21 (18 22)	0 (-2 3)	-11 (-14 -8)	-0.8 (-1 -0.7)	-1.7 (-2.3 -1.4)	-1 (-1.2 -0.8)	(2047 2055)
	1.5°C-high-OS	36	29 (26 36)	1 (-1 6)	-14 (-16 -11)	-0.4 (-0.6 0)	-1.1 (-1.5 -0.5)	-1.3 (-1.8 -1.1)	(2049 2059)
	Lower-2°C	67	27 (22 30)	9 (7 13)	-4 (-9 0)	-0.5 (-0.7 -0.3)	-1.2 (-1.9 -0.9)	-0.8 (-1 -0.6)	(2065 2096)
	Higher-2°C	54	33 (31 35)	18 (12 19)	-3 (-11 1)	-0.2 (-0.4 0)	-0.7 (-0.9 -0.5)	-0.8 (-1 -0.6)	(2070 post-2100)
CO_2 from fossil fuels and industry (gross)	Below-1.5°C	5	18 (14 21)	10 (0 21)	8 (0 12)	-0.7 (-1.0 -0.6)	-1.5 (-2.2 -0.9)	-0.4 (-0.7 -0.0)	-
	1.5°C-low-OS	37	22 (19 24)	10 (8 14)	6 (3 8)	-0.5 (-0.6 -0.4)	-1.3 (-1.7 -0.9)	-0.6 (-0.7 -0.5)	-
	1.5°C-high-OS	36	28 (26 37)	13 (12 17)	7 (3 9)	-0.2 (-0.3 0.2)	-0.8 (-1.1 -0.2)	-0.7 (-1 -0.6)	-
	Lower-2°C	67	26 (21 31)	14 (11 18)	8 (4 10)	-0.3 (-0.6 -0.1)	-0.9 (-1.4 -0.6)	-0.6 (-0.7 -0.4)	-
	Higher-2°C	54	31 (29 33)	19 (17 23)	8 (5 11)	-0.1 (-0.2 0.1)	-0.5 (-0.7 -0.2)	-0.6 (-0.7 -0.5)	-
CO_2 from fossil fuels and industry (net)	Below-1.5°C	5	16 (13 18)	1 (0 7)	-3 (-10 0)	-0.8 (-1.0 -0.7)	-1.8 (-2.2 -1.2)	-0.6 (-0.9 -0.5)	-
	1.5°C-low-OS	37	21 (18 22)	3 (-1 6)	-9 (-12 -4)	-0.6 (-0.7 -0.5)	-1.4 (-1.8 -1.1)	-0.8 (-1.1 -0.7)	-
	1.5°C-high-OS	36	27 (25 35)	4 (1 10)	-11 (-13 -7)	-0.3 (-0.3 0.1)	-0.9 (-1.2 -0.3)	-1.2 (-1.5 -0.9)	-
	Lower-2°C	67	26 (21 30)	11 (8 14)	-2 (-5 2)	-0.3 (-0.6 -0.1)	-1 (-1.4 -0.6)	-0.7 (-1 -0.4)	-
	Higher-2°C	54	31 (29 33)	17 (13 19)	-3 (-8 3)	-0.1 (-0.2 0.1)	-0.5 (-0.7 -0.2)	-0.7 (-1 -0.5)	-
CO_2 from AFOLU	Below-1.5°C	5	-2 (-5 0)	-4 (-11 -1)	-4 (-5 -3)	-0.3 (-0.4 -0.2)	-0.5 (-0.8 -0.4)	-0.1 (-0.4 0)	-
	1.5°C-low-OS	37	0 (-1 1)	-2 (-4 -1)	-2 (-4 -1)	-0.2 (-0.3 -0.2)	-0.4 (-0.5 -0.3)	-0.1 (-0.2 -0.1)	-
	1.5°C-high-OS	36	1 (0 3)	-2 (-5 0)	-2 (-5 -1)	-0.1 (-0.3 -0.1)	-0.2 (-0.5 -0.1)	-0.2 (-0.3 0)	-
	Lower-2°C	67	1 (0 2)	-2 (-3 -1)	-2 (-4 -1)	-0.2 (-0.3 -0.1)	-0.3 (-0.4 -0.2)	-0.2 (-0.2 -0.1)	-
	Higher-2°C	54	2 (1 3)	0 (-2 2)	-1 (-4 0)	-0.2 (-0.2 -0.1)	-0.2 (-0.4 -0.1)	-0.1 (-0.1 0)	-
Bioenergy combined with carbon capture and storage (BECCS)	Below-1.5°C	5	0 (-1 0)	-3 (-8 0)	-6 (-13 0)	0 (-0.1 0)	0 (-0.1 0)	-0.2 (-0.4 0)	-
	1.5°C-low-OS	37	0 (-1 0)	-5 (-6 -4)	-12 (-16 -7)	0 (-0.1 0)	0 (-0.1 0)	-0.2 (-0.3 -0.2)	-
	1.5°C-high-OS	36	0 (0 0)	-7 (-9 -4)	-15 (-16 -12)	0 (0 0)	0 (0 0)	-0.3 (-0.4 -0.2)	-
	Lower-2°C	54	0 (0 0)	-4 (-5 -2)	-10 (-12 -7)	0 (0 0)	0 (0 0)	-0.2 (-0.2 -0.1)	-
	Higher-2°C	47	0 (0 0)	-3 (-5 -2)	-11 (-15 -8)	0 (0 0)	0 (0 0)	-0.1 (-0.2 -0.1)	-
Kyoto GHG (AR4) [$GtCO_2e$]	Below-1.5°C	5	22 (21 23)	3 (-3 8)	-3 (-11 3)	-1.4 (-1.5 -1.3)	-2.9 (-3.3 -2.1)	-0.9 (-1.3 -0.7)	(2044 post-2100)
	1.5°C-low-OS	31	28 (26 31)	7 (5 10)	-4 (-8 -2)	-1.1 (-1.2 -0.9)	-2.3 (-2.8 -1.8)	-1.1 (-1.2 -0.9)	(2061 2080)
	1.5°C-high-OS	32	40 (36 49)	8 (6 12)	-9 (-11 -6)	-0.5 (-0.7 0)	-1.3 (-1.8 -0.6)	-1.5 (-2.1 -1.3)	(2058 2067)
	Lower-2°C	59	38 (31 43)	17 (14 20)	3 (0 7)	-0.6 (-1 -0.3)	-1.8 (-2.4 -1.1)	-1 (-1.1 -0.6)	(2099 post-2100)
	Higher-2°C	42	45 (39 49)	26 (23 28)	5 (-5 11)	-0.2 (-0.6 0)	-1 (-1.2 -0.6)	-1 (-1.2 -0.7)	(2085 post-2100)

Emissions of fluorinated gases (IPCC/TEAP, 2005; US EPA, 2013; Velders et al., 2015; Purohit and Höglund-Isaksson, 2017) in 1.5°C-consistent pathways are reduced by roughly 75–80% relative to 2010 levels (interquartile range across 1.5°C-consistent pathways) in 2050, with no clear differences between the classes. Although unabated HFC evolutions have been projected to increase (Velders et al., 2015), the Kigali Amendment recently added HFCs to the basket of gases controlled under the Montreal Protocol (Höglund-Isaksson et al., 2017). As part of the larger group of fluorinated gases, HFCs are also assumed to decline in 1.5°C-consistent pathways. Projected reductions by 2050 of fluorinated gases under 1.5°C-consistent pathways are deeper than published estimates of what a full implementation of the Montreal Protocol's Kigali Amendment would achieve (Höglund-Isaksson et al., 2017), which project roughly a halving of fluorinated gas emissions in 2050 compared to 2010. Assuming the application of technologies that are currently commercially available and at least to a limited extent already tested and implemented, potential fluorinated gas emissions reductions of more than 90% have been estimated (Höglund-Isaksson et al., 2017).

There is a general agreement across 1.5°C-consistent pathways that until 2030 forcing from the warming SLCFs is reduced less strongly than the net cooling forcing from aerosol effects, compared to 2010. As a result, the net forcing contributions from all SLCFs combined are projected to increase slightly by about 0.2–0.4 W/m^2, compared to 2010. Also, by the end of the century, about 0.1–0.3 W/m^2 of SLCF forcing is generally currently projected to remain in 1.5°C-consistent scenarios (Figure 2.8). This is similar to developments in 2°C-consistent pathways (Rose et al., 2014b; Riahi et al., 2017) which show median forcing contributions from these forcing agents that are generally no more than 0.1 W/m^2 higher. Nevertheless, there can be additional gains from targeted deeper reductions of CH_4 emissions and tropospheric ozone precursors, with some scenarios projecting less than 0.1 W/m^2 forcing from SLCFs by 2100.

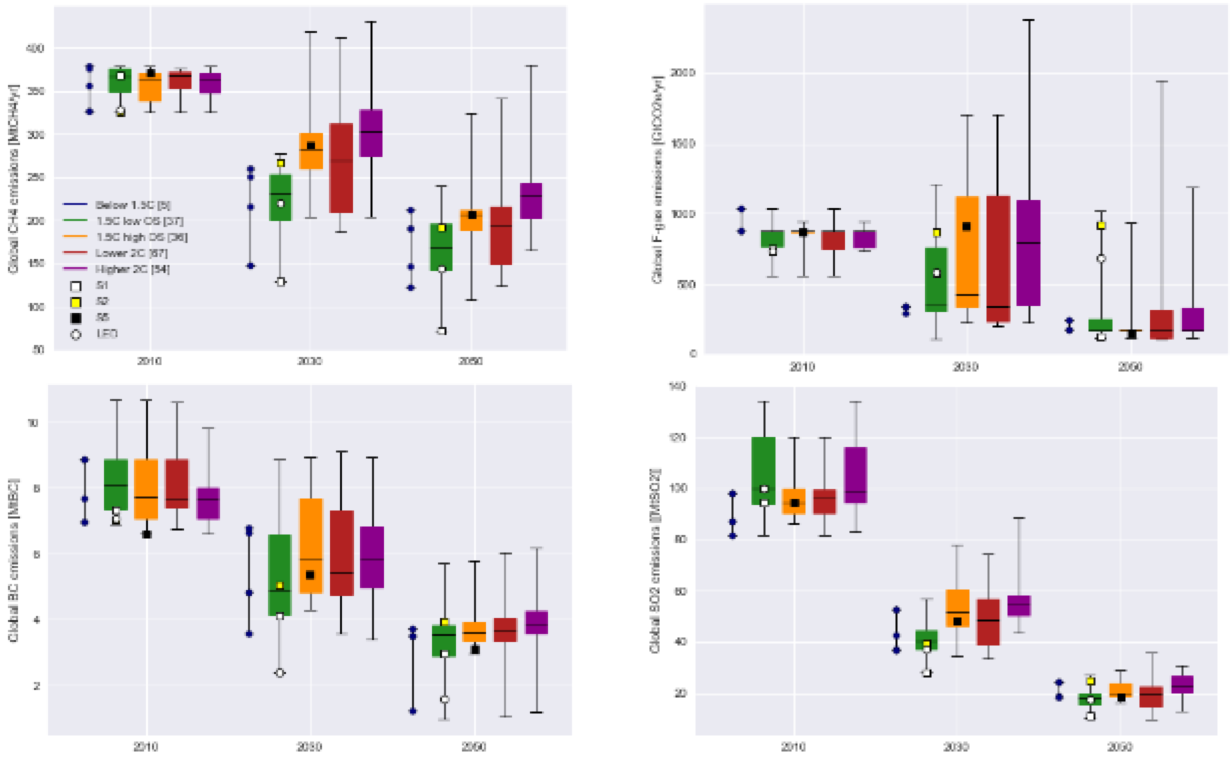

Figure 2.7: **Global characteristics of a selection of short-lived non-CO_2 emissions until mid-century for five pathway classes used in this chapter.** Data are shown for methane (CH_4), fluorinated gases (F-gas), black carbon (BC), and sulphur dioxide (SO_2) emissions. Boxes with different colours refer to different scenario classes. Icons on top the ranges show four illustrative pathway archetypes that apply different mitigation strategies for limiting warming to 1.5°C. Boxes show the interquartile range, horizontal black lines the median, while whiskers the minimum-maximum range. F-gases are expressed in units of CO_2-equivalence computed with 100-year Global Warming Potentials reported in IPCC AR4.

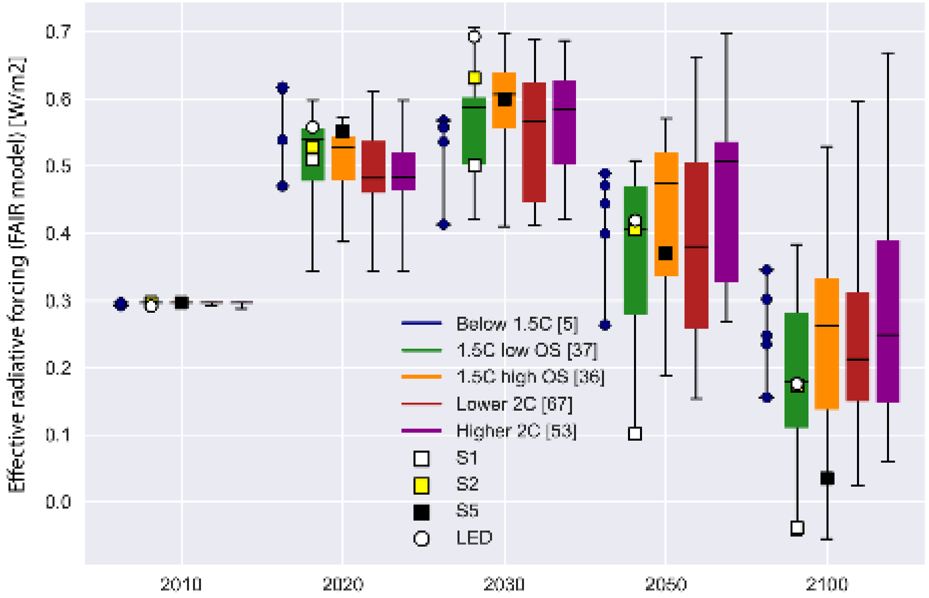

Figure 2.8: Estimated aggregated effective radiative forcing of SLCFs for 1.5°C and 2°C pathway classes in 2010, 2030, 2050, and 2100, as estimated by the FAIR model (Smith et al., 2018). Aggregated SLCF radiative forcing is estimated as the difference between total anthropogenic radiative forcing the sum of CO_2 and N_2O radiative forcing over time and expressed relative to 1750. Symbols indicate the four pathways archetype used in this chapter. Horizontal black lines indicate the median, boxes the interquartile range, and whiskers the minimum-maximum range per pathway class. Due to very few pathways falling into the Below-1.5°C class, only the minimum-maximum is provided here.

2.3.4 CDR in 1.5°C-consistent pathways

Deep mitigation pathways assessed in AR5 showed significant deployment of CDR, in particular through BECCS (Clarke et al., 2014). This has led to increased debate about the necessity, feasibility and desirability of large-scale CDR deployment, sometimes also called 'negative emissions technologies' in the literature (Fuss et al., 2014; Anderson and Peters, 2016; Williamson, 2016; van Vuuren et al., 2017a; Obersteiner et al., 2018). Most CDR technologies remain largely unproven to date and raise substantial concerns about adverse side-effects on environmental and social sustainability (Smith et al., 2015; Dooley and Kartha, 2018). A set of key questions emerge: how strongly do 1.5°C-consistent pathways rely on CDR deployment and what types of CDR measures are deployed at which scale? How does this vary across available 1.5°C-consistent pathways and on which factors does it depend? How does CDR deployment compare between 1.5°C and 2°C-consistent pathways and how does it compare with the findings at the time of the AR5? How does CDR deployment in 1.5°C-consistent pathways relate to questions about availability, policy implementation, and sustainable development implications that have been raised about CDR technologies? The first three questions are assessed in this section with the goal to provide an overview and assessment of CDR deployment in the 1.5°C-consistent pathway literature. The fourth question is only touched upon here and is addressed in greater depth in Section 4.3.7, which assesses the rapidly growing literature on costs, potentials, availability, and sustainability implications of individual CDR measures (Minx et al., 2017, 2018; Fuss et al., 2018; Nemet et al., 2018). In addition, Section 2.3.5 assesses the relationship between delayed mitigation action and increased CDR reliance. CDR deployment is intricately linked to the land-use transformation in 1.5°C-consistent pathways. This transformation is assessed in Section 2.4.4. Bioenergy and BECCS impacts on sustainable land management are further assessed in Section 3.6.2 and Cross-Chapter Box 7 in Chapter 3. Ultimately, a comprehensive assessment of the land implication of land-based CDR measures will be provided in the IPCC AR6 Special Report on Climate Change and Land (SRCCL).

2.3.4.1 CDR technologies and deployment levels in 1.5°C-consistent pathways

A number of approaches to actively remove carbon-dioxide from the atmosphere are increasingly discussed in the literature (Minx et al., 2018) (see also Section 4.3.7). Approaches under consideration include the enhancement of terrestrial and coastal carbon storage in plants and soils such as afforestation and reforestation (Canadell and Raupach, 2008), soil carbon enhancement (Paustian et al., 2016; Frank et al., 2017; Zomer et al., 2017), and other conservation, restoration, and management options for natural and managed land (Griscom et al., 2017) and coastal ecosystems (McLeod et al., 2011). Biochar sequestration (Woolf et al., 2010; Smith, 2016; Werner et al., 2018) provides an additional route for terrestrial carbon storage. Other approaches are concerned with storing atmospheric carbon dioxide in geological formations. They include the combination of biomass use for energy production with carbon capture and storage (BECCS) (Obersteiner et al., 2001; Keith and Rhodes, 2002; Gough and Upham, 2011) and direct air capture with storage (DACCS) using chemical solvents and sorbents (Zeman and Lackner, 2004; Keith et al., 2006; Socolow et al., 2011). Further approaches investigate the mineralisation of atmospheric carbon dioxide (Mazzotti et al., 2005; Matter et al., 2016) including enhanced weathering of rocks (Schuiling and Krijgsman, 2006; Hartmann et al., 2013; Strefler et al., 2018a). A fourth group of approaches is concerned with the sequestration of carbon dioxide in the oceans, for example by means of ocean alkalinisation (Kheshgi, 1995; Rau, 2011; Ilyina et al., 2013; Lenton et al., 2018). The costs, CDR potential and environmental side effects of several of these measures are increasingly investigated and compared in the literature, but large uncertainties remain, in particular concerning the feasibility and impact of large-scale deployment of CDR measures (The Royal Society, 2009; Smith et al., 2015; Psarras et al., 2017; Fuss et al., 2018) (see Chapter 4.3.7). There are also proposals to remove methane, nitrous oxide and halocarbons via photocatalysis from the atmosphere (Boucher and Folberth, 2010; de Richter et al., 2017), but a broader assessment of their effectiveness, cost, and sustainability impacts is lacking to date.

Only some of these approaches have so far been considered in IAMs (see Section 2.3.1.2). The mitigation scenario literature up to AR5 mostly included BECCS and to a more limited extent afforestation and reforestation (Clarke et al., 2014). Since then, some 2°C and 1.5°C-consistent pathways including additional CDR measures such as DACCS (Chen and Tavoni, 2013; Marcucci et al., 2017; Lehtilä and Koljonen, 2018; Strefler et al., 2018b) and soil carbon sequestration (Frank et al., 2017) have become available. Other, more speculative approaches, in particular ocean-based CDR and removal of non-CO_2 gases, have not yet been taken up by the literature on mitigation pathways. See Annex 2.A.2 for an overview on the coverage of CDR measures in models which contributed pathways to this assessment. Chapter 4.3.7 assesses the potential, costs, and sustainability implications of the full range of CDR measures.

Integrated assessment modelling has not yet explored land conservation, restoration and management options to remove carbon dioxide from the atmosphere in sufficient depth, despite land management having a potentially considerable impact on the terrestrial carbon stock (Erb et al., 2018). Moreover, associated CDR measures have low technological requirements, and come with potential environmental and social co-benefits (Griscom et al., 2017). Despite the evolving capabilities of IAMs in accounting for a wider range of CDR measures, 1.5°C-consistent pathways assessed here continue to predominantly rely on BECCS and afforestation / reforestation (See Annex 2.A.2). However, IAMs with spatially explicit land-use modelling include a full accounting of land-use change emissions comprising carbon stored in the terrestrial biosphere and soils. Net CDR in the AFOLU sector, including but not restricted to afforestation and reforestation, can thus in principle be inferred by comparing AFOLU CO_2 emissions between a baseline scenario and a 1.5°C-consistent pathway from the same model and study. However, baseline LUC emissions cannot only be reduced by CDR in the AFOLU sector, but also by measures to reduce deforestation and preserve land carbon stocks. The pathway literature and pathway data available to this assessment do not yet allow to separate the two contributions. As a conservative approximation, the additional net negative AFOLU CO_2 emissions below the baseline are taken as a proxy for AFOLU CDR in this assessment. Because this does not include CDR that was deployed before reaching net zero AFOLU emissions, this approximation is a lower-bound for terrestrial CDR in the AFOLU sector (including the factors that lead to net negative LUC emissions).

The scale and type of CDR deployment in 1.5°C-consistent pathways varies widely (Figure 2.9 and 2.10). Overall CDR deployment over the 21st century is substantial in most of the pathways, and deployment levels cover a wide range (770 [260-1170] $GtCO_2$, for median and 5th–95th percentile range). Both BECCS (560 [0 to 1000] $GtCO_2$) and AFOLU CDR measures including afforestation and reforestation (200 [0-550] $GtCO_2$)

can play a major role[4], but for both cases pathways exist where they play no role at all. This shows the flexibility in substituting between individual CDR measures, once a portfolio of options becomes available. The high end of the CDR deployment range is populated by high overshoot pathways, as illustrated by pathway archetype S5 based on SSP5 (fossil-fuelled development, see Section 2.3.1.1) and characterized by very large BECCS deployment to return warming to 1.5°C by 2100 (Kriegler et al., 2017). In contrast, the low end is populated with pathways with no or limited overshoot that limit CDR to in the order of 100–200 $GtCO_2$ over the 21st century coming entirely from terrestrial CDR measures with no or small use of BECCS. These are pathways with very low energy demand facilitating the rapid phase-out of fossil fuels and process emissions that exclude BECCS and CCS use (Grubler et al., 2018) and/or pathways with rapid shifts to sustainable food consumption freeing up sufficient land areas for afforestation and reforestation (Haberl et al., 2011; van Vuuren et al., 2018). Some pathways uses neither BECCS nor afforestation but still rely on CDR through considerable net negative emissions in the AFOLU sector around mid-century (Holz et al., 2018b). We conclude that the role of BECCS as dominant CDR measure in deep mitigation pathways has been reduced since the time of the AR5. This is related to three factors: a larger variation of underlying assumptions about socio-economic drivers (Riahi et al., 2017; Rogelj et al., 2018) and associated energy (Grubler et al., 2018) and food demand (van Vuuren et al., 2018); the incorporation of a larger portfolio of mitigation and CDR options (Liu et al., 2017; Marcucci et al., 2017; Grubler et al., 2018; Lehtilä and Koljonen, 2018; van Vuuren et al., 2018); and targeted analysis of deployment limits for (specific) CDR measures (Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b) including on the availability of bioenergy (Bauer et al., 2018), CCS (Krey et al., 2014a; Grubler et al., 2018) and afforestation (Popp et al., 2014b, 2017). As additional CDR measures are being built into IAMs, the prevalence of BECCS is expected to be further reduced.

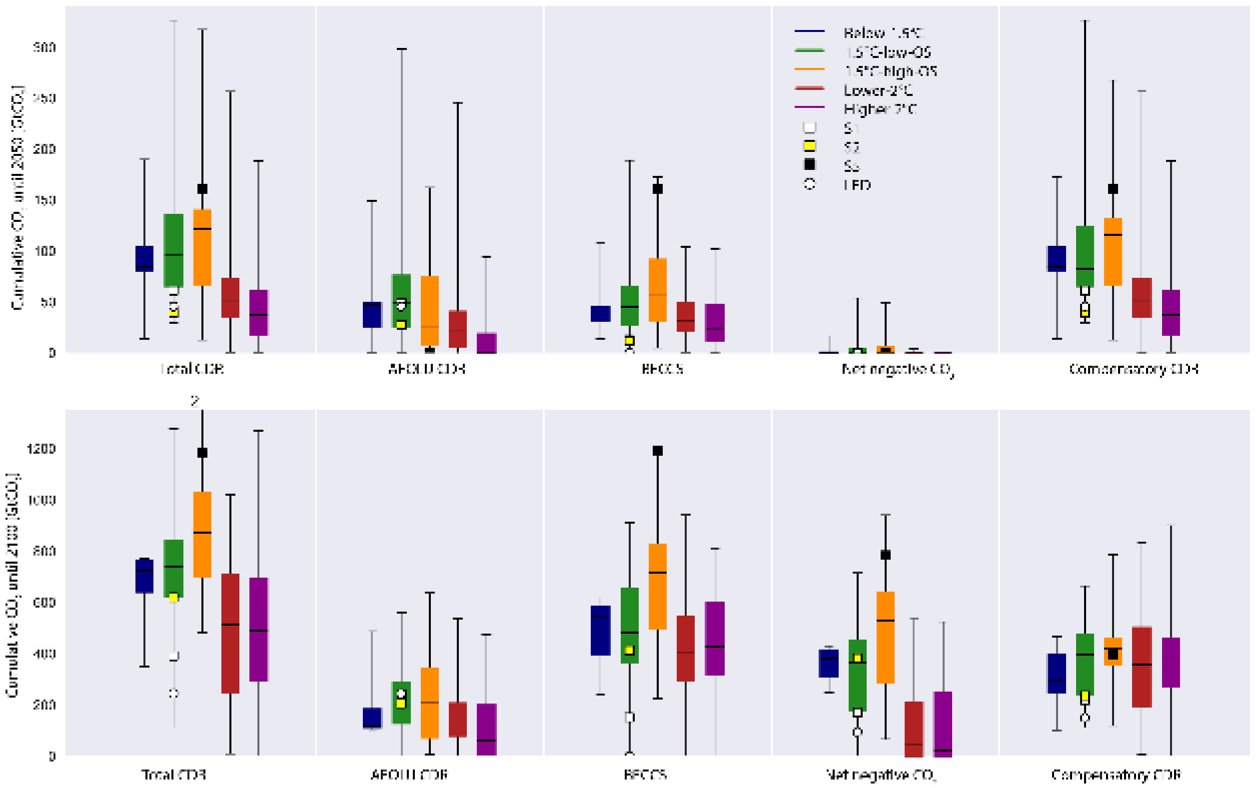

Figure 2.9: Cumulative CDR deployment in 1.5°C-consistent pathways in the literature as reported in the database collected for this assessment. Total CDR comprises all forms of CDR, including AFOLU CDR and BECCS, and in a few pathways other CDR measures like DACCS. It does not include CCS combined with fossil fuels (which is not a CDR technology as it does not result in active removal of CO_2 from the atmosphere). AFOLU CDR has not been reported directly and is hence represented by means of a proxy: the additional amount of net negative CO_2 emissions in the AFOLU sector compared to a baseline scenario (see text for a discussion). 'Compensate CO_2' depicts the cumulative amount of CDR that is used to neutralize concurrent residual CO_2 emissions. 'Net negative CO_2' describes the additional

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[4] FOOTNOTE: The median and percentiles of the sum of two quantities is in general not equal to the sum of the medians of the two quantitites.

amount of CDR that is used to produce net negative emissions, once residual CO_2 emissions are neutralized. The two quantities add up to total CDR for individual pathways (not for percentiles and medians, see Footnote 4).

As discussed in Section 2.3.2, CDR can be used in two ways: (i) to move more rapidly towards the point of carbon neutrality and maintain it afterwards to stabilize global-mean temperature rise, and (ii) to produce net negative emissions drawing down anthropogenic CO_2 in the atmosphere to enable temperature overshoot by declining global-mean temperature rise after its peak (Kriegler et al., 2018a; Obersteiner et al., 2018). Both uses are important in 1.5°C-consistent pathways (Figure 2.9). Because of the tighter remaining 1.5°C carbon budget, and because many pathways in the literature do not restrict exceeding this budget prior to 2100, the relative weight of the net negative emissions component of CDR increases compared to 2°C-consistent pathways. The amount of compensatory CDR remains roughly the same over the century. This is the net effect of stronger deployment of compensatory CDR until mid-century to accelerate the approach to carbon neutrality and less compensatory CDR in the second half of the century due to deeper mitigation of end-use sectors in 1.5°C-consistent pathways (Luderer et al., 2018). Comparing median levels, end-of-century net cumulative CO_2 emissions are roughly 600 $GtCO_2$ smaller in 1.5°C compared to 2°C-consistent pathways, with approximately two thirds coming from further reductions of gross CO_2 emissions and the remaining third from increased CDR deployment. As a result, total CDR deployment in the combined body of 1.5°C-consistent pathways is often larger than in 2°C-consistent pathways (Figure 2.9), but with marked variations in each pathway class.

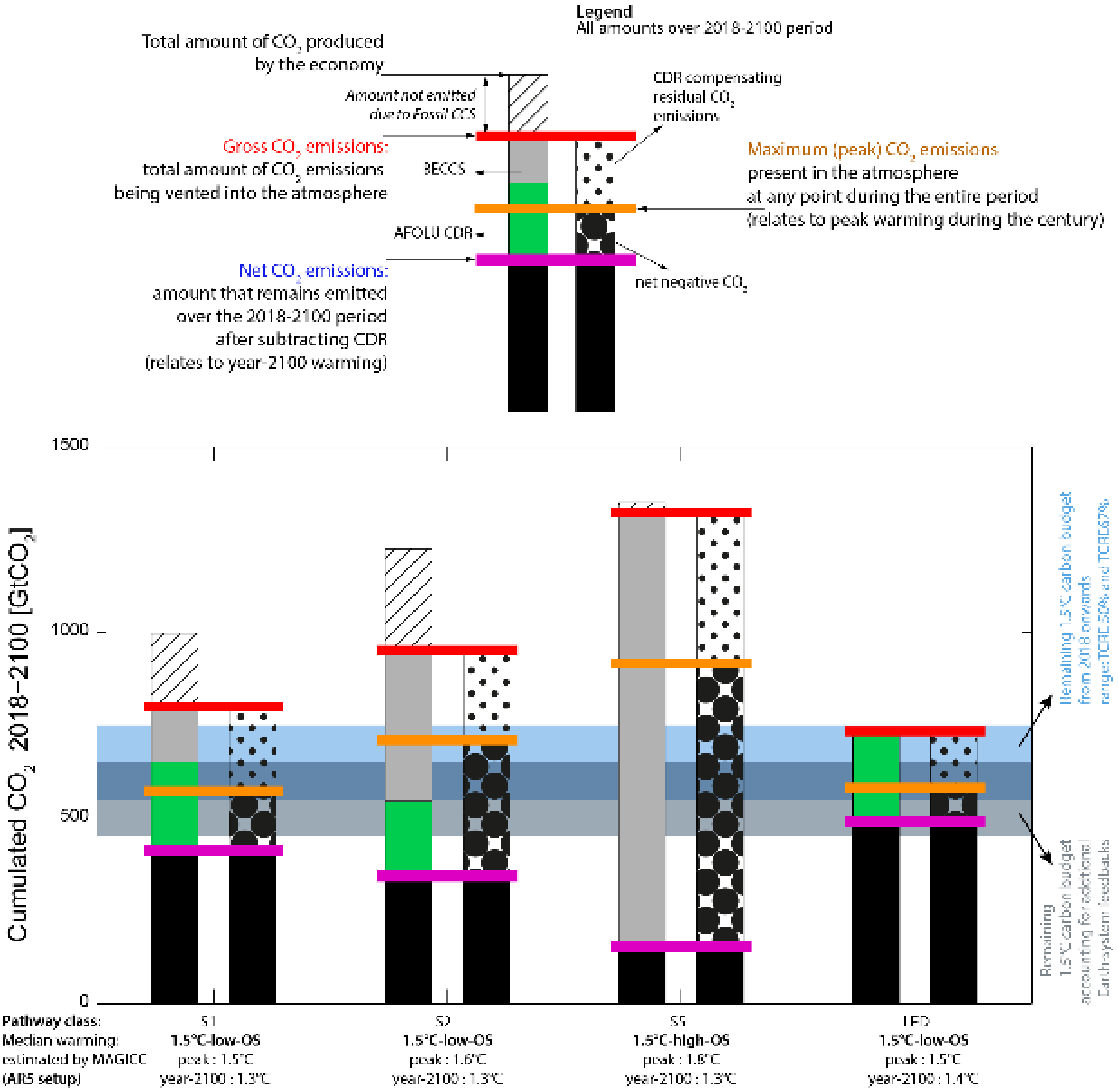

Figure 2.10: **Accounting of cumulative CO_2 emissions for the four 1.5°C-consistent pathway archetypes.** See top panel for explanation of the barplots. Total CDR is the difference between gross (red horizontal bar) and net (purple horizontal bar) cumulative CO_2 emissions over the period 2018–2100. Total CDR is the sum of the BECCS (grey) and AFOLU CDR (green) contributions. Cumulative net negative emissions are the difference between peak (orange horizontal bar) and net (purple) cumulative CO_2 emissions. The blue shaded area depicts the estimated range of the remaining carbon budget for a two-in-three to one-in-two chance of staying below1.5°C. The grey shaded area depicts the range when accounting for additional Earth-system feedbacks. These remaining carbon budgets have been adjusted for the difference in starting year compared to Table 2.2

Ramp-up rates of individual CDR measures in 1.5°C-consistent pathways are provided in Table 2.4. BECCS deployment is still limited in 2030, but ramped up to median levels of 3 (Below-1.5°C), 5 (1.5°C-low-OS) and 7 $GtCO_2$ yr^{-1} (1.5°C-high-OS) in 2050, and to 6 (Below-1.5°C), 12 (1.5°C-low-OS) and 15 $GtCO_2$ yr^{-1} (1.5°C-high-OS) in 2100, respectively. Net CDR in the AFOLU sector reaches slightly lower levels in 2050, and stays more constant until 2100, but data reporting limitations prevent a more quantitative assessment here. In contrast to BECCS, AFOLU CDR is more strongly deployed in non-overshoot than overshoot pathways. This indicates differences in the timing of the two CDR approaches. Afforestation is scaled up until around mid-century, when the time of carbon neutrality is reached in 1.5°C-consistent pathways, while BECCS is projected to be used predominantly in the 2nd half of the century. This reflects that afforestation is a readily available CDR technology, while BECCS is more costly and much less mature a technology. As a result, the two options contribute differently to compensating concurrent CO_2 emissions (until 2050) and to producing net negative CO_2 emissions (post-2050). BECCS deployment is particularly strong in pathways with high overshoots but could equally feature in pathways with a low temperature peak but a fast temperature decline thereafter (see Figure 2.1). Annual deployment levels until mid-century are not found to be significantly different between 2°C-consistent pathways and 1.5°C-consistent pathways with no or low overshoot. This suggests similar implementation challenges for ramping up CDR deployment at the rates projected in the pathways (Honegger and Reiner, 2018; Nemet et al., 2018). The feasibility and sustainability of upscaling CDR at these rates is assessed in Chapter 4.3.7.

Concerns have been raised that building expectations about large-scale CDR deployment in the future can lead to an actual reduction of near-term mitigation efforts (Geden, 2015; Anderson and Peters, 2016; Dooley and Kartha, 2018). The pathway literature confirms that CDR availability influences the shape of mitigation pathways critically (Krey et al., 2014a; Holz et al., 2018b; Kriegler et al., 2018b; Strefler et al., 2018b). Deeper near-term emissions reductions are required to reach the 1.5°C-2°C target range, if CDR availability is constrained. As a result, the least-cost benchmark pathways to derive GHG emissions gap estimates (UNEP, 2017) are dependent on assumptions about CDR availability. Using GHG benchmarks in climate policy makes implicit assumptions about CDR availability (Fuss et al., 2014; van Vuuren et al., 2017a). At the same time, the literature also shows that rapid and stringent mitigation as well as large-scale CDR deployment occur simultaneously in 1.5°C pathways due to the tight remaining carbon budget (Luderer et al., 2018). Thus, an emissions gap is identified even for high CDR availability (Strefler et al., 2018b), contradicting a wait-and-see approach. There are significant trade-offs between near-term action, overshoot and reliance on CDR deployment in the long-term which are assessed in Section 2.3.5.

Box 2.1: Bioenergy and BECCS deployment in integrated assessment modelling

Bioenergy can be used in various parts of the energy sector of IAMs, including for electricity, liquid fuel, biogas, and hydrogen production. It is this flexibility that makes bioenergy and bioenergy technologies valuable for the decarbonisation of energy use (Klein et al., 2014; Krey et al., 2014a; Rose et al., 2014a; Bauer et al., 2017, 2018). Most bioenergy technologies in IAMs are also available in combination with CCS (BECCS). Assumed capture rates differ between technologies, for example, about 90% for electricity and hydrogen production, and about 40-50% for liquid fuel production. Decisions about bioenergy deployment in IAMs are based on economic considerations to stay within a carbon budget that is consistent with a long-term climate goal. IAMs consider both the value of bioenergy in the energy system and the value of BECCS in removing CO_2 from the atmosphere. Typically, if bioenergy is strongly limited, BECCS technologies with high capture rates are favoured. If bioenergy is plentiful IAMs tend to choose biofuel technologies with lower capture rate, but high value for replacing fossil fuels in transport (Kriegler et al., 2013a; Bauer et al., 2018). Most bioenergy use in IAMS is combined with CCS if available (Rose et al., 2014a). If CCS is unavailable, bioenergy use remains largely unchanged or even increases due to the high value of bioenergy for the energy transformation (Bauer et al., 2018). As land impacts are tied to bioenergy use, the exclusion of BECCS from the mitigation portfolio, will not automatically remove the trade-offs with food, water and other sustainability objectives due to the continued and potentially increased use of bioenergy.

IAMs assume bioenergy to be supplied mostly from second generation biomass feedstocks such as dedicated cellulosic crops (for example Miscanthus or Poplar) as well as agricultural and forest residues. Detailed process IAMs include land-use models that capture competition for land for different uses (food, feed, fiber, bioenergy, carbon storage, biodiversity protection) under a range of dynamic factors including socio-economic drivers, productivity increases in crop and livestock systems, food demand, and land, environmental, biodiversity, and carbon policies. Assumptions about these factors can vary widely between different scenarios (Calvin et al., 2014; Popp et al., 2017; van Vuuren et al., 2018). IAMs capture a number of potential environmental impacts from bioenergy production, in particular indirect land-use change emissions from land conversion and nitrogen and water use for bioenergy production (Kraxner et al., 2013; Bodirsky et al., 2014; Bonsch et al., 2014; Obersteiner et al., 2016; Humpenöder et al., 2017). Especially the impact of bioenergy production on soil degradation is an area of active IAM development and was not comprehensively accounted for in the mitigation pathways assessed in this report (but is, for example, in (Frank et al., 2017)). Whether bioenergy has large adverse impacts on environmental and societal goals depends in large parts on the governance of land use (Haberl et al., 2013; Erb et al., 2016b; Obersteiner et al., 2016; Humpenöder et al., 2017). Here IAMs often make idealized assumptions about effective land management such as full protection of the land carbon stock by conservation measures and a global carbon price, respectively, but also variations on these assumptions have been explored (Calvin et al., 2014; Popp et al., 2014a)).

2.3.4.2 *Sustainability implications of CDR deployment in 1.5°C-consistent pathways*

Strong concerns about the sustainability implications of large-scale CDR deployment in deep mitigation pathways have been raised in the literature (Williamson and Bodle, 2016; Boysen et al., 2017b; Dooley and Kartha, 2018; Heck et al., 2018), and a number of important knowledge gaps have been identified (Fuss et al., 2016). An assessment of the literature on implementation constraints and sustainable development implications of CDR measures is provided in Section 4.3.7 and the Cross-chapter Box 7 in Chapter 3. Potential environmental side effects as initial context for the discussion of CDR deployment in 1.5°C-consistent pathways are provided in this section. Section 4.3.7 then contrasts CDR deployment in 1.5°C-consistent pathways with other branches of literature on limitations of CDR. Integrated modelling aims to explore a range of developments compatible with specific climate goals and often does not include the full set of broader environmental and societal concerns beyond climate change. This has given rise to the concept of sustainable development pathways (van Vuuren et al., 2015) (Cross-Chapter Box 1 in Chapter 1), and there is an increasing body of work to extend integrated modelling to cover a broader range of sustainable development goals (Section 2.6). However, only some of the available 1.5°C-consistent pathways were developed within a larger sustainable development context (Bertram et al., 2018; Grubler et al., 2018; Rogelj et al., 2018; van Vuuren et al., 2018). As discussed in Section 2.3.4.1, those pathways are characterized by low energy and/or food demand effectively limiting fossil-fuel substitution and alleviating land competition, respectively. They also include regulatory policies for deepening early action and ensuring environmental protection (Bertram et al., 2018). Overall sustainability implications of 1.5°C-consistent pathways are assessed in Section 2.5.3 and Section 5.4.

Individual CDR measures have different characteristics and therefore would carry different risks for their sustainable deployment at scale (Smith et al., 2015). Terrestrial CDR measures, BECCS and enhanced weathering of rock powder distributed on agricultural lands require land. Those land-based measures could have substantial impacts on environmental services and ecosystems (Smith and Torn, 2013; Boysen et al., 2016; Heck et al., 2016; Krause et al., 2017) (Cross-Chapter Box 7 in Chapter 3). Measures like afforestation and bioenergy with and without CCS that directly compete with other land uses could have significant impacts on agricultural and food systems (Creutzig et al., 2012, 2015; Calvin et al., 2014; Popp et al., 2014b, 2017; Kreidenweis et al., 2016; Boysen et al., 2017a; Frank et al., 2017; Humpenöder et al., 2017; Stevanović et al., 2017; Strapasson et al., 2017). BECCS using dedicated bioenergy crops could substantially increase agricultural water demand (Bonsch et al., 2014; Séférian et al., 2018) and nitrogen fertilizer use (Bodirsky et al., 2014). DACCS and BECCS rely on CCS and would require safe storage space in geological formations, including management of leakage risks (Pawar et al., 2015) and induced seismicity (Nicol et al., 2013). Some approaches like DACCS have high energy demand (Socolow et al., 2011). Most of the CDR measures currently discussed could have significant impacts on either land, energy, water, or nutrients if deployed at scale (Smith et al., 2015). However, actual trade-offs depend on a multitude factors (Haberl et al., 2011; Erb et al., 2012; Humpenöder et al., 2017), including the modalities of CDR deployment (e.g., on marginal vs. productive land) (Bauer et al., 2018), socio-economic developments (Popp et al., 2017), dietary choices (Stehfest et al., 2009; Popp et al., 2010; van Sluisveld et al., 2016; Weindl et al., 2017; van Vuuren et al., 2018), yield increases, livestock productivity and other advances in agricultural technology (Havlik et al., 2013; Valin et al., 2013; Havlík et al., 2014; Weindl et al., 2015; Erb et al., 2016b), land policies (Schmitz et al., 2012; Calvin et al., 2014; Popp et al., 2014a) and governance of land use (Unruh, 2011; Buck, 2016; Honegger and Reiner, 2018).

Figure 2.11 shows the land requirements for BECCS and afforestation in the selected 1.5°C-consistent pathway archetypes, including the LED (Grubler et al., 2018) and S1 pathways (Fujimori, 2017; Rogelj et al., 2018) following a sustainable development paradigm. As discussed, these land-use patterns are heavily influenced by assumptions about, inter alia, future population levels, crop yields, livestock production systems, and food and livestock demand, which all vary between the pathways (Popp et al., 2017) (Section 2.3.1.1). In pathways that allow for large-scale afforestation in addition to BECCS, land demand for afforestation can be larger than for BECCS (Humpenöder et al., 2014). This follows from the assumption in the modelled pathways that, unlike bioenergy crops, forests are not harvested to allow unabated carbon storage on the same patch of land. If wood harvest and subsequent processing or burial are taken into account, this finding can change. There are also synergies between the various uses of land, which are not reflected in the depicted pathways. Trees can grow on agricultural land (Zomer et al., 2016) and harvested wood can be used with BECCS and pyrolysis systems (Werner et al., 2018). The pathways show a very substantial land demand for the two CDR measures combined, up to the magnitude of the current global cropland area. This is achieved in IAMs in particular by a conversion of pasture land freed by intensification of livestock production systems, pasture intensification and/or demand changes (Weindl et al., 2017), and to more limited extent cropland for food production, as well as expansion into natural land. However, pursuing such large scale changes in land use would pose significant food supply, environmental and governance challenges, concerning both land management and tenure (Unruh, 2011; Erb et al., 2012, 2016b; Haberl et al., 2013; Haberl, 2015; Buck, 2016), particularly if synergies between land uses, the relevance of dietary changes for reducing land demand, and co-benefits with other sustainable development objectives are not fully recognized. A general discussion of the land-use transformation in 1.5°C-consistent pathways is provided in Section 2.4.4.

An important consideration for CDR which moves carbon from the atmosphere to the geological, oceanic or terrestrial carbon pools is the permanence of carbon stored in these different pools (Matthews and Caldeira, 2008; NRC, 2015; Fuss et al., 2016; Jones et al., 2016) (see also Section 4.3.7 for a discussion). Terrestrial carbon can be returned to the atmosphere on decadal timescales by a variety of mechanisms such as soil degradation, forest pest outbreaks and forest fires, and therefore requires careful consideration of policy frameworks to manage carbon storage, e.g., in forests (Gren and Aklilu, 2016). There are similar concerns about outgassing of CO_2 from ocean storage (Herzog et al., 2003), unless it is transformed to a substance that does not easily exchange with the atmosphere, e.g., ocean alkalinity or buried marine biomass (Rau, 2011). Understanding of the assessment and management of the potential risk of CO_2 release from geological storage of CO_2 has improved since the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) with experience and the development of management practices in geological storage projects, including risk management to prevent sustentative leakage (Pawar et al., 2015). Estimates of leakage risk have been updated to include scenarios of unregulated drilling and limited wellbore integrity (Choi et al., 2013), finding ca. 70% of stored CO_2 still retained after 10,000 years in these circumstances (Alcalde et al., 2018). The literature on the potential environmental impacts from the leakage of CO_2 – and approaches to minimize these impacts should a leak occur – has also grown and is reviewed by Jones et al. (2015). To the extent non-permanence of terrestrial and geological carbon storage is driven by socio-economic and political factors, it has parallels to questions of fossil-fuel reservoirs remaining in the ground (Scott et al., 2015).

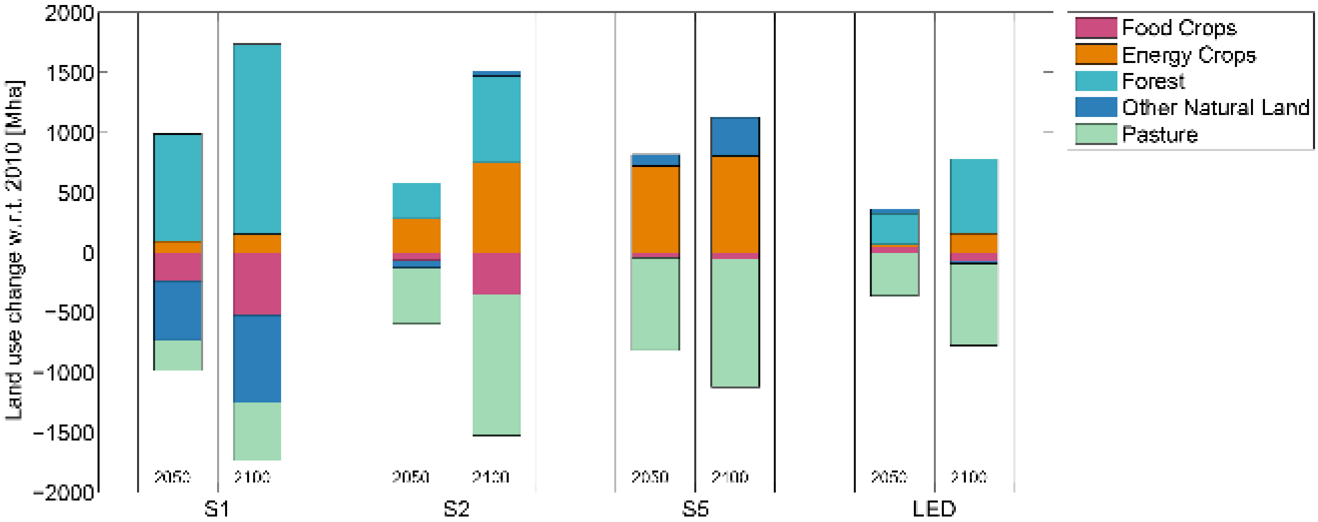

Figure 2.11: Land-use changes in 2050 and 2100 in the illustrative 1.5°C-consistent pathway archetypes (Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Grubler et al., 2018; Rogelj et al., 2018).

2.3.5 Implications of near-term action in 1.5°C-consistent pathways

Less CO_2 emission reductions in the near term imply steeper and deeper reductions afterwards (Riahi et al., 2015; Luderer et al., 2016a). This is a direct consequence of the quasi-linear relationship between the total cumulative amount of CO_2 emitted into the atmosphere and global mean temperature rise (Matthews et al., 2009; Zickfeld et al., 2009; Collins et al., 2013; Knutti and Rogelj, 2015). Besides this clear geophysical trade-off over time, delaying GHG emissions reductions over the coming years also leads to economic and institutional lock-in into carbon-intensive infrastructure, that is, the continued investment in and use of carbon-intensive technologies that are difficult or costly to phase-out once deployed (Unruh and Carrillo-Hermosilla, 2006; Jakob et al., 2014; Erickson et al., 2015; Steckel et al., 2015; Seto et al., 2016; Michaelowa et al., 2018). Studies show that to meet stringent climate targets despite near-term delays in emissions reductions, models prematurely retire carbon-intensive infrastructure, in particular coal without CCS (Bertram et al., 2015a; Johnson et al., 2015). The AR5 reports that delaying mitigation action leads to substantially higher rates of emissions reductions afterwards, a larger reliance on CDR technologies in the long term, and higher transitional and long-term economic impacts (Clarke et al., 2014). The literature mainly focuses on delayed action until 2030 in the context of meeting a 2°C goal (den Elzen et al., 2010; van Vuuren and Riahi, 2011; Kriegler et al., 2013b; Luderer et al., 2013, 2016a; Rogelj et al., 2013b; Riahi et al., 2015; OECD/IEA and IRENA, 2017). However, because of the smaller carbon budget consistent with limiting warming to 1.5°C and the absence of a clearly declining long-term trend in global emissions to date, these general insights apply equally or even more so to the more stringent mitigation context of 1.5°C-consistent pathways. This is further supported by estimates of committed emissions due to fossil fuel-based infrastructure (Seto et al., 2016; Edenhofer et al., 2018).

All available 1.5°C pathways that explore consistent mitigation action from 2020 onwards peak global Kyoto-GHG emissions in the next decade and already decline Kyoto-GHG emissions to below 2010 levels by 2030. The near-term emissions development in these pathways can be compared with estimated emissions in 2030 implied by the Nationally Determined Contributions (NDCs) submitted by Parties to the Paris Agreement (Figure 2.12). Altogether, these NDCs are assessed to result in global Kyoto-GHG emissions on the order of 50–58 $GtCO_2e\ yr^{-1}$ in 2030 (for example, den Elzen et al., 2016; Fujimori et al., 2016; UNFCCC, 2016; Rogelj et al., 2017; Rose et al., 2017b; Benveniste et al., 2018; Vrontisi et al., 2018), see Cross-Chapter Box 11 in Chapter 4 for detailed assessment). In contrast, 1.5°C-consistent pathways available to this assessment show an interquartile range of about 26–38 (median 31) $GtCO_2e\ yr^{-1}$ in 2030, reducing to 26–31 (median 28) $GtCO_2e\ yr^{-1}$ if only pathways with low overshoot are taken into account[5], and still lower if pathways without overshoot are considered (Table 2.4, Section 2.3.3). Published estimates of the emissions gap between conditional NDCs and 1.5°C-consistent pathways in 2030 range from 16 (14–22) $GtCO_2e\ yr^{-1}$ (UNEP, 2017) for a greater than one-in-to chance of limiting warming below 1.5°C in 2100 to 25 (19–29) $GtCO_2e\ yr^{-1}$ (Vrontisi et al., 2018) for a greater than two-in-three chance of meeting the 1.5°C limit.

The later emissions peak and decline, the more CO_2 will have accumulated in the atmosphere. Peak cumulated CO_2 emissions and consequently also peak temperatures increase with 2030 emissions levels (Figure 2.12). Current NDCs (Cross-Chapter Box 11 in Chapter 4) are estimated to lead to CO_2 emissions of about 400–560 $GtCO_2$ from 2018 to 2030 (Rogelj et al., 2016a). Available 1.5°C- and 2°C-consistent pathways with 2030 emissions in the range estimated for the NDCs rely on an assumed swift and widespread deployment of CDR after 2030, and show peak cumulative CO_2 emissions from 2018 of about 800–1000 $GtCO_2$, above the remaining carbon budget for a one-in-two chance of remaining below 1.5°C. These emissions reflect that no pathway is able to project a phase out of CO_2 emissions starting from year-2030 NDC levels of about 40 $GtCO_2\ yr^{-1}$ (Fawcett et al., 2015; Rogelj et al., 2016a) to net zero in less than ca. 15 years. Based on the implied emissions until 2030, the high challenges of the assumed post-2030 transition, and the assessment of carbon budgets in Section 2.2.2, global warming is assessed to exceed 1.5°C if emissions stay at the levels implied by the NDCs until 2030 (Figure 2.12). The chances of remaining below 1.5°C in these circumstances remain conditional upon geophysical properties that are uncertain, but these

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[5] FOOTNOTE: Note that aggregated Kyoto-GHG emissions implied by the NDCs from Cross-Chapter Box 4.3 and Kyoto-GHG ranges from the pathway classes in Chapter 2 are only approximately comparable, because this chapter applies GWP-100 values from the IPCC Fourth Assessment Report while the NDC Cross-Chapter Box 4.3 applies GWP-100 values from the IPCC Second Assessment Report. At a global scale, switching between GWP-100 values of the Second to the Fourth IPCC Assessment Report would result in an increase in estimated aggregated Kyoto-GHG emissions of about no more than 3% in 2030 (UNFCCC, 2016).

Earth system response uncertainties would have to serendipitously align beyond current median estimates in order for current NDCs to become consistent with limiting warming to 1.5°C.

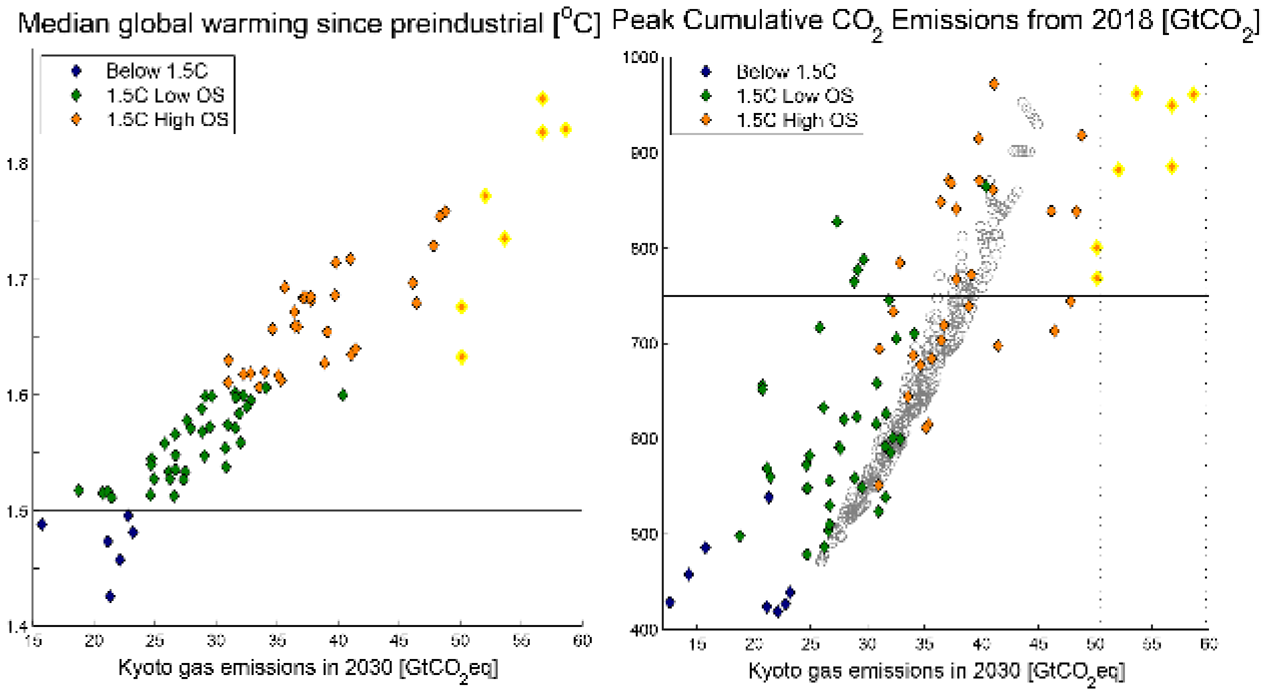

Figure 2.12: Median global warming estimated by MAGICC (left panel) and peak cumulative CO$_2$ emissions (right panel) in 1.5°C-consistent pathways in the SR1.5 scenario database as a function of CO$_2$-equivalent emissions (based on AR4 GWP-100) of Kyoto-GHGs in 2030. Pathways that were forced to go through the NDCs or a similarly high emissions point in 2030 by design are highlighted by yellow marker edges (see caption of Figure 2.13 and text for further details on the design of these pathways). The NDC range of global Kyoto-GHG emissions in 2030 assessed in Cross-Chapter Box 11 in Chapter 4 is shown by black dotted lines (adjusted to AR4 GWPs for comparison). As a second line of evidence, peak cumulative CO$_2$ emissions derived from a 1.5°C pathway sensitivity analysis (Kriegler et al., 2018a) are shown by grey circles in the right-hand panel. Numbers show gross fossil-fuel and industry emissions of the sensitivity cases increased by assumptions about the contributions from AFOLU (5 GtCO$_2$ yr^{-1} until 2020, followed by a linear phase out until 2040) and non-CO$_2$ Kyoto-GHGs (median non-CO$_2$ contribution from 1.5°C-consistent pathways available in the database: 10 GtCO$_2$e yr^{-1} in 2030), and reduced by assumptions about CDR deployment until the time of net zero CO$_2$ emissions (limiting case for CDR deployment assumed in (Kriegler et al., 2018a) (logistic growth to 1, 4, 10 GtCO$_2$ yr^{-1} in 2030, 2040, and 2050, respectively, leading to approx. 100 GtCO$_2$ CDR by mid-century).

It is unclear whether following NDCs until 2030 would still allow global mean temperature to return to 1.5°C by 2100 after a temporary overshoot, due to the uncertainty associated with the Earth system response to net negative emissions after a peak (Section 2.2). Available IAM studies are working with reduced-form carbon cycle-climate models like MAGICC which assume a largely symmetric Earth-system response to positive and net negative CO$_2$ emissions. The IAM findings on returning warming to 1.5°C from NDCs after a temporary temperature overshoot are hence all conditional on this assumption. Two types of pathways with 1.5°C-consistent action starting in 2030 have been considered in the literature (Luderer et al., 2018) (Figure 2.13): pathways aiming to obtain the same end-of-century carbon budget despite higher emissions until 2030, and pathways assuming the same mitigation stringency after 2030 (approximated by using the same global price of emissions as found in least-cost pathways starting from 2020). An IAM comparison study found increasing challenges to implement pathways with the same end-of-century 1.5°C-consistent carbon budgets after following NDCs until 2030 (ADVANCE) (Luderer et al., 2018). The majority of model experiments (four out of seven) failed to produce NDC pathways that would return cumulative CO$_2$ emissions over the 2016–2100 period to 200 GtCO$_2$, indicating limitations to the availability and timing of CDR. The few such pathways that were identified show highly disruptive features in 2030 (including abrupt transitions from moderate to very large emissions reduction and low carbon energy deployment rates) indicating a high risk that the required post-2030 transformations are too steep and abrupt to be achieved by the mitigation measures in the models (*high confidence*). NDC pathways aiming for a cumulative 2016–2100 CO$_2$ emissions budget of 800 GtCO$_2$ were more readily obtained (Luderer et al., 2018), and some were classified as 1.5°C-high-OS pathways in this assessment (Section 2.1).

NDC pathways that apply a post-2030 price of emissions after 2030 as found in least-cost pathways starting from 2020 show infrastructural carbon lock-in as a result of following NDCs instead of least-cost action until 2030. A key finding is that carbon lock-ins persist long after 2030, with the majority of additional CO_2 emissions occurring during the 2030–2050 period. Luderer et al. (2018) find 90 (80–120) $GtCO_2$ additional emissions until 2030, growing to 240 (190–260) $GtCO_2$ by 2050 and 290 (200–200) $GtCO_2$ by 2100. As a result, peak warming is about 0.2°C higher and not all of the modelled pathways return warming to 1.5°C by the end of the century. There is a four sided trade-off between (i) near-term ambition, (ii) degree of overshoot, (iii) transitional challenges during the 2030–2050 period, and (iv) the amount of CDR deployment required during the century (Figure 2.13) (Holz et al., 2018b; Strefler et al., 2018b). Transition challenges, overshoot, and CDR requirements can be significantly reduced if global emissions peak before 2030 and fall below levels in line with current NDCs by 2030. For example, Strefler et al. (2018b) find that CDR deployment levels in the second half of the century can be halved in 1.5°C-consistent pathways with similar CO_2 emissions reductions rates during the 2030–2050 period if CO_2 emissions by 2030 are reduced by an additional 30% compared to NDC levels. Kriegler et al. (2018b) investigate a global roll out of selected regulatory policies and moderate carbon pricing policies. They show that additional reductions of ca. 10 $GtCO_2e\ yr^{-1}$ can be achieved in 2030 compared to the current NDCs. Such 20% reduction of year-2030 emissions compared to current NDCs would effectively lower the disruptiveness of post-2030 action. Strengthening of short-term policies in deep mitigation pathways has hence been identified as bridging options to keep the Paris climate goals within reach (Bertram et al., 2015b; IEA, 2015a; Spencer et al., 2015; Kriegler et al., 2018b).

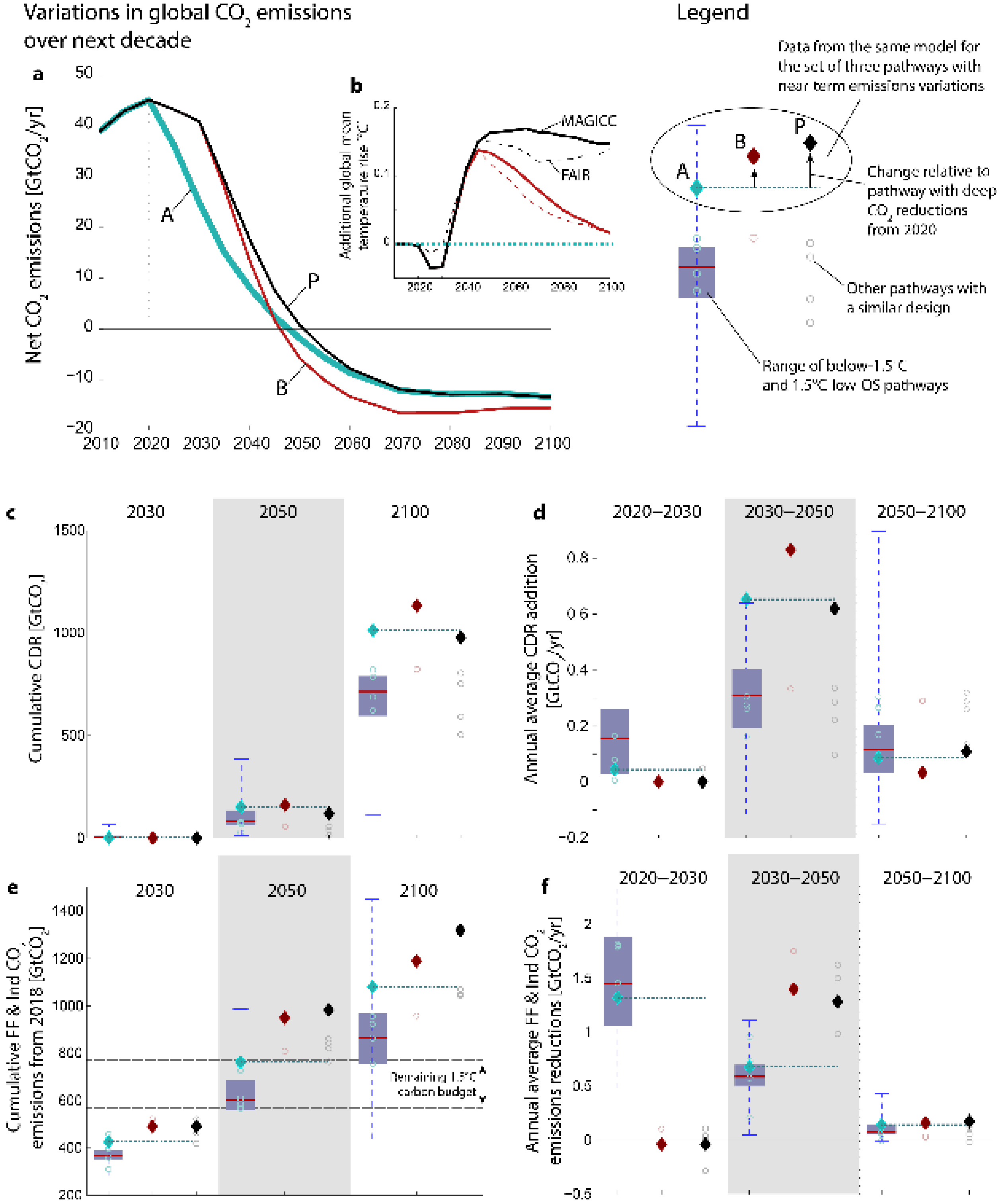

Figure 2.13: Comparison of pathways starting action for limiting warming to 1.5°C as of 2020 (A; light-blue diamonds) with pathways following the NDCs until 2030 and aiming to limit warming to 1.5°C thereafter. 1.5°C pathways following the NDCs either aim for the same cumulative CO$_2$ emissions by 2100 (B; red diamonds) or assume the same mitigation stringency as reflected by the price of emissions in associated least-cost 1.5°C-consistent pathways starting from 2020 (P; black diamonds). Panels show the underlying emissions pathways (a), additional warming in the delay scenarios compared to 2020 action case (b), cumulated CDR (c), CDR ramp-up rates (d), cumulated gross CO$_2$ emissions from fossil-fuel combustion and industrial (FFI) processes over the 2018–2100 period (e), and gross FFI CO$_2$ emissions reductions rates (f). Scenario pairs / triplets (circles and diamonds) with 2020 and 2030 action variants were calculated by six (out of seven) models in the ADVANCE study symbols (Luderer et al., 2018) and five of them (passing near-term plausibility checks) are shown by symbols. Only two of five models could identify pathways with post-2030 action leading to a 2016–2100 carbon budget of ca. 200 GtCO$_2$ (red). The range of all 1.5°C-consistent pathways with no and low overshoot is shown by the boxplots.

2.4 Disentangling the whole-system transformation

Mitigation pathways map out prospective transformations of the energy, land and economic systems over this century (Clarke et al., 2014). There is a diversity of potential pathways consistent with 1.5°C, yet they share some key characteristics summarized in Table 2.5. To explore characteristics of 1.5°C pathways in greater detail, this section focuses on changes in energy supply and demand, and changes in the AFOLU sector.

Table 2.5: Overview of key characteristics of 1.5°C pathways.

1.5°C pathway characteristic	Supporting information	Reference
Rapid and profound near-term decarbonisation of energy supply	Strong upscaling of renewables and sustainable biomass and reduction of unabated (no CCS) fossil fuels, along with the rapid deployment of CCS lead to a zero-emission energy supply system by mid-century.	Section 2.4.1 Section 2.4.2
Greater mitigation efforts on the demand side	All end-use sectors show marked demand reductions beyond the reductions projected for 2°C pathways. Demand reductions from IAMs for 2030 and 2050 lie within the potential assessed by detailed sectorial bottom-up assessments.	Section 2.4.3
Switching from fossil fuels to electricity in end-use sectors	Both in the transport and the residential sector, electricity covers marked larger shares of total demand by mid-century.	Section 2.4.3.2 Section 2.4.3.3
Comprehensive emission reductions are implemented in the coming decade	Virtually all 1.5°C-consistent pathways decline net annual CO_2 emissions between 2020 and 2030, reaching carbon neutrality around mid-century. Below-1.5°C and 1.5°C-low-OS show maximum net CO2 emissions in 2030 of 18 and 28 $GtCO_2$ yr^{-1}, respectively. GHG emissions in these scenarios are not higher than 34 $GtCO_2e$ yr^{-1} in 2030.	Section 2.3.4
Additional reductions, on top of reductions from both CO2 and non-CO2 required for 2°C, are mainly from CO2	Both CO_2 and the non-CO_2 GHGs and aerosols are strongly reduced by 2030 and until 2050 in 1.5°C pathways. The greatest difference to 2°C pathways, however, lies in additional reductions of CO_2, as the non-CO_2 mitigation potential that is currently included in integrated pathways is mostly already fully deployed for reaching a 2°C pathway.	Section 2.3.1.2
Considerable shifts in investment patterns	Low-carbon investments in the energy supply side (energy production and refineries) are projected to average 1.6-3.8 trillion 2010USD yr^{-1} globally to 2050. Investments in fossil fuels decline, with investments in unabated coal halted by 2030 in most available 1.5°C-consistent projections, while the literature is less conclusive for investments in unabated gas and oil. Energy demand investments are a critical factor for which total estimates are uncertain.	Section 2.5.2
Options are available to align 1.5°C pathways with sustainable development	Synergies can be maximized, and risks of trade-offs limited or avoided through an informed choice of mitigation strategies. Particularly pathways that focus on a lowering of demand show many synergies and few trade-offs.	Section 2.5.3
CDR at scale before mid-century	By 2050, 1.5°C pathways project deployment of BECCS at a scale of 3–7 $GtCO_2yr^{-1}$ (range of medians across 1.5°C pathway classes), depending on the level of energy demand reductions and mitigation in other sectors. Some 1.5°C pathways are available that do not use BECCS, but only focus terrestrial CDR in the AFOLU sector.	Section 2.3.3, 2.3.4.1

2.4.1 Energy System Transformation

The energy system links energy supply (Section 2.4.2) with energy demand (Section 2.4.3) through final energy carriers including electricity and liquid, solid or gaseous fuels that are tailored to their end-uses. To chart energy-system transformations in mitigation pathways, four macro-level decarbonisation indicators associated with final energy are useful: limits to the increase of final energy demand, reductions in the carbon intensity of electricity, increases in the share of final energy provided by electricity, and reductions in the carbon intensity of final energy other than electricity (referred to in this section as the carbon intensity of the residual fuel mix). Figure 2.14 shows changes of these four indicators for the pathways in the scenario database (Section 2.1.3 and Annex 2.A.3) for 1.5°C and 2°C pathways (Table 2.1).

Pathways in both the 1.5°C and 2°C classes (Figure 2.14) generally show rapid transitions until mid-century with a sustained but slower evolution thereafter. Both show an increasing share of electricity accompanied by a rapid decline in the carbon intensity of electricity. Both also show a generally slower decline in the carbon intensity of the residual fuel mix, which arises from the decarbonisation of liquids, gases and solids provided to industry, residential and commercial activities, and the transport sector.

The largest differences between 1.5°C and 2°C pathways are seen in the first half of the century (Figure 2.14), where 1.5°C pathways generally show lower energy demand, a faster electrification of energy end-use, and a faster decarbonisation of the carbon intensity of electricity and the residual fuel mix. There are very few pathways in the Below-1.5°C class (Figure 2.14). Those scenarios that are available, however, show a faster decline in the carbon intensity of electricity generation and residual fuel mix by 2030 than most pathways that are projected to temporarily overshoot 1.5°C and return by 2100 (or 2°C pathways), and also appear to distinguish themselves already by 2030 by reductions in final energy demand and an increased electricity share (Figure 2.14).

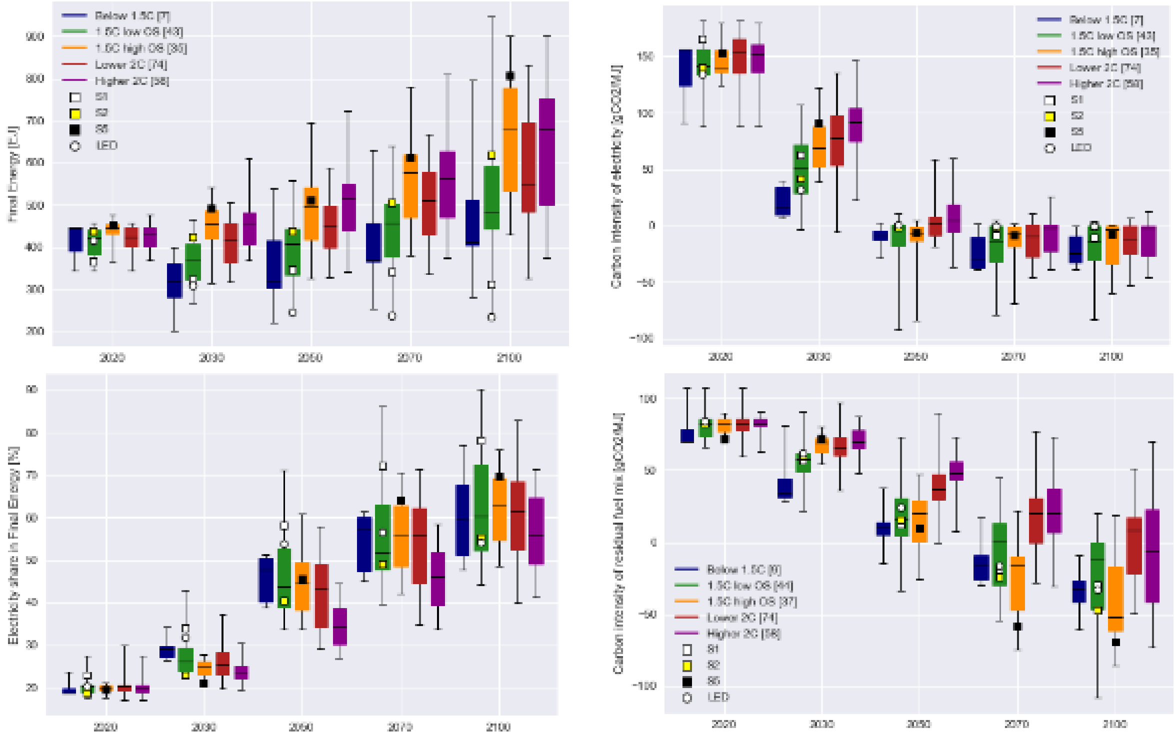

Figure 2.14: Decomposition of transformation pathways into energy demand (top left), carbon intensity of electricity (top right), the electricity share in final energy (bottom left), and the carbon intensity of the residual (non-electricity) fuel mix (bottom right). Boxplots show median, interquartile range and full range of pathways. Pathway temperature classes (Table 2.1) and illustrative pathway archetypes are indicated in the legend. Values following the class labels give the number of available pathways in each class.

2.4.2 *Energy supply*

Several energy supply characteristics are evident in 1.5°C pathways assessed in this section: i) growth in the share of energy derived from low carbon-emitting sources (including renewables, nuclear, and fossil fuel with CCS) and a decline in the overall share of fossil fuels without CCS (Section 2.4.2.1), ii) rapid decline in the carbon intensity of electricity generation simultaneous with further electrification of energy end-use (Section 2.4.2.2), and iii) the growth in the use of CCS applied to fossil and biomass carbon in most 1.5°C pathways (Section 2.4.2.3).

2.4.2.1 Evolution of primary energy contributions over time

By mid-century, the majority of primary energy comes from non-fossil-fuels (i.e., renewables and nuclear energy) in most 1.5°C pathways (Table 2.6). Figure 2.15 shows the evolution of primary energy supply over this century across 1.5°C pathways, and in detail for the four illustrative pathway archetypes highlighted in this chapter. Note that this section reports primary energy using the direct equivalent method on a lower heating values basis (Bruckner et al., 2014).

Renewable energy (including biomass, hydro, solar, wind, and geothermal) increases across all 1.5°C pathways with the renewable energy share of primary energy reaching 28–88% in 2050 (Table 2.6) with an interquartile range of 49–67%. The magnitude and split between bioenergy, wind, solar, and hydro differ between pathways, as can be seen in the illustrative pathway archetypes in Figure 2.15. Bioenergy is a major supplier of primary energy, contributing to both electricity and other forms of final energy such as liquid fuels for transportation (Bauer et al., 2018). In 1.5°C pathways, there is a significant growth in bioenergy used in combination with CCS for pathways where it is included (Figure 2.15).

Nuclear power increases its share in most 1.5°C pathways by 2050, but in some pathways both the absolute capacity and share of power from nuclear generators declines (Table 2.15). There are large differences in nuclear power between models and across pathways (Kim et al., 2014; Rogelj et al., 2018). One of the reasons for this variation is that the future deployment of nuclear can be constrained by societal preferences assumed in narratives underlying the pathways (O'Neill et al., 2017; van Vuuren et al., 2017b). Some 1.5°C pathways no longer see a role for nuclear fission by the end of the century, while others project over 200 EJ yr^{-1} of nuclear power in 2100 (Figure 2.15).

The share of primary energy provided by total fossil fuels decreases from 2020 to 2050 in all 1.5°C pathways, however, trends for oil, gas and coal differ (Table 2.6). By 2050, the share of primary energy from coal decreases to 0–13% across 1.5°C pathways with an interquartile range of 1–7%. From 2020 to 2050 the primary energy supplied by oil changes by –93 to +6% (interquartile range –75 to –32%); natural gas changes by –88 to +99% (interquartile range –60 to –13%), with varying levels of CCS. Pathways with higher use of coal and gas tend to deploy CCS to control their carbon emissions (see Section 2.4.2.3). As the energy transition is accelerated by several decades in 1.5°C pathways compared to 2°C pathways, residual fossil-fuel use (i.e., fossil fuels not used for electricity generation) without CCS is generally lower in 2050 than in 2°C pathways, while combined hydro, solar, and wind power deployment is generally higher than in 2°C pathways (Figure 2.15).

In addition to the 1.5°C pathways included in the scenario database (Annex 2.A.3), there are other analyses in the literature including, for example, sector-based analyses of energy demand and supply options. Even though not necessarily developed in the context of the 1.5°C target, they explore in greater detail some options for deep reductions in GHG emissions. For example, there are analyses of transition to up to 100% renewable energy by 2050 (Creutzig et al., 2017; Jacobson et al., 2017), which describe what is entailed for a renewable energy share largely from solar and wind (and electrification) that is above the range of 1.5°C pathways available in the database, although there have been challenges to the assumptions used in high renewable analyses (e.g., Clack et al., 2017). There are also analyses that result in a large role for nuclear energy in mitigation of GHGs (Hong et al., 2015; Berger et al., 2017a, 2017b; Xiao and Jiang, 2017). BECCS could also contribute a larger share, but faces challenges related to its land use and impact on food supply (Burns and Nicholson, 2017) (assessed in greater detail in Sections 2.3.4.2, 4.3.7 and 5.4). These analyses could, provided their assumptions prove plausible, expand the range of 1.5°C pathways.

In summary, the share of primary energy from renewables increases while that from coal decreases across 1.5°C pathways (*high confidence*). This statement is true for all 1.5°C pathways in the scenario database and associated literature (Annex 2.A.3), and is consistent with the additional studies mentioned above, an increase in energy supply from lower-carbon-intensity energy supply, and a decrease in energy supply from higher-carbon-intensity energy supply.

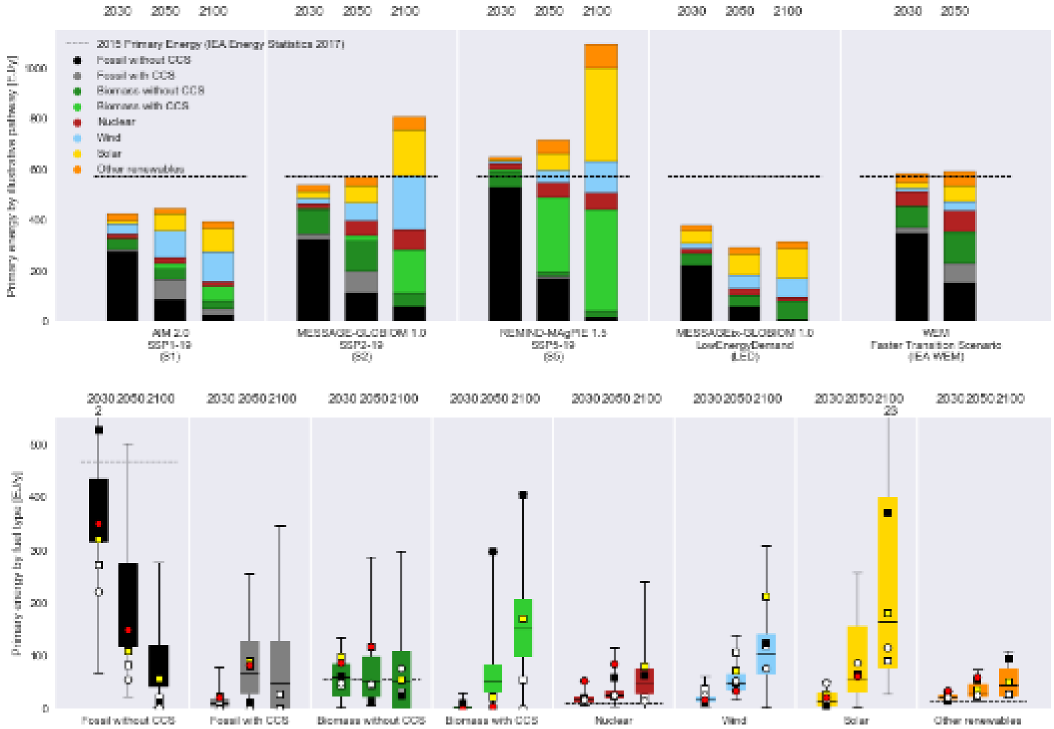

Figure 2.15: Primary energy supply for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (top panel), and their relative location in the ranges for 1.5°C and 2°C pathway classes (lower panel). The category 'Other renewables' includes primary energy sources not covered by the other categories, for example, hydro and geothermal energy. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicates the level of primary energy supply in 2015 (IEA, 2017e). Boxplots in the lower panel show the minimum-maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA's Faster Transition Scenario (red disc).

Table 2.6: Global primary energy supply of 1.5°C pathways from the scenario database (Annex 2.A.3). Values given for the median (maximum, minimum) across the full range of 85 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) – 1].

	Primary energy supply [EJ]			Share of primary energy [%]		Growth Factor
	2020	**2030**	**2050**	**2020**	**2050**	**2020-2050**
total primary	582.12 (636.98, 483.22)	502.81 (749.05, 237.37)	580.78 (1012.50, 289.02)			0.03 (0.59, -0.51)
renewables	87.70 (101.60, 60.16)	139.48 (203.90, 87.75)	293.80 (584.78, 176.77)	15.03 (20.39, 10.60)	60.80 (87.89, 28.47)	2.62 (6.71, 0.91)
biomass	61.35 (73.03, 40.54)	75.28 (113.02, 44.42)	154.13 (311.72, 40.36)	10.27 (14.23, 7.14)	26.38 (54.10, 10.29)	1.71 (5.56, -0.42)
non-biomass	26.35 (36.58, 17.60)	61.60 (114.41, 25.79)	157.37 (409.94, 53.79)	4.40 (7.19, 2.84)	28.60 (61.61, 9.87)	4.63 (13.46, 1.38)
nuclear	10.93 (18.55, 8.52)	16.22 (41.73, 6.80)	24.48 (115.80, 3.09)	1.97 (3.37, 1.45)	4.22 (13.60, 0.43)	1.34 (7.22, -0.64)
fossil	493.44 (638.04, 376.30)	347.62 (605.68, 70.14)	199.63 (608.39, 43.87)	83.56 (114.75, 77.73)	33.58 (74.63, 7.70)	-0.58 (0.12, -0.91)
coal	147.09 (193.55, 83.23)	49.46 (176.99, 5.97)	23.84 (134.69, 0.36)	25.72 (30.82, 17.19)	4.99 (13.30, 0.05)	-0.85 (-0.30, -1.00)
gas	135.58 (169.50, 105.01)	127.99 (208.55, 17.30)	88.97 (265.66, 14.92)	23.28 (28.39, 18.09)	13.46 (34.83, 2.80)	-0.37 (0.99, -0.88)
oil	195.02 (245.15, 151.02)	175.69 (319.80, 38.94)	93.48 (208.04, 15.07)	33.79 (42.24, 28.07)	16.22 (27.30, 2.89)	-0.54 (0.06, -0.93)

Table 2.7: Global electricity generation of 1.5°C pathways from the scenarios database (Annex 2.A.3). Values given for the median (maximum, minimum) values across the full range across 89 available 1.5°C pathways. Growth Factor = [(primary energy supply in 2050)/(primary energy supply in 2020) – 1].

	Electricty generation [EJ]			Share of electricity generation [%]		Growth Factor
	2020	**2030**	**2050**	**2020**	**2050**	**2020-2050**
total electricity	100.09 (113.98, 83.53)	120.01 (177.51, 81.28)	224.78 (363.10, 126.96)			1.31 (2.55, 0.28)
renewables	26.38 (41.80, 18.26)	59.50 (111.70, 30.06)	153.72 (324.26, 84.69)	27.95 (41.84, 17.38)	77.52 (96.65, 35.58)	5.08 (10.88, 2.37)
biomass	1.52 (7.00, 0.66)	3.55 (11.96, 0.79)	16.32 (40.32, 0.21)	1.55 (7.30, 0.63)	8.02 (30.28, 0.08)	6.53 (38.14, -0.93)
non-biomass	24.48 (35.72, 17.60)	55.68 (101.90, 25.79)	136.40 (323.91, 53.79)	25.00 (40.43, 16.75)	66.75 (96.46, 27.51)	4.75 (10.64, 1.38)
nuclear	10.84 (18.55, 8.52)	15.49 (41.73, 6.80)	22.64 (115.80, 3.09)	10.91 (18.34, 8.62)	8.87 (39.61, 1.02)	1.21 (7.22, -0.64)
fossil	61.35 (76.76, 39.48)	38.41 (87.54, 2.25)	14.10 (118.12, 0.00)	61.55 (71.03, 47.26)	8.05 (33.19, 0.00)	-0.76 (0.54, -1.00)
coal	32.37 (46.20, 14.40)	10.41 (43.12, 0.00)	1.29 (46.72, 0.00)	32.39 (40.88, 17.23)	0.59 (12.87, 0.00)	-0.96 (0.01, -1.00)
gas	24.70 (41.20, 13.44)	25.00 (51.99, 2.01)	11.92 (67.94, 0.00)	24.71 (39.20, 11.80)	6.78 (32.59, 0.00)	-0.52 (1.63, -1.00)
oil	1.82 (13.36, 1.12)	0.92 (7.56, 0.24)	0.08 (8.78, 0.00)	2.04 (11.73, 1.01)	0.04 (3.80, 0.00)	-0.97 (0.98, -1.00)

2.4.2.2 Evolution of electricity supply over time

Electricity supplies an increasing share of final energy, reaching 34 to 71% in 2050, across 1.5°C pathways (Figure 2.14), extending the historical increases in electricity share seen over the past decades (Bruckner et al., 2014). From 2020 to 2050, the quantity of electricity supplied in most 1.5°C pathways more than doubles (Table 2.7). By 2050, the carbon intensity of electricity has fallen rapidly to -92 to +11 gCO_2/MJ electricity across 1.5°C pathways from a value of around 140 gCO_2/MJ (range: 88–181 gCO_2/MJ) in 2020 (Figure 2.14). A negative contribution to carbon intensity is provided by BECCS in most pathways (Figure 2.16).

By 2050, the share of electricity supplied by renewables increases from 23% in 2015 (IEA, 2017b) to 36–97% across 1.5°C pathways. Wind, solar, and biomass together make a major contribution in 2050, although the share for each spans a wide range across 1.5°C pathways (Figure 2.16). Fossil fuels on the other hand have a decreasing role in electricity supply with their share falling to 0–33% by 2050 (Table 2.7).

In summary, 1.5°C pathways include a rapid decline in the carbon intensity of electricity and an increase in electrification of energy end use (*high confidence*). This is the case across all 1.5°C pathways and their associated literature (Annex 2.A.3), with pathway trends that extend those seen in past decades, and results that are consistent with additional analyses (see Section 2.4.2.2).

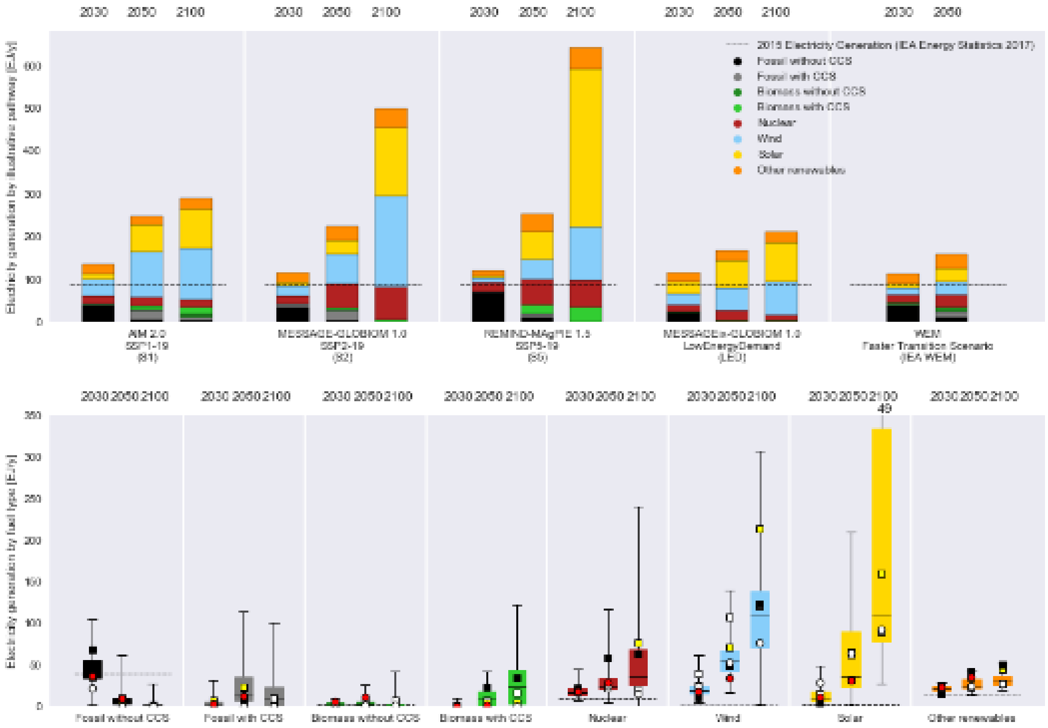

Figure 2.16: Electricity generation for the four illustrative pathway archetypes plus the IEA's Faster Transition Scenario (OECD/IEA and IRENA, 2017) (top panel), and their relative location in the ranges for 1.5°C and 2°C scenario classes (lower panel). The category 'Other renewables' includes electricity generation not covered by the other categories, for example, hydro and geothermal. The number of pathways that have higher primary energy than the scale in the bottom panel are indicated by the numbers above the whiskers. Black horizontal dashed lines indicate the level of primary energy supply in 2015 (IEA, 2017e). Boxplots in the lower panel show the minimum-maximum range (whiskers), interquartile range (box), and median (vertical thin black line). Symbols in the lower panel show the four pathway archetypes S1 (white square), S2 (yellow square), S5 (black square), LED (white disc), as well as the IEA's Faster Transition Scenario (red disc).

2.4.2.3 Deployment of Carbon Capture and Storage

Studies have shown the importance of CCS for deep mitigation pathways (Krey et al., 2014a; Kriegler et al., 2014b), based on its multiple roles to limit fossil-fuel emissions in electricity generation, liquids production, and industry applications along with the projected ability to remove CO_2 from the atmosphere when combined with bioenergy. This remains a valid finding for those 1.5°C and 2°C pathways that do not radically reduce energy demand nor offer carbon-neutral alternatives to liquids and gases that do not rely on bioenergy.

There is a wide range of CCS that is deployed across 1.5°C pathways (Figure 2.17). A few 1.5°C pathways with very low energy demand do not include CCS at all (Grubler et al., 2018). For example, the LED pathway has no CCS, whereas other pathways like the S5 pathway rely on a large amount of BECCS to get to net-zero carbon emissions. The cumulative fossil and biomass CO_2 stored through 2050 ranges from zero to 460 $GtCO_2$ across 1.5°C pathways, with zero up to 190 $GtCO_2$ from biomass captured and stored. Some pathways have very low fossil-fuel use overall, and consequently little CCS applied to fossil fuels. In 1.5°C pathways where the 2050 coal use remains above 20 EJ yr^{-1} in 2050, 33–100% is combined with CCS. While deployment of CCS for natural gas and coal vary widely across pathways, there is greater natural gas primary energy connected to CCS than coal primary energy connected to CCS in many pathways (Figure 2.17).

CCS combined with fossil-fuel use remains limited in some 1.5°C pathways (Rogelj et al., 2018) as the limited 1.5°C carbon budget penalizes CCS if it is assumed to have incomplete capture rates or if fossil fuels are assumed to continue to have significant lifecycle GHG emissions (Pehl et al., 2017). However, high capture rates are technically achievable now at higher cost, although effort to date have focussed on cost reduction of capture (IEAGHG, 2006; DOE/NETL, 2013).

The quantity of CO_2 stored via CCS over this century in 1.5°C pathways ranges from zero to 1,900 $GtCO_2$, (Figure 2.17). The IPCC Special Report on on Carbon Dioxide Capture and Storage (IPCC, 2005) found that that, worldwide, it is *likely* that there is a technical potential of at least about 2,000 $GtCO_2$ of storage capacity in geological formations. Furthermore the IPCC (2005) recognised that there could be a much larger potential for geological storage in saline formations, but the upper limit estimates are uncertain due to lack of information and an agreed methodology. Since IPCC (2005), understanding has improved and there have been detailed regional surveys of storage capacity (Vangkilde-Pedersen et al., 2009; Ogawa et al., 2011; Wei et al., 2013; Bentham et al., 2014; Riis and Halland, 2014; Warwick et al., 2014; NETL, 2015) and improvement and standardisation of methodologies (e.g., Bachu et al. 2007a, b). Dooley (2013) synthesised published literature on both the global geological storage resource as well as the potential demand for geologic storage in mitigation pathways, and found that the cumulative demand for CO_2 storage was small compared to a practical storage capacity estimate (as defined by Bachu et al., 2007a) of 3,900 $GtCO_2$ worldwide. Differences, however, remain in estimates of storage capacity due to, e.g. the potential storage limitations of subsurface pressure build-up (Szulczewski et al., 2014) and assumptions on practices that could manage such issues (Bachu, 2015). Kearns et al. (2017) constructed estimates of global storage capacity of 8,000 to 55,000 $GtCO_2$ (accounting for differences in detailed regional and local estimates), which is sufficient at a global level for this century, but found that at a regional level, robust demand for CO_2 storage exceeds their lower estimate of regional storage available for some regions. However, storage capacity is not solely determined by the geological setting, and Bachu (2015) describes storage engineering practices that could further extend storage capacity estimates. In summary, the storage capacity of all of these global estimates is larger than the cumulative CO_2 stored via CCS of 1.5°C pathways over this century.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Bruckner et al., 2014; Clarke et al., 2014; Riahi et al., 2017). Given the importance of CCS in most mitigation pathways and its current slow pace of improvement, the large-scale deployment of CCS as an option depends on the further development of the technology in the near term. Chapter 4 discusses how progress on CCS might be accelerated.

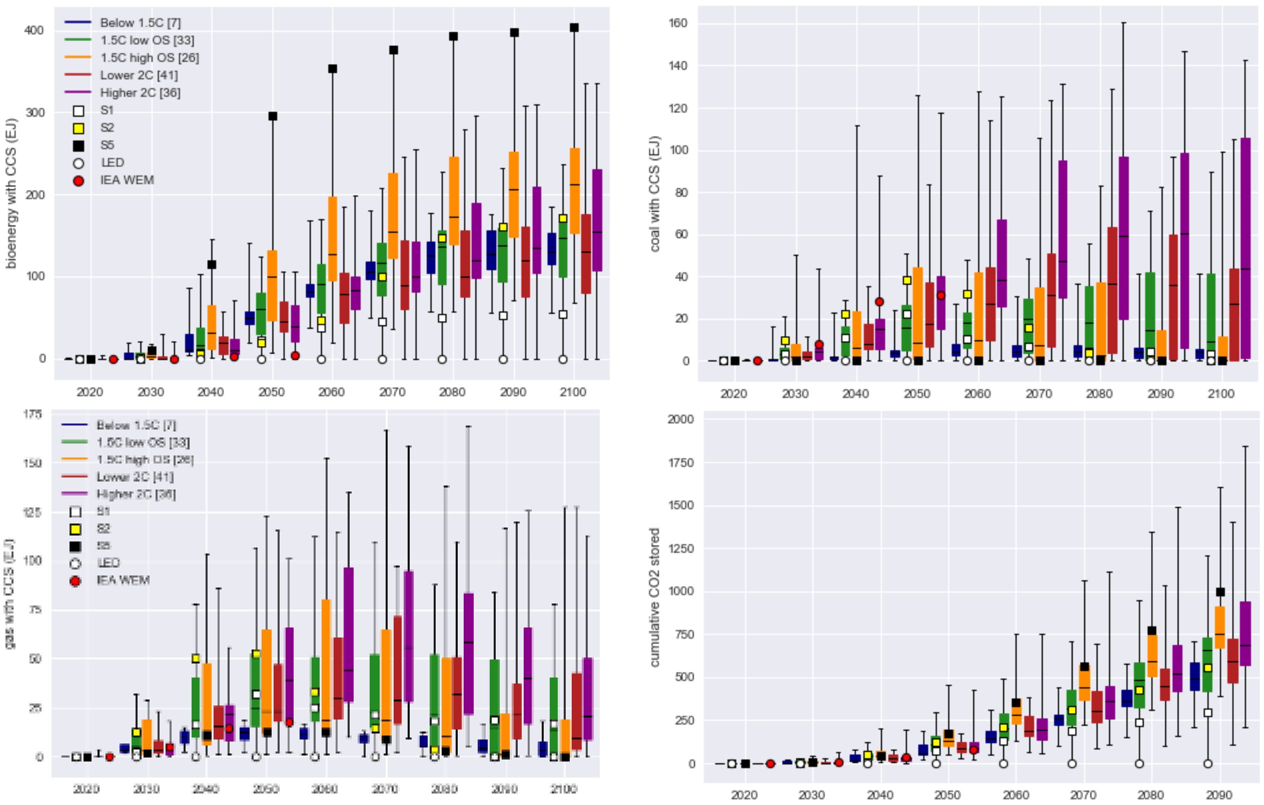

Figure 2.17: CCS deployment in 1.5°C and 2°C pathways for biomass, coal and natural gas (EJ of primary energy) and the cumulative quantity of fossil (including from, e.g., cement production) and biomass CO_2 stored via CCS (lower right in $GtCO_2$ stored). Boxplots show median, interquartile range and full range of pathways in each temperature class. Pathway temperature classes (Table 2.1), illustrative pathway archetypes, and the IEA's Faster Transition Scenario (IEA WEM) (OECD/IEA and IRENA, 2017) are indicated in the legend.

2.4.3 *Energy end-use sectors*

Since the power sector is almost decarbonized by mid-century in both 1.5°C and 2°C pathways, major differences come from CO_2 emission reductions in end-use sectors. Energy-demand reductions are key and common features in 1.5˚C-consistent pathways, which can be achieved by efficiency improvements and various specific demand-reduction measures. Another important feature is end-use decarbonisation including by electrification, although the potential and challenges in each end-use sector vary significantly.

In the following sections, the potential and challenges of CO_2 emission reductions towards 1.5°C and 2°C-consistent pathways are discussed for each end-use energy sector (industry, buildings, and transport sectors). For this purpose, two types of pathways are analysed and compared: IAM (integrated assessment modelling) studies and sectoral (detailed) studies. IAM data are extracted from the database that was compiled for this assessment (see Annex 2.A.3), and the sectoral data are taken from a recent series of publications; 'Energy Technology Perspectives' (ETP) (IEA, 2014, 2015b, 2016a, 2017a), the IEA/IRENA report (OECD/IEA and IRENA, 2017), and the Shell Sky report (Shell International B.V., 2018). The IAM pathways are categorized according to their temperature rise in 2100 and the overshoot of temperature during the century (see Table 2.1 in Section 2.1). Since the number of Below-1.5°C pathways is small, the following analyses focus only on the featured of the 1.5°C-low-OS and 1.5°C-high-OS pathways (hereafter denoted together as 1.5°C overshoot pathways or IAM-1.5DS-OS) and 2°C-consistent pathways (IAM-2DS). In order to show the diversity of IAM pathways, we again show specific data from the four illustrative pathways archetypes used throughout this chapter (see Sections 2.1 and 2.3).

IEA ETP-B2DS ('Beyond 2 Degrees') and ETP-2DS are pathways with a 50% chance of limiting temperature rise below 1.75°C and 2°C by 2100, respectively (IEA, 2017a). The IEA-66%2DS pathway keeps global-mean temperature rise below 2°C not just in 2100 but also over the course of the 21st century with a 66% chance of being below 2°C by 2100 (OECD/IEA and IRENA, 2017). The comparison of CO_2 emission trajectories between ETP-B2DS and IAM-1.5DS-OS show that these are consistent up to 2060 (Figure 2.18). IEA scenarios assume that only a very low level of BECCS is deployed to help offset emissions in difficult-to-decarbonize sectors, and that global energy-related CO_2 emissions cannot turn net-negative at any time and stay zero from 2060 to 2100 (IEA, 2017a). Therefore, although its temperature rise in 2100 is below 1.75°C rather than below 1.5°C, this scenario can give information related to 1.5°C-consistent overshoot pathway up to 2050. The trajectory of IEA-66%2DS (also referred to in other publications as IEA's 'Faster Transition Scenario') lies between IAM-1.5DS-OS and IAM-2DS pathway ranges, and IEA-2DS stays in the range of 2°C-consistent IAM pathways. The Shell-Sky scenario aims to hold the temperature rise to well-below 2°C, but it is a delayed action pathway relative to others, as can be seen in Figure 2.18.

Energy-demand reduction measures are key to reduce CO_2 emissions from end-use sectors for low-carbon pathways. The up-stream energy reductions can be several times to an order of magnitude larger than the initial end-use demand reduction. There are interdependencies among the end-use sectors and also between energy-supply and end-use sectors, which raise the importance of a wide, systematic approach. As shown in Figure 2.19, global final-energy consumption grows by 30% and 10% from 2010 to 2050 for 2°C-consistent and 1.5°C overshoot pathways from IAMs, respectively, while much higher growth of 75% is projected for reference scenarios. The ranges within a specific pathway class are due to a variety of factors as introduced in Section 2.3.1, as well as differences between modelling frameworks. The important energy efficiency improvements and energy conservation that facilitate many of the 1.5°C pathways raise the issue of potential rebound effects (Saunders, 2015), which, while promoting development, can make the achievement of low-energy demand futures more difficult than modelling studies anticipate (see Sections 2.5 and 2.6).

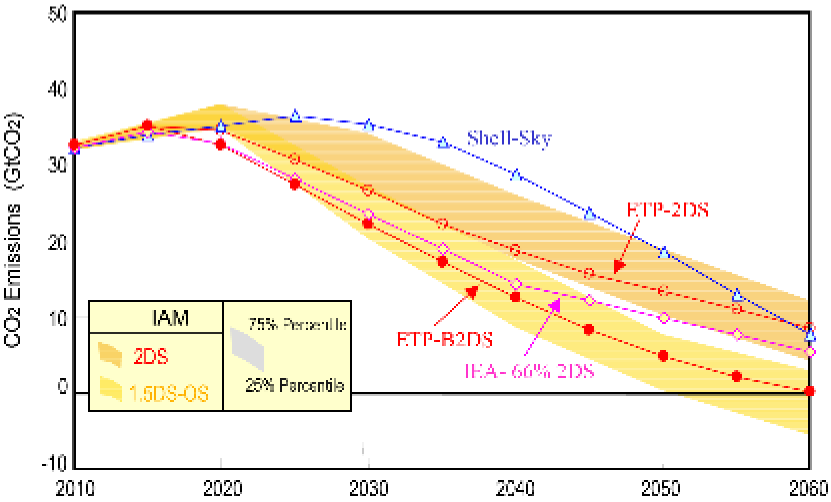

Figure 2.18: Comparison of CO_2 emission trajectories of sectoral pathways (IEA ETP-B2DS, ETP-2DS, IEA-66%2DS, Shell-Sky) with the ranges of IAM pathway (2DS are 2°C-consistent pathways and 1.5DS-OS are1.5°C-consistent overshoot pathways). The CO_2 emissions shown here are the energy-related emissions including industrial process emissions.

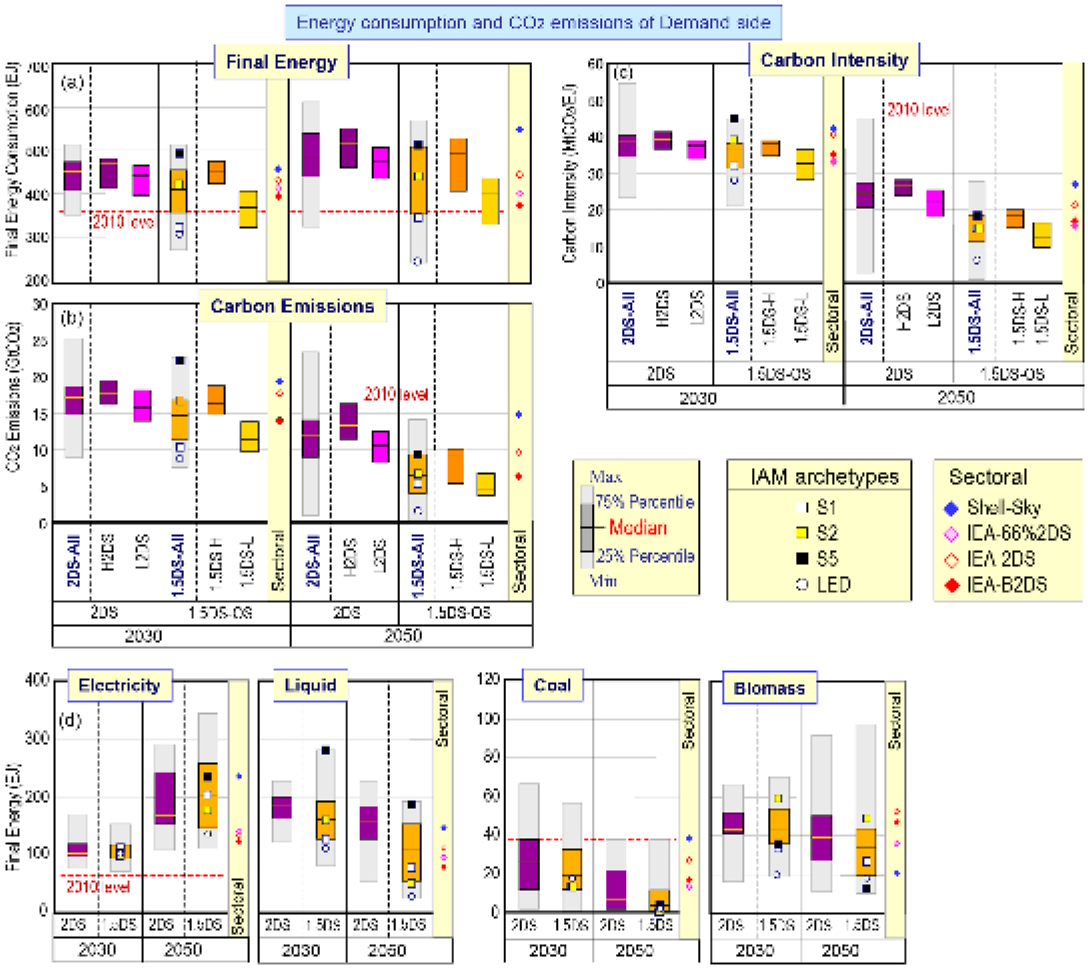

Figure 2.19: (a) Global final energy, (b) direct CO₂ emissions from the all energy demand sectors, (c) carbon intensity, and (d) structure of final energy (electricity, liquid fuel, coal, and biomass). The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

Final-energy demand is driven by demand in energy services for mobility, residential and commercial activities (buildings), and manufacturing. This heavily depends on assumptions about socio-economic futures as represented by the SSPs (Bauer et al., 2017) (see Sections 2.1, 2.3 and 2.5). The structure of this demand drives the composition of final energy use in terms of energy carriers (electricity, liquids, gases, solids, hydrogen etc.).

Figure 2.19 shows the structure of global final energy demand in 2030 and 2050, indicating the trend toward electrification and fossil fuel usage reduction. This trend is more significant in 1.5°C pathways than 2°C pathways. Electrification continues throughout the second half of the century leading to a 3.5 to 6-fold increase in electricity demand (interquartile range; median 4.5) by the end of the century relative to today (Grubler et al., 2018; Luderer et al., 2018). Since the electricity sector is completely decarbonised by mid-century in 1.5°C pathways (see Figure 2.20), electrification is the primary means to decarbonize energy end-use sectors.

The CO_2 emissions[6] of end-use sectors and carbon intensity are shown in Figure 2.20. The projections of IAMs and IEA studies show rather different trends, especially in the carbon intensity. These differences come from various factors, including the deployment of CCS, the level of fuel switching and efficiency

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[6] FOOTNOTE: This section reports "direct" CO_2 emissions as reported for pathways in the database for the report. As shown below, the emissions from electricity are nearly zero around 2050, so the impact of indirect emissions on the whole emission contributions of each sector is very small in 2050.

improvements, and the effect of structural and behavioural changes. IAM projections are generally optimistic for the industry sectors, but not for buildings and transport sectors. Although GDP increases by a factor of 3.4 from 2010 to 2050, the total energy consumption of end-use sectors grows by only about 30% and 20% in 1.5°C overshoot and 2°C-consistent pathways, respectively. However, CO_2 emissions would need to be reduced further to achieve the stringent temperature limits. Fig. 2.20 shows that the reduction in CO_2 emissions of end-use sectors is larger and more rapid in 1.5°C overshoot than 2°C-consistent pathways, while emissions from the power sector are already almost zero in 2050 in both sets of pathways indicating that supply-side emissions reductions are almost fully exploited already in 2°C-consistent pathways (see Figure 2.20) (Rogelj et al., 2015b, 2018; Luderer et al., 2016b). The emission reductions in end-use sectors is largely made possible due to efficiency improvements, demand reduction measures and electrification, but its level differs among end-use sectors. While the carbon intensity of industry and the buildings sector decreases to a very low level of around 10 $gCO_2\ MJ^{-1}$, the carbon intensity of transport becomes the highest of any sector by 2040 due to its higher reliance on oil-based fuels. In the following subsections, the potential and challenges of CO_2 emission reduction in each end-use sector are discussed in detail.

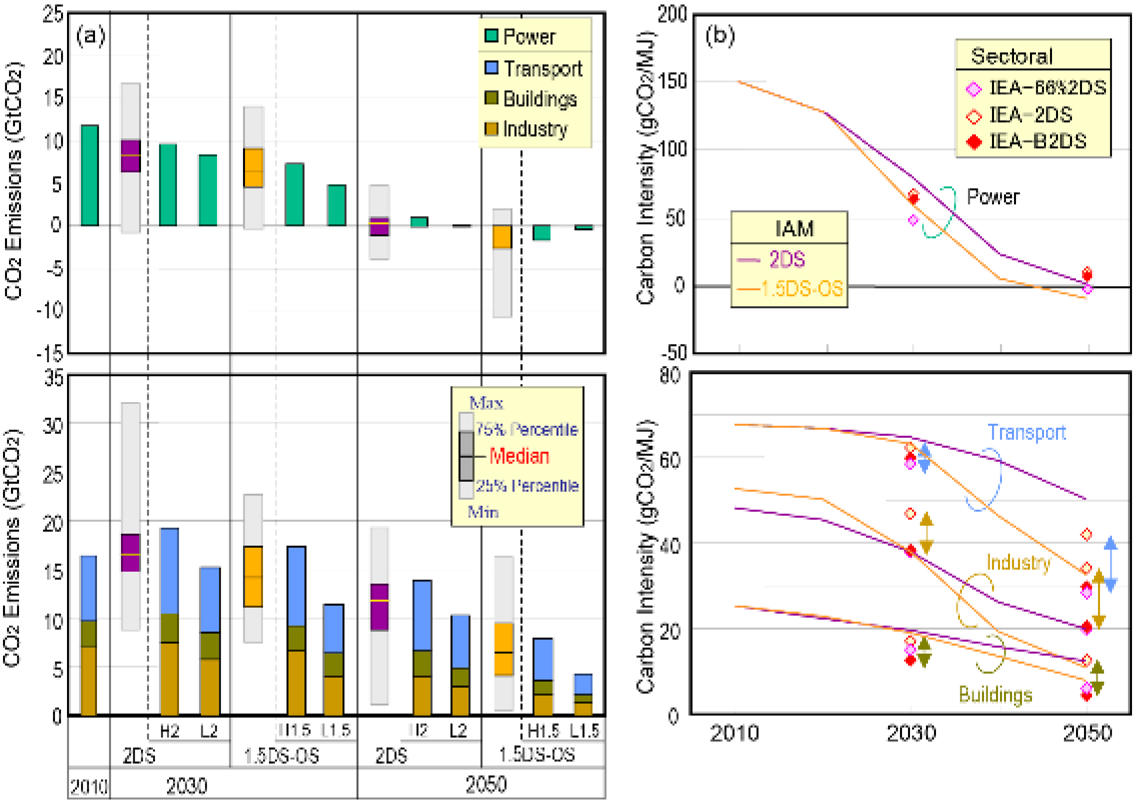

Figure 2.20: Comparison of (a) direct CO_2 emissions and (b) carbon intensity of the power and energy end-use sectors (industry, buildings, and transport sectors) between IAMs and sectoral studies (IEA-ETP and IEA/IRENA). Diamond markers in panel (b) show data for IEA-ETP scenarios (2DS and B2DS), and IEA/IRENA scenario (66%2DS). Note: for the data of IAM studies, there is rather large variation of projections for each indicator. Please see the details in the following figures in each end-use sector section.

2.4.3.1 Industry

The industry sector is the largest end-use sector both in terms of final-energy demand and GHG emissions. Its direct CO_2 emissions currently account for about 25% of total energy-related and process CO_2 emissions, and have increased with an average annual rate of 3.4% between 2000 and 2014, significantly faster than total CO_2 emissions (Hoesly et al., 2018). In addition to emissions from the combustion of fossil fuels, non-energy uses of fossil fuels in the petro-chemical industry and metal smelting, as well as non-fossil fuel process emissions (e.g., from cement production) contribute a small amount (~5%) to the sector’s CO_2 emissions inventory. Material industries are particularly energy and emissions intensive: steel, non-ferrous metals, chemicals, non-metallic minerals, and pulp and paper alone accounted for close to 66% of final-energy demand, and 72% of direct industry sector emissions in 2014 (IEA, 2017a). In terms of end-uses, the bulk of energy in manufacturing industries is required for process heating and steam generation, while most electricity (but smaller shares of total final energy) is used for mechanical work (Banerjee et al., 2012; IEA, 2017a).

As shown in Figure 2.21, a major share of the additional emission reductions required for 1.5°C-overshoot pathways beyond those in 2°C-consistent pathways comes from industry. Final energy, CO_2 emissions, and carbon intensity are consistent in IAM and sectoral studies, but in IAM-1.5°C-overshoot pathways the share of electricity is higher than IEA-B2DS (40% vs. 25%) and hydrogen is also considered to have a share of about 5% vs. 0%. In 2050, final energy is increased by 30% and 5% compared with the 2010 level (red dotted line) for 1.5°C-overshoot and 2°C-consistent pathways, respectively, but CO_2 emissions are decreased by 80% and 50% and carbon intensity by 80% and 60%, respectively. This additional decarbonisation is brought by switching to low carbon fuels and CCS deployment.

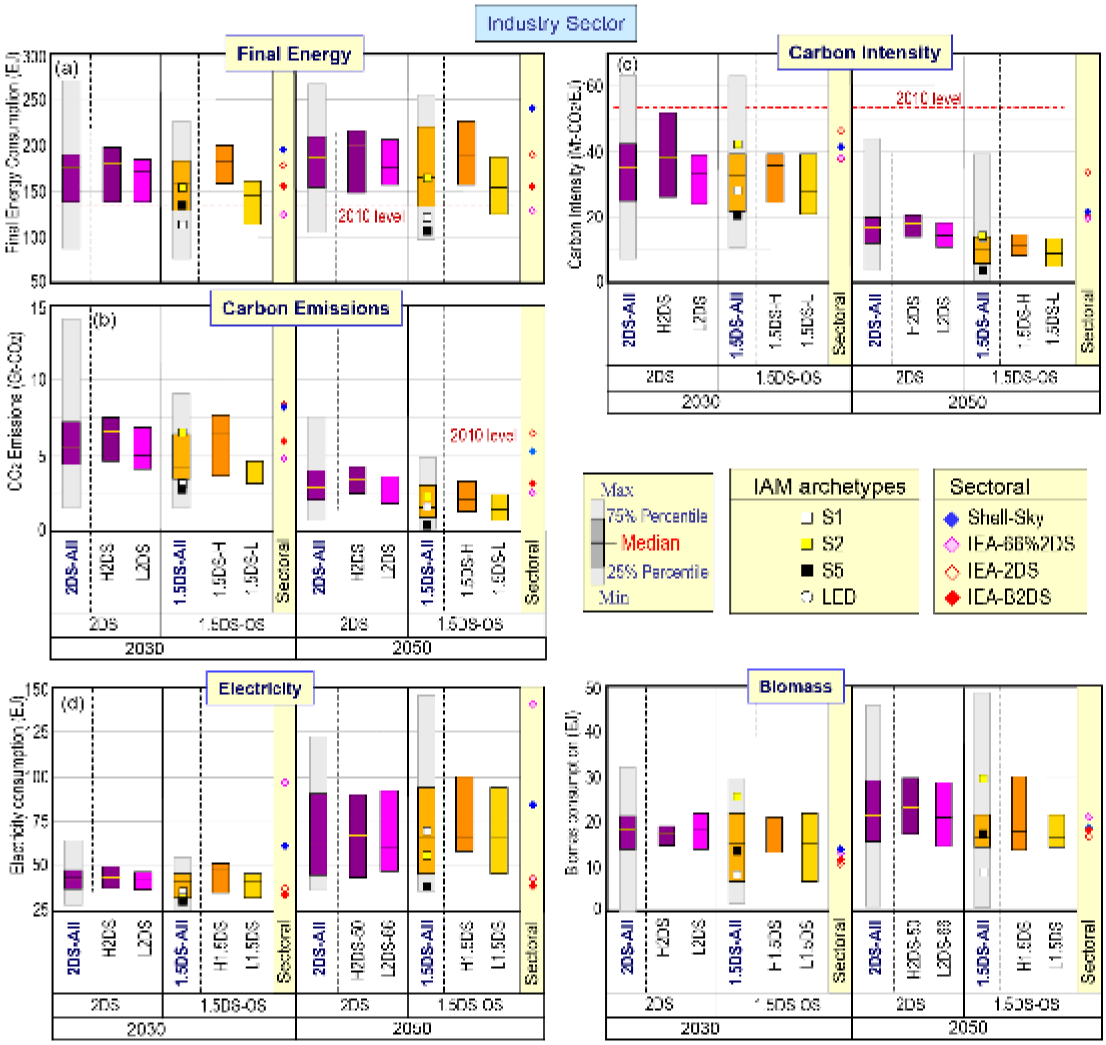

Figure 2.21: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the industry sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

Broadly speaking, the industry sector's mitigation measures can be categorized in terms of the following five strategies: (i) reductions in the demand, (ii) energy efficiency, (iii) increased electrification of energy demand, (iv) reducing the carbon content of non-electric fuels, and (v) deploying innovative processes and application of CCS. IEA ETP estimates the relative contribution of different measures for CO_2 emission reduction in their B2DS scenario compared with their reference scenario in 2050 as follows: energy efficiency 42%, innovative process and CCS 37%, switching to low carbon fuels and feed-stocks 13% and material efficiency (include efficient production and use to contribute to demand reduction) 8%. The remainder of this section delves more deeply into the potential mitigation contributions of these strategies as well as their limitations.

Reduction in the use of industrial materials, while delivering similar services, or improving the quality of products could help to reduce energy demand and overall system-level CO_2 emissions. Strategies include using materials more intensively, extension of product lifetimes, increasing recycling, and increasing inter-industry material synergies, such as clinker substitution in cement production (Allwood et al., 2013; IEA, 2017a). Related to material efficiency, use of fossil-fuel feed-stocks could shift to lower-carbon feed-stocks such as oil to natural gas and biomass and end-uses could shift to more sustainable materials such as biomass-based materials, reducing the demand for energy-intensive materials (IEA, 2017a).

Reaping energy efficiency potentials hinges critically on advanced management practices in industrial facilities such as energy management systems, as well as targeted policies to accelerate adoption of best available technology (see Section 2.5). Although excess energy, usually as waste heat, is inevitable, recovering and reusing this waste heat under economically and technically viable conditions benefits the overall energy system. Furthermore, demand-side management strategies could modulate the level of industrial activity in line with the availability of resources in the power system. This could imply a shift away from peak demand and as power supply decarbonizes, this demand-shaping potential could shift some load to times with high portions of low-carbon electricity generation (IEA, 2017a).

In the industry sector, energy demand increases more than 40% between 2010 and 2050 in baseline scenarios. However, in the 1.5°C-overshoot and 2°C-consistent pathways from IAMs, the increase is only 30% and 5%, respectively (Figure 2.21). These energy demand reductions encompass both efficiency improvements in production as well as reductions in material demand, as most IAMs do not discern these two factors.

CO_2 emissions from industry increase by 30% in 2050 compared to 2010 in baseline scenarios. By contrast, these emissions are reduced by 80% and 50% relative to 2010 levels in 1.5°C-overshoot and 2°C-consistent pathways from IAMs, respectively (Figure 2.21). By mid-century, CO_2 emissions per unit electricity are projected to decrease to near zero in both sets of pathways (see Figure 2.20). An accelerated electrification of the industry sector thus becomes an increasingly powerful mitigation option. In the IAM pathways, the share of electricity increases up to 30% by 2050 in 1.5°C-overshoot pathways (Figure 2.21) from 20% in 2010. Some industrial fuel uses are substantially more difficult to electrify than others, and electrification would have other effects on the process, including impacts on plant design, cost and available process integration options (IEA, 2017a)[7].

In 1.5°C-overshoot pathways, the carbon intensity of non-electric fuels consumed by industry decreases to 16 $gCO_2\ MJ^{-1}$ by 2050, compared to 25 $gCO_2\ MJ^{-1}$ in 2°C-consistent pathways. Considerable carbon intensity reductions are already achieved by 2030, largely via a rapid phase-out of coal. Biomass becomes an increasingly important energy carrier in the industry sector in deep-decarbonisation pathways, but primarily in the longer term (in 2050, biomass accounts for only 10% of final energy consumption even in 1.5°C-overshoot pathways). In addition, hydrogen plays a considerable role as a substitute for fossil-based non-electric energy demands in some pathways.

Without major deployment of new sustainability-oriented low-carbon industrial processes, the 1.5°C-overshoot target is difficult to achieve. Bringing such technologies and processes to commercial deployment requires significant investment in research and development. Some examples of innovative low-carbon process routes include: new steelmaking processes such as upgraded smelt reduction and upgraded direct reduced iron, inert anodes for aluminium smelting, and full oxy-fuelling kilns for clinker production in cement manufacturing (IEA, 2017a).

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[7] FOOTNOTE: Electrification can be linked with the heating and drying process by electric boilers and electro-thermal processes, and also low-temperature heat demand by heat pumps. In iron and steel industry, hydrogen produced by electrolysis can be used as a reduction agent of iron instead of coke. Excess resources, such as black liquor will provide the opportunity to increase the systematic efficiency to use for electricity generation.

CCS plays a major role in decarbonizing the industry sector in the context of 1.5°C and 2°C pathways, especially in industries with higher process emissions, such as cement, iron and steel industries. In 1.5°C-overshoot pathways, CCS in industry reaches 3 $GtCO_2$ yr^{-1} by 2050, albeit with strong variations across pathways. Given project long-lead times and the need for technological innovation, early scale-up of industry CCS is essential to achieve the stringent temperature target. Development and demonstration of such projects has been slow, however. Currently, only two large-scale industrial CCS projects outside of oil and gas processing are in operation (Global CCS Institute, 2016). The estimated current cost[8] of CO_2 avoided (in 2015-US$) ranges from $20-27 tCO_2^{-1} for gas processing and bio-ethanol production, and $60-138 tCO_2^{-1} for fossil fuel-fired power generation up to $104-188 tCO_2^{-1} for cement production (Irlam, 2017).

2.4.3.2 Buildings

In 2014, the buildings sector accounted for 31% of total global final-energy use, 54% of final-electricity demand, and 8% of energy-related CO_2 emissions (excluding indirect emission due to electricity). When upstream electricity generation is taken into account, buildings were responsible for 23% of global energy-related CO_2 emissions, with one-third of those from direct fossil fuel consumption (IEA, 2017a).

Past growth of energy consumption has been mainly driven by population and economic growth, with improved access to electricity, and higher use of electrical appliances and space cooling resulting from increasing living standards, especially in developing countries (Lucon et al., 2014). These trends will continue in the future and in 2050, energy consumption is projected to increase by 20% (50%) compared to 2010 in IAM-1.5°C-overshoot (2°C-consistent) pathways (Figure 2.22). However, sectoral studies (IEA-ETP scenarios) show different trends. Energy consumption in 2050 decreases compared to 2010 in ETP-B2DS, and the reduction rate of CO_2 emissions is higher than in IAM pathways (Figure 2.22). Mitigation options are often more widely covered in sectoral studies (Lucon et al., 2014), leading to greater reductions in energy consumption and CO_2 emissions.

Emissions reductions are driven by a clear tempering of energy demand and a strong electrification of the buildings sector. The share of electricity in 2050 is 60% in 1.5°C-overshoot pathways, compared with 50% in 2°C-consistent pathways (Figure 2.22). Electrification contributes to the reduction of direct CO_2 emissions by replacing carbon-intensive fuels, like oil and coal. Furthermore, when combined with a rapid decarbonisation of the power system (see Section 2.4.1) it also enables further reduction of indirect CO_2 emissions from electricity. Sectoral bottom-up models in general estimate lower electrification potentials for the buildings sector in comparison to global IAMs (see Figure 2.22). Besides CO_2 emissions, increasing global demand for air conditioning in buildings may also lead to increased emissions of HFCs in this sector over the next few decades. Although these gases are currently a relatively small proportion of annual GHG emissions, their use in the air conditioning sector is expected to grow rapidly over the next few decades if alternatives are not adopted. However, their projected future impact can be significantly mitigated through better servicing and maintenance of equipment and switching of cooling gases (Shah et al., 2015; Purohit and Höglund-Isaksson, 2017).

IEA-ETP (IEA, 2017a) analysed the relative importance of various technology measures toward the reduction of energy and CO_2 emissions in the buildings sector. The largest energy savings potential is in heating and cooling demand largely due to building envelope improvements and high efficiency and renewable equipment. In the ETP-B2DS, energy demand for space heating and cooling is 33% lower in 2050 than the reference scenario and these reductions account for 54% of total reductions from the reference scenario. Energy savings from shifts to high-performance lighting, appliances, and water heating equipment account for a further 24% of the total reduction. The long-term, strategic shift away from fossil-fuel use in buildings, alongside the rapid uptake of energy efficient, integrated and renewable energy technologies (with clean power generation), leads to a drastic reduction of CO_2 emissions. In ETP-B2DS, the direct CO_2 emissions are 79% lower than the reference scenario in 2050 and the remaining emissions come mainly from the continued use of natural gas.

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[8] FOOTNOTE: These are first-of-a-kind (FOAK) cost data.

The buildings sector is characterized by very long-living infrastructure and immediate steps are hence important to avoid lock-in of inefficient carbon and energy-intensive buildings. This applies both to new buildings in developing countries where substantial new construction is expected in the near future and to retrofits of existing building stock in developed regions. This represents both a significant risk and opportunity for mitigation[9]. A recent study highlights the benefits of deploying the most advanced renovation technologies, which would avoid lock-in into less efficient measures (Güneralp et al., 2017). Aside from the effect of building envelope measures, adoption of energy-efficient technologies such as heat pumps and more recently light-emitting diodes is also important for the reduction of energy and CO_2 emissions (IEA, 2017a). Consumer choices, behaviour and building operation can also significantly affect energy consumption (see Section 4.3).

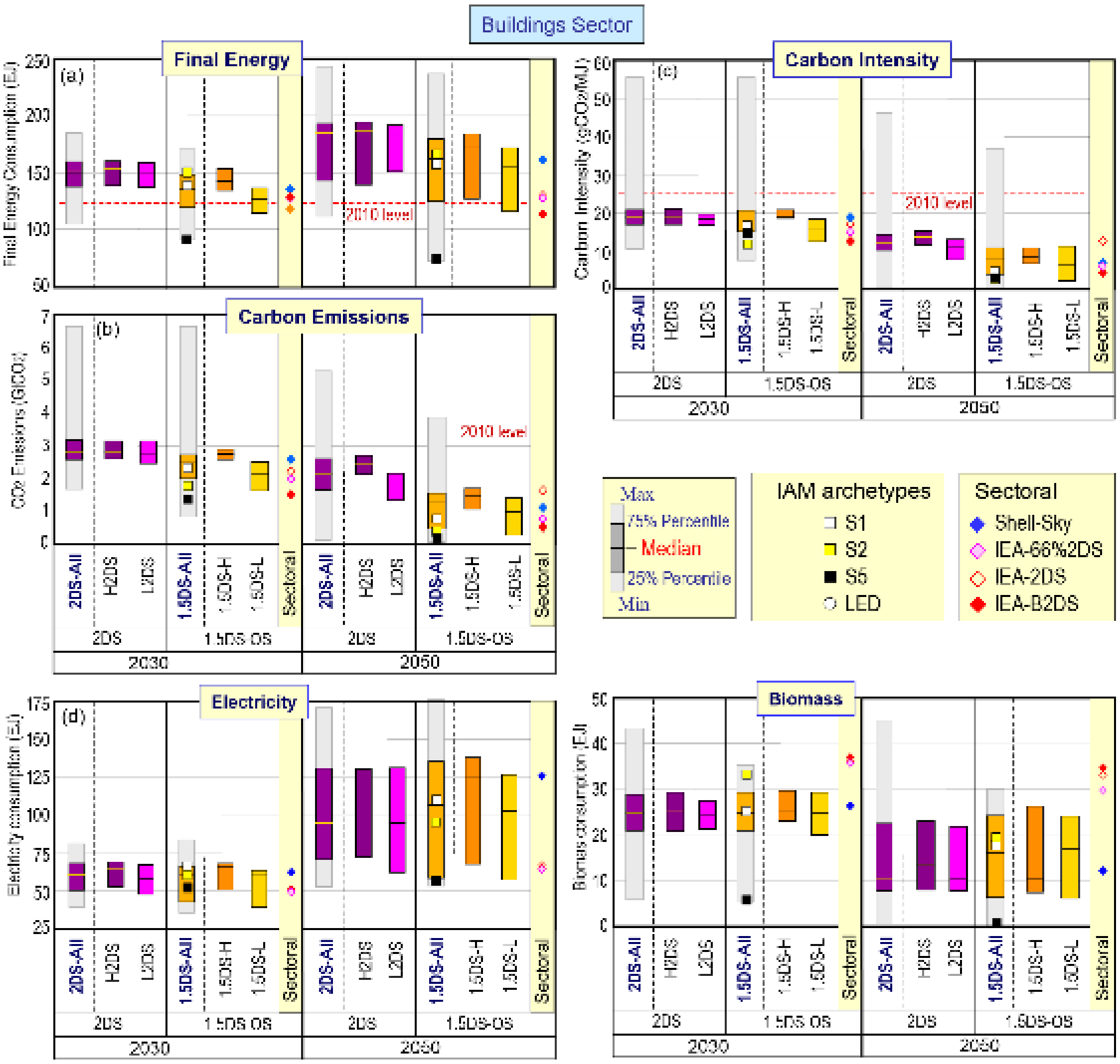

Figure 2.22: Comparison of (a) final energy, (b) direct CO_2 emissions, (c) carbon intensity, (d) electricity and biomass consumption in the buildings sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

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[9] FOOTNOTE: In this section, we only discuss the direct emissions from the sector, but the selection of building materials have a significant impact on the reduction of energy and emissions during the production, such as shift from the steel and concrete to wood-based materials.

2.4.3.3 Transport

Transport accounted for 28% of global final-energy demand and 23% of global energy-related CO_2 emissions in 2014. Emissions increased by 2.5% annually between 2010 and 2015, and over the past half century the sector has witnessed faster emissions growth than any other. The transport sector is the least diversified energy end-use sector; the sector consumed 65% of global oil final-energy demand, with 92% of transport final-energy demand consisting of oil products (IEA, 2017a), suggesting major challenges for deep decarbonisation.

Final energy, CO_2 emissions, and carbon intensity for the transport sector are shown in Figure 2.23. The projections of IAMs are more pessimistic than IEA-ETP scenarios, though both clearly project deep cuts in energy consumption and CO_2 emissions by 2050. For example, 1.5°C-overshoot pathways from IAMs project a reduction of 15% in energy consumption between 2015 and 2050, while ETP-B2DS projects a reduction of 30% (Figure 2.23). Furthermore, IAM pathways are generally more pessimistic in the projections of CO_2 emissions and carbon intensity reductions. In AR5 (Clarke et al., 2014; Sims et al., 2014), similar comparisons between IAMs and sectoral studies were performed and these were in good agreement with each other. Since the AR5, two important changes can be identified; rapid growth of electric vehicle sales in passenger cars, and more attention towards structural changes in this sector. The former contributes to reduction of CO_2 emissions and the latter reduction of energy consumption.

Deep emissions reductions in the transport sector would be achieved by several means. Technology focused measures such as energy efficiency and fuel-switching are two of these. Structural changes that avoid or shift transport activity are also important. While the former solutions (technologies) always tend to figure into deep decarbonisation pathways in a major way, this is not always the case with the latter, especially in IAM pathways. Comparing different types of global transport models, Yeh et al. (2016) find that sectoral (intensive) studies generally envision greater mitigation potential from structural changes in transport activity and modal choice. Though, even there, it is primarily the switching of passengers and freight from less- to more-efficient travel modes (e.g., cars, trucks and airplanes to buses and trains) that is the main strategy; other actions, such as increasing vehicle load factors (occupancy rates) and outright reductions in travel demand (e.g., as a result of integrated transport, land-use and urban planning), figure much less prominently. Whether these dynamics accurately reflect the actual mitigation potential of structural changes in transport activity and modal choice is a point of investigation. According to the recent IEA-ETP scenarios, the share of avoid (reduction of mobility demand) and shift (shifting to more efficient modes) measures in the reduction of CO_2 emissions from the reference to B2DS scenarios in 2050 amounts to 20% (IEA, 2017a).

The potential and strategies to reduce energy consumption and CO_2 emissions differ significantly among transport modes. In ETP-B2DS, the shares of energy consumption and CO_2 emissions in 2050 for each mode are rather different (see Table 2.8), indicating the challenge of decarbonizing heavy-duty vehicles (HDV, trucks), aviation, and shipping. The reduction of CO_2 emissions in the whole sector from the reference scenario to ETP-B2DS is 60% in 2050, with varying contributions per mode (Table 2.8). Since there is no silver bullet for this deep decarbonisation, every possible measure would be required to achieve this stringent emissions outcome. The contribution of various measures for the CO_2 emission reduction from the reference scenario to the IEA-B2DS in 2050 can be decomposed to efficiency improvement (29%), biofuels (36%), electrification (15%), and avoid/shift (20%) (IEA, 2017a). It is noted that the share of electrification becomes larger compared with older studies, reflected by the recent growth of electric vehicle sales worldwide. Another new trend is the allocation of biofuels to each mode of transport. In IEA-B2DS, the total amount of biofuels consumed in the transport sector is 24EJ[10] in 2060, and allocated to LDV (light-duty vehicles, 17%), HDV (35%), aviation (28%), and shipping (21%), that is, more biofuels is allocated to the difficult-to-decarbonize modes (see Table 2.8).

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[10] FOOTNOTE: This is estimated for the biofuels produced in a "sustainable manner" from non-food crop feed-stocks, which are capable of delivering significant lifecycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.

Table 2.8: Transport sector indicators by mode in 2050 (IEA, 2017a). Share of Energy consumption, biofuel consumption, CO_2 emissions, and reduction of energy consumption and CO_2 emissions from 2014. (CO_2 emissions are Well-to-Wheel emissions, including the emission during the fuel production.), LDV: Light Duty Vehicle, HDV: Heavy Duty Vehicle

	Share of each mode (%)			Reduction from 2014 (%)	
	Energy	Biofuel	CO_2	Energy	CO_2
LDV	36	17	30	51	81
HDV	33	35	36	8	56
Rail	6		-1	-136	107
Aviation	12	28	14	14	56
Shipping	17	21	21	26	29

In road transport, incremental vehicle improvements (including engines) are relevant, especially in the short to medium term. Hybrid electric vehicles (HEVs) are also instrumental to enabling the transition from ICEs (internal combustion engine vehicles) to electric vehicles, especially plug-in hybrid electric vehicles (PHEVs). Electrification is a powerful measure to decarbonize short-distance vehicles (passenger cars and two and three wheelers) and the rail sector. In road freight transport (trucks), systemic improvements (e.g., in supply chains, logistics, and routing) would be effective measures with efficiency improvement of vehicles. Shipping and aviation are more challenging to decarbonize, while their demand growth is projected to be higher than other transport modes. Both modes would need to pursue highly ambitious efficiency improvements and use of low-carbon fuels. In the near and medium term, this would be advanced biofuels while in the long term it could be hydrogen as direct use for shipping or an intermediate product for synthetic fuels for both modes (IEA, 2017a).

The share of low-carbon fuels in the total transport fuel mix increases to 10% (16%) by 2030 and to 40% (58%) by 2050 in 1.5°C-overshoot pathways from IAMs. The IEA-B2DS scenario is on the more ambitious side, especially in the share of electricity. Hence, there is wide variation among scenarios, including the IAM pathways, regarding changes in the transport fuel mix over the first half of the century. As seen in Figure 2.23, the projections of energy consumption, CO_2 emissions, and carbon intensity are quite different between IAM and ETP scenarios. These differences can be explained by more weight on efficiency improvements and avoid/shift decreasing energy consumption, and the higher share of biofuels and electricity accelerating the speed of decarbonisation in ETP scenarios. Although biofuel consumption and electric vehicle sales have increased significantly in recent years, the growth rates projected in these pathways would be unprecedented and far higher than has been experienced to date.

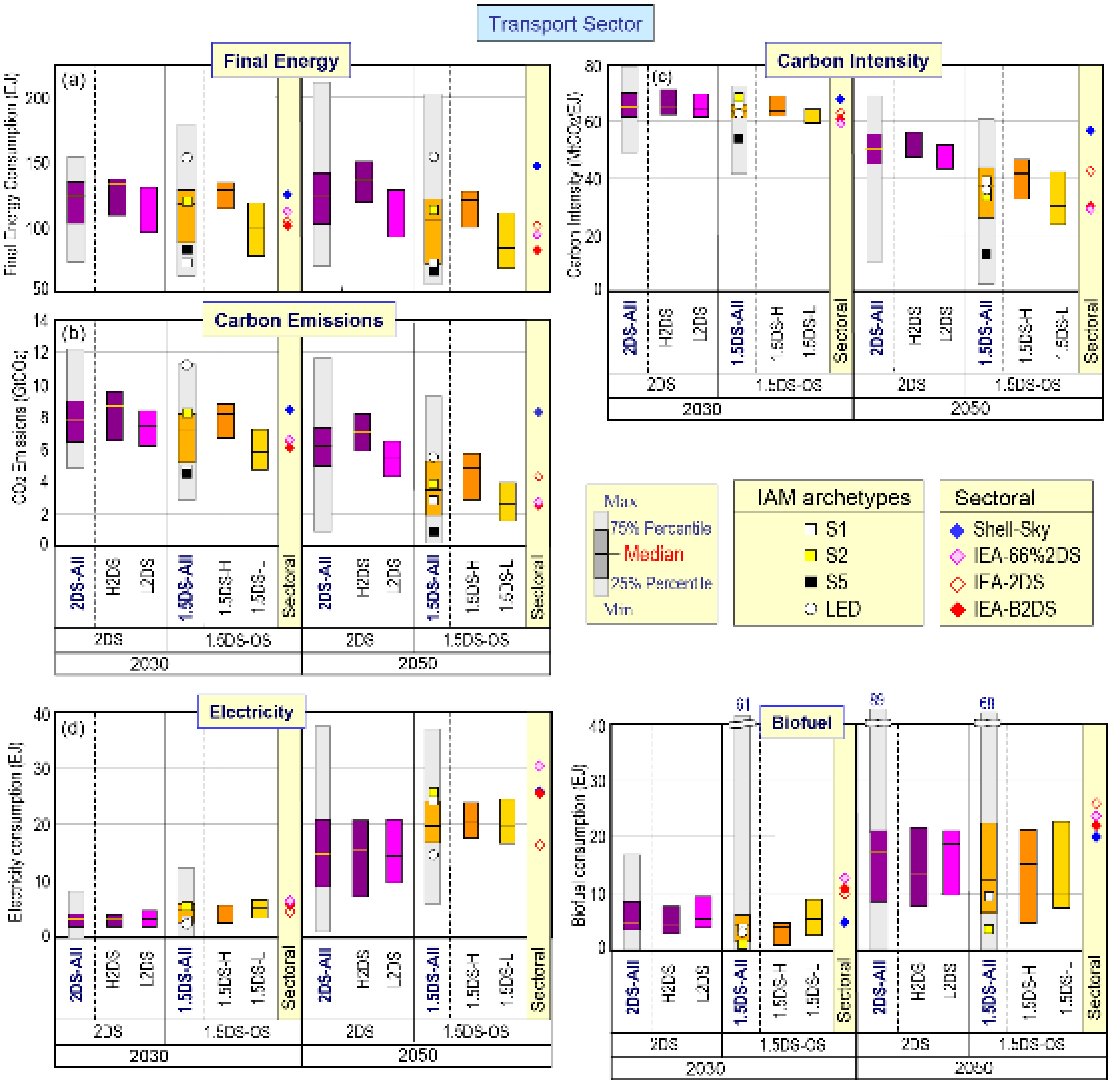

Figure 2.23: Comparison of (a) final energy, (b) direct CO₂ emissions, (c) carbon intensity, (d) electricity and biofuel consumption in the transport sector between IAM and sectoral studies. The squares and circles indicate the IAM archetype pathways and diamonds the data of sectoral scenarios. The red dotted line indicates the 2010 level. H2DS: Higher-2°C, L2DS: Lower-2°C, 1.5DS-H: 1.5°C-high-OS, 1.5DS-L: 1.5°C-low-OS, 1.5DS = 1.5DS-OS: 1.5°C-consistent pathways with overshoot. Section 2.1 for descriptions.

1.5°C pathways require an acceleration of the mitigation solutions already featured in 2°C-consistent pathways (e.g., more efficient vehicle technologies operating on lower-carbon fuels), as well as those having received lesser attention in most global transport decarbonisation pathways up to now (e.g., mode-shifting and travel demand management). Current-generation, global pathways generally do not include these newer transport sector developments, whereby technological solutions are related to shifts in traveller's behaviour.

2.4.4 Land-use transitions and changes in the agricultural sector

The agricultural and land system described together under the umbrella of the AFOLU (Agriculture, Forestry, and Other Land Use) sector plays an important role in 1.5°C pathways (Clarke et al., 2014; Smith and Bustamante, 2014; Popp et al., 2017). On the one hand, its emissions need to be limited over the course of this century to be in line with pathways limiting warming to 1.5°C (see Sections 2.2-3). On the other hand, the AFOLU system is responsible for food and feed production, for wood production for pulp and construction, for the production of biomass that is used for energy, CDR or other uses, and for the supply of non-provisioning (ecosystem) services (Smith and Bustamante, 2014). Meeting all demands together requires changes in land use, as well as in agricultural and forestry practices, for which a multitude of potential options have been identified (Smith and Bustamante, 2014; Popp et al., 2017) (see also Annex 2.A.2 and Chapter 4, Section 4.3.1, 4.3.2 and 4.3.7).

This section assesses the transformation of the AFOLU system, mainly making use of pathways from IAMs (see Section 2.1) that are based on quantifications of the SSPs and that report distinct land-use evolutions in line with limiting warming to 1.5°C (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017; Kriegler et al., 2017; Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017b; Doelman et al., 2018; Rogelj et al., 2018). The SSPs were designed to vary mitigation challenges (O'Neill et al., 2014) (Cross-Chapter Box 1.1), including for the AFOLU sector (Popp et al., 2017; Riahi et al., 2017). The SSP pathway ensemble hence allows for a structured exploration of AFOLU transitions in the context of climate change mitigation in line with 1.5°C, taking into account technological and socio-economic aspects. Other considerations, like food security, livelihoods and biodiversity, are also of importance when identifying AFOLU strategies. These are at present only tangentially explored by the SSPs. Further assessments of AFOLU mitigation options are provided in other parts of this report and in the IPCC AR6 Special Report on Climate Change and Land (SRCCL). Chapter 4 provides an assessment of bioenergy (including feedstocks, see Section 4.3.1), livestock management (Section 4.3.1), reducing rates of deforestation and other land-based mitigation options (as mitigation and adaptation option, see Section 4.3.2), and BECCS, Afforestation and Reforestation options (including the bottom-up literature of their sustainable potential, mitigation cost and side effects, Section 4.3.7). Chapter 3 discusses impacts land-based CDR (Cross-Chapter Box 7 in Chapter 3). Chapter 5 assesses the sustainable development implications of AFOLU mitigation, including impacts on biodiversity (Section 5.4). Finally, the SRCCL will undertake a more comprehensive assessment of land and climate change aspects. For the sake of complementarity, this section focusses on the magnitude and pace of land transitions in 1.5°C pathways, as well as on the implications of different AFOLU mitigation strategies for different land types. The interactions with other societal objectives and potential limitations of identified AFOLU measures link to these large-scale evolutions, but these are assessed elsewhere (see above).

Land-use changes until mid-century occur in the large majority of SSP pathways, both under stringent and in absence of mitigation (Figure 2.24). In the latter case, changes are mainly due to socio-economic drivers like growing demands for food, feed and wood products. General transition trends can be identified for many land types in 1.5°C pathways, which differ from those in baseline scenarios and depend on the interplay with mitigation in other sectors (Figure 2.24) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Mitigation that demands land mainly occurs at the expense of agricultural land for food and feed production. Additionally, some biomass is projected to be grown on marginal land or supplied from residues and waste, but at lower shares. Land for second generation energy crops (such as miscanthus or poplar) expands by 2030 and 2050 in all available pathways that assume a cost-effective achievement of a 1.5°C temperature goal in 2100 (Figure 2.24), but the scale depends strongly on underlying socioeconomic assumptions (see later discussion of land pathway archetypes). Reducing rates of deforestation restricts agricultural expansion and forest cover can expand strongly in 1.5°C and 2°C pathways alike compared to its extent in no-climate policy baselines due to reduced deforestation, afforestation and reforestation measures. However, the extent to which forest cover expands varies highly across models in the literature, with some models projecting forest cover to stay virtually constant or decline slightly. This is due to whether afforestation and reforestation is included as a mitigation technology in these pathways and interactions with other sectors.

As a consequence of other land use changes, pasture land is generally projected to be reduced compared to both baselines in which no climate change mitigation action is undertaken and 2°C-consistent pathways. Furthermore, cropland for food and feed production decreases in most 1.5°C pathways, both compared to a no-climate baseline and relative to 2010. These reductions in agricultural land for food and feed production are facilitated by intensification on agricultural land and in livestock production systems (Popp et al., 2017), as well as changes in consumption patterns (Frank et al., 2017; Fujimori, 2017) (see also 4.3.2 for an assessment of these mitigation options). For example, in a scenario based on rapid technological progress (Kriegler et al., 2017), global average cereal crop yields in 2100 are assumed to be above 5 tDM/ha.yr in mitigation scenarios aiming at limiting end-of-century radiative forcing to 4.5 or 2.6 W/m^2, compared to 4 tDM/ha.yr in the SSP5 baseline to ensure the same food production. Similar improvements are present in 1.5°C variants of such scenarios. Historically, cereal crop yields are estimated at 1 tDM/ha.yr and ca. 3 tDM/ha.yr in 1965 and 2010, respectively (calculations based on FAOSTAT, 2017). For aggregate energy crops, models assume 4.2-8.9 tDM/ha.yr in 2010, increasing to about 6.9-17.4 tDM/ha.yr in 2050, which fall within the range found in the bottom-up literature yet depend on crop, climatic zone, land quality, and plot size (Searle and Malins, 2014).

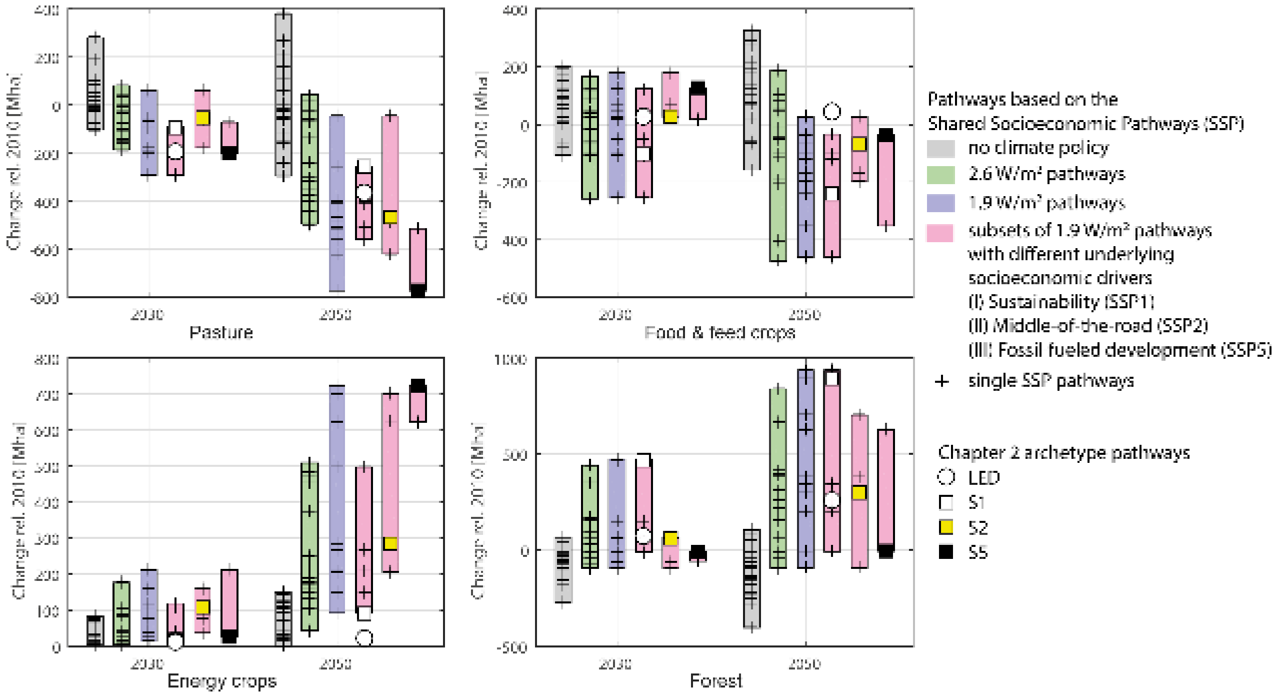

Figure 2.24: Overview of land-use change transitions in 2030 and 2050, relative to 2010 based on pathways based on the Shared Socioeconomic Pathways (SSP) (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Grey: no-climate-policy baseline; green: 2.6 W/m^2 pathways; blue: 1.9 W/m^2 pathways. Pink: 1.9 W/m^2 pathways grouped per underlying socioeconomic assumption (from left to right: SSP1 sustainability, SSP2 middle-of-the-road, SSP5 fossil-fuelled development). Ranges show the minimum-maximum range across the SSPs. Single pathways are shown with plus signs. Illustrative archetype pathways are highlighted with distinct icons. Each panel shows the changes for a different land type. 1.9 and 2.6 W/m^2 are taken as proxies for 1.5°C and 2°C pathways, respectively. 2.6 W/m^2 pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. 1.9 W/m^2 pathways are consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. In 2010, pasture was estimated to cover about 3-3.5 10^3 Mha, food and feed crops about 1.5-1.6 10^3 Mha, energy crops about 0-14 Mha and forest about 3.7-4.2 10^3 Mha, across the models that reported SSP pathways (Popp et al., 2017).

The pace of projected land transitions over the coming decades can differ strongly between 1.5°C and baseline scenarios without climate change mitigation and from historical trends (Table 2.9). However, there is uncertainty in the sign and magnitude of these future land-use changes (Prestele et al., 2016; Popp et al., 2017; Doelman et al., 2018). The pace of projected cropland changes overlaps with historical trends over the past four decades, but in several cases also goes well beyond this range. By the 2030-2050 period, the projected reductions in pasture and potentially strong increases in forest cover imply a reversed dynamic compared to historical and baseline trends. For forest increases, this suggests that distinct policy and government measures would be needed to achieve this, particularly in a context of projected increased bioenergy use.

Table 2.9: Annual pace of land-use change in baseline, 2°C and 1.5°C pathways. All values in Mha/yr. 2.6 W/m^2 pathways are mostly consistent with the Lower-2°C and Higher-2°C pathway classes. 1.9 W/m^2 pathways are broadly consistent with the 1.5°C-low-OS (mostly SSP1 and SSP2) and 1.5°C-high-OS (SSP5) pathway classes. Baseline projections reflect land-use developments projected by integrated assessment models under the assumptions of the Shared Socioeconomic Pathways (SSP) in absence of climate policies (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018). Values give the full range across SSP scenarios. According to the Food and Agriculture Organization of the United Nations (FAOSTAT, 2017), 4.9 billion hectares (approximately 40% of the land surface) was under agricultural use in 2005, either as cropland (1.5 billion hectares) or pasture (3.4 billion hectares). FAO data in the table are equally from FAOSTAT (2017).

Annual pace of land-use change [Mha yr^{-1}] Land type	**Pathway**	**Time window**		**Historical**	
		2010-2030	**2030-2050**	**1970-1990**	**1990-2010**
Pasture	1.9 W m^{-2}	[-14.6/3.0]	[-28.7/-5.2]	8.7	0.9
	2.6 W m^{-2}	[-9.3/4.1]	[-21.6/0.4]	Permanent meadows and pastures (FAO)	Permanent meadows and pastures (FAO)
	Baseline	[-5.1/14.1]	[-9.6/9.0]		
Cropland for food, feed and material	1.9 W m^{-2}	[-12.7/9.0]	[-18.5/0.1]		
	2.6 W m^{-2}	[-12.9/8.3]	[-16.8/2.3]		
	Baseline	[-5.3/9.9]	[-2.7/6.7]		
Cropland for energy	1.9 W m^{-2}	[0.7/10.5]	[3.9/34.8]		
	2.6 W m^{-2}	[0.2/8.8]	[2.0/22.9]		
	Baseline	[0.2/4.2]	[-0.2/6.1]		
Total cropland (Sum of cropland for food and feed & energy)	1.9 W m^{-2}	[-6.8/12.8]	[-5.8/26.7]	4.6	0.9
	2.6 W m^{-2}	[-8.4/9.3]	[-7.1/17.8]	Arable land and Permanent crops	Arable land and Permanent crops
	Baseline	[-3.0/11.3]	[0.6/11.0]		
Forest	1.9 W m^{-2}	[-4.8/23.7]	[0.0/34.3]	N.A.	-5.6
	2.6 W m^{-2}	[-4.7/22.2]	[-2.4/31.7]	Forest (FAO)	Forest (FAO)
	Baseline	[-13.6/3.3]	[-6.5/4.3]		

Changes of the AFOLU sector are driven by three main factors: demand changes, efficiency of production, and policy assumptions (Smith et al., 2013; Popp et al., 2017). Demand for agricultural products and other land-based commodities is influenced by consumption patterns (including dietary preferences and food waste affecting demand for food and feed) (Smith et al., 2013; van Vuuren et al., 2018), demand for forest products for pulp and construction (including less wood waste), and demand for biomass for energy production (Lambin and Meyfroidt, 2011; Smith and Bustamante, 2014). Efficiency of agricultural and forestry production relates to improvements in agricultural and forestry practices (including product cascades, by-products as well as more waste- and residue-based biomass for energy production), agricultural and forestry yield increases as well as intensification of livestock production systems leading to higher feed efficiency and changes in feed composition (Havlík et al., 2014; Weindl et al., 2015). Policy assumptions relate to the level of land protection, the treatment of food waste, policy choices about the timing of mitigation action (early vs late), the choice and preference of land-based mitigation options (for example, the inclusion of afforestation and reforestation as mitigation options), interactions with other sectors (Popp et al., 2017) and trade (Schmitz et al., 2012; Wiebe et al., 2015).

A global study (Stevanović et al., 2017) reported similar GHG reduction potentials for production (agricultural production measures in combination with reduced deforestation) and consumption side (diet change in combination with lower shares of food waste) measures of in the order of 40% in 2100[11] (compared to a baseline scenario without land-based mitigation). Lower consumption of livestock products by 2050 could also substantially reduce deforestation and cumulative carbon losses (Weindl et al., 2017). On

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[11] FOOTNOTE: Land-based mitigation options on the supply and the demand side are assessed in 4.3.2 and CDR options with a land component in 4.3.7. Chapter 5 (Section 5.4) assesses the implications of land-based mitigation for related SDGs, e.g., food security.

the supply side, minor productivity growth in extensive livestock production systems is projected to lead to substantial CO_2 emission abatement, but the emission saving potential of productivity gains in intensive systems is limited, mainly due to trade-offs with soil carbon stocks (Weindl et al., 2017). In addition, even within existing livestock production systems, a transition from extensive to more productive systems bears substantial GHG abatement potential, while improving food availability (Gerber et al., 2013; Havlík et al., 2014). Many studies highlight the capability of agricultural intensification for reducing GHG emissions in the AFOLU sector or even enhancing terrestrial carbon stocks (Valin et al., 2013; Popp et al., 2014a; Wise et al., 2014). Also the importance of immediate and global land-use regulations for a comprehensive reduction of land-related GHG emissions (especially related to deforestation) has been shown by several studies (Calvin et al., 2017; Fricko et al., 2017; Fujimori, 2017). Ultimately, there are also interactions between these three factors and the wider society and economy, for example, if CDR technologies that are not land based are deployed (like direct air capture – DACCS, see Chapter 4, Section 4.3.7) or if other sectors over- or underachieve their projected mitigation contributions (Clarke et al., 2014). Variations in these drivers can lead to drastically different land-use implications (Popp et al., 2014b) (Figure 2.24).

Stringent mitigation pathways inform general GHG dynamics in the AFOLU sector. First, CO_2 emissions from deforestation can be abated at relatively low carbon prices if displacement effects in other regions (Calvin et al., 2017) or other land-use types with high carbon density (Calvin et al., 2014; Popp et al., 2014a; Kriegler et al., 2017) can be avoided. However, efficiency and costs of reducing rates of deforestation strongly depend on governance performance, institutions and macroeconomic factors (Wang et al., 2016). Secondly, besides CO_2 reductions, the land system can play an important role for overall CDR efforts (Rogelj et al., 2018) via BECCS, afforestation and reforestation, or a combination of options. The AFOLU sector also provides further potential for active terrestrial carbon sequestration, e.g., via land restoration, improved management of forest and agricultural land (Griscom et al., 2017), or biochar applications (Smith, 2016) (see also Section 4.3.7). These options have so far not been extensively integrated in the mitigation pathway literature (see Annex 2.A.2), but in theory their availability would impact the deployment of other CDR technologies, like BECCS (Section 2.3.4) (Strefler et al., 2018a). These interactions will be discussed further in the SRCCL.

Residual agricultural non-CO_2 emissions of CH_4 and N_2O play an important role for temperature stabilisation pathways and their relative importance increases in stringent mitigation pathways in which CO_2 is reduced to net zero emissions globally (Gernaat et al., 2015; Popp et al., 2017; Stevanović et al., 2017; Rogelj et al., 2018), for example, through their impact on the remaining carbon budget (Section 2.2). Although agricultural non-CO_2 emissions show marked reduction potentials in 2°C-consistent pathways, complete elimination of these emission sources does not occur in IAMs based on the evolution of agricultural practice assumed in integrated models (Figure 2.25) (Gernaat et al., 2015). CH_4 emissions in 1.5°C pathways are reduced through improved agricultural management (e.g., improved management of water in rice production, manure and herds, and better livestock quality through breeding and improved feeding practices) as well as dietary shifts away from emissions-intensive livestock products. Similarly, N_2O emissions decrease due to improved N-efficiency and manure management (Frank et al., 2018). However, high levels of bioenergy production can also result in increased N_2O emissions (Kriegler et al., 2017) highlighting the importance of appropriate management approaches (Davis et al., 2013). Residual agricultural emissions can be further reduced by limiting demand for GHG-intensive foods through shifts to healthier and more sustainable diets (Tilman and Clark, 2014; Erb et al., 2016b; Springmann et al., 2016) and reductions in food waste (Bajželj et al., 2014; Muller et al., 2017; Popp et al., 2017) (see also Chapter 4, and SRCCL). Finally, several mitigation measures that could affect these agricultural non-CO_2 emissions are not, or only to a limited degree, considered in the current integrated pathway literature (see Annex 2.A.2). Such measures (like plant-based and synthetic proteins, methane inhibitors and vaccines in livestock, alternate wetting and drying in paddy rice, or nitrification inhibitors) are very diverse and differ in their development or deployment stages. Their potentials have not been explicitly assessed here.

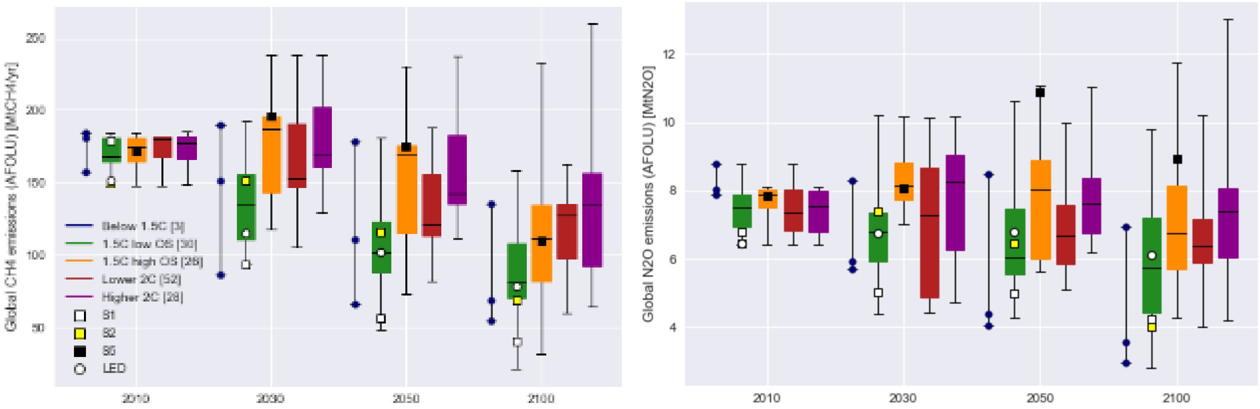

Figure 2.25: Agricultural emissions in transformation pathways. Global agricultural CH_4 (left) and N_2O (right) emissions. Boxplots show median, interquartile range and full range. Classes are defined in Section 2.1.

Pathways consistent with 1.5°C rely on one or more of the three strategies highlighted above (demand changes, efficiency gains, and policy assumptions), and can apply these in different configurations. For example, among the four illustrative archetypes used in this chapter (Section 2.1) the LED and S1 pathways focus on generally low resource and energy consumption (including healthy diets with low animal-calorie shares and low food waste) as well as significant agricultural intensification in combination with high levels of nature protection. Under such assumptions, comparably small amounts of land are needed for land demanding mitigation activities such as BECCS and afforestation and reforestation, leaving the land footprint for energy crops in 2050 virtually the same compared to 2010 levels for the LED pathway. In contrast, future land-use developments can look very differently under the resource- and energy-intensive S5 pathway that includes unhealthy diets with high animal shares and high shares of food waste (Tilman and Clark, 2014; Springmann et al., 2016) combined with a strong orientation towards technology solutions to compensate for high reliance on fossil-fuel resources and associated high levels of GHG emissions in the baseline. In such pathways, climate change mitigation strategies strongly depend on the availability of CDR through BECCS (Humpenöder et al., 2014). As a consequence, the S5 pathway sources significant amounts of biomass through bioenergy crop expansion in combination with agricultural intensification. Also, further policy assumptions can strongly affect land-use developments, highlighting the importance for land use of making appropriate policy choices. For example, within the SSP set, some pathways rely strongly on a policy to incentivise afforestation and reforestation for CDR together with BECCS, which results in an expansion of forest area and a corresponding increase in terrestrial carbon stock. Finally, the variety of pathways illustrates how policy choices in the AFOLU and other sectors strongly affect land-use developments and associated sustainable development interactions (Section 5.4) in 1.5°C pathways.

The choice of strategy or mitigation portfolio impacts the GHG dynamics of the land system and other sectors (see Section 2.3), as well as the synergies and trade-offs with other environmental and societal objectives (see Section 2.5.3 and Section 5.4). For example, AFOLU developments in 1.5°C pathways range from strategies that differ almost an order of magnitude in their projected land requirements for bioenergy (Figure 2.24), and some strategies would allow an increase in forest cover over the 21st century compared to strategies under which forest cover remains approximately constant. High agricultural yields and application of intensified animal husbandry, implementation of best-available technologies for reducing non-CO_2 emissions, or lifestyle changes including a less-meat-intensive diet and less CO_2-intensive transport modes, have been identified to allow for such a forest expansion and reduced footprints from bioenergy without compromising food security (Frank et al., 2017; Doelman et al., 2018; van Vuuren et al., 2018).

The IAMs used in the pathways underlying this assessment (Popp et al., 2017; Riahi et al., 2017; Rogelj et al., 2018) do not include all potential land-based mitigation options and side-effects, and their results are hence subject to uncertainty. For example, recent research has highlighted the potential impact of forest management practices on land carbon content (Erb et al., 2016a; Naudts et al., 2016) and the uncertainty surrounding future crop yields (Haberl et al., 2013; Searle and Malins, 2014), and water availability (Liu et al., 2014). These aspects are included in IAMs in varying degrees, but were not assessed in this report. Furthermore, land-use modules of some IAMs can depict spatially resolved climate damages to agriculture (Nelson et al., 2014), but this option was not used in the SSP quantifications (Riahi et al., 2017). Damages (e.g., due to ozone exposure or varying indirect fertilization due to atmospheric N and Fe deposition (e.g., Shindell et al., 2012; Mahowald et al., 2017) are also not included. Finally, this assessment did not look into the literature of agricultural sector models which could provide important additional detail and granularity to the here presented discussion[12]. This limits their ability to capture the full mitigation potentials and benefits between scenarios. An in-depth assessment of these aspects lies outside the scope of this Special Report. However, their existence affects the confidence assessment of the AFOLU transition in 1.5°C pathways.

Despite the limitations of current modelling approaches, there is *high agreement* and *robust evidence* across models and studies that the AFOLU sector plays an important role in stringent mitigation pathways. The findings from these multiple lines of evidence also result in *high confidence* that AFOLU mitigation strategies can vary significantly based on preferences and policy choices, facilitating the exploration of strategies that can achieve multiple societal objectives simultaneously (see also Section 2.5.3). At the same time, given the many uncertainties and limitations, only *low to medium confidence* can be attributed by this assessment to the more extreme AFOLU developments found in the pathway literature, and *low to medium confidence* to the level of residual non-CO_2 emissions.

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[12] FOOTNOTE: For example, the GLEAM (http://www.fao.org/gleam/en/) model from the UN Food and Agricultural Organisation (FAO).

2.5 Challenges, opportunities and co-impacts of transformative mitigation pathways

This section examines aspects other than climate outcomes of 1.5°C mitigation pathways. Focus is given to challenges and opportunities related to policy regimes, price of carbon and co-impacts, including sustainable development issues, which can be derived from the existing integrated pathway literature. Attention is also given to uncertainties and critical assumptions underpinning mitigation pathways. The challenges and opportunities identified in this section are further elaborated Chapter 4 (e.g., policy choice and implementation) and Chapter 5 (e.g., sustainable development). The assessment indicates unprecedented policy and geopolitical challenges.

2.5.1 Policy frameworks and enabling conditions

Moving from a 2°C to a 1.5°C pathway implies bold integrated policies that enable higher socio-technical transition speeds, larger deployment scales, and the phase-out of existing systems that may lock in emissions for decades (Geels et al., 2017; Kuramochi et al., 2017; Rockström et al., 2017; Vogt-Schilb and Hallegatte, 2017; Kriegler et al., 2018b; Michaelowa et al., 2018) (*high confidence*). This requires higher levels of transformative policy regimes in the near term, which allow deep decarbonisation pathways to emerge and a net zero carbon energy-economy system to emerge in the 2040–2060 period (Rogelj et al., 2015b; Bataille et al., 2016b). This enables accelerated levels of technological deployment and innovation (Geels et al., 2017; IEA, 2017a; Grubler et al., 2018) and assumes more profound behavioural, economic and political transformation (Sections 2.3, 2.4 and 4.4). Despite inherent levels of uncertainty attached to modelling studies (e.g., related to climate and carbon-cycle response), studies stress the urgency for transformative policy efforts to reduce emissions in the short term (Riahi et al., 2015; Kuramochi et al., 2017; Rogelj et al., 2018).

The available literature indicates that mitigation pathways in line with 1.5°C-consistent pathways would require stringent and integrated policy interventions (*very high confidence*). Higher policy ambition often takes the form of stringent economy-wide emission targets (and resulting peak-and-decline of emissions), larger coverage of NDCs to more gases and sectors (e.g., land-use, international aviation), much lower energy and carbon intensity rates than historically seen, carbon prices much higher than the ones observed in real markets, increased climate finance, global coordinated policy action, and implementation of additional initiatives (e.g., by non-state actors) (Sections 2.3, 2.4 and 2.5.2). The diversity (beyond carbon pricing) and effectiveness of policy portfolios are of prime importance, particularly in the short-term (Mundaca and Markandya, 2016; Kuramochi et al., 2017; OECD, 2017; Kriegler et al., 2018b; Michaelowa et al., 2018). For instance, deep decarbonisation pathways in line with a 2˚C target (covering 74% of global energy-system emissions) include a mix of stringent regulation (e.g., building codes, minimum performance standards), carbon pricing mechanisms and R&D (research and development) innovation policies (Bataille et al., 2016a). Carbon pricing, direct regulation and public investment to enable innovation are critical for deep decarbonisation pathways (Grubb et al., 2014). Effective planning (including compact city measures) and integrated regulatory frameworks are also key drivers in the IEA-ETP B2DS study for the transport sector (IEA, 2017a). Effective urban planning can reduce GHG emissions from urban transport between 20% and 50% (Creutzig, 2016). Comprehensive policy frameworks would be needed if the decarbonisation of the power system is pursued while increasing end-use electrification (including transport) (IEA, 2017a). Technology policies (e.g., feed-in-tariffs), financing instruments, carbon pricing and system integration management driving the rapid adoption of renewable energy technologies are critical for the decarbonisation of electricity generation (Bruckner et al., 2014; Luderer et al., 2014; Creutzig et al., 2017; Pietzcker et al., 2017). Likewise, low-carbon and resilient investments are facilitated by a mix of coherent policies including fiscal and structural reforms (e.g., labour markets), public procurement, carbon pricing, stringent standards, information schemes, technology policies, fossil-fuel subsidy removal, climate risk disclosure, and land-use and transport planning (OECD, 2017). Pathways in which CDR options are restricted emphasise the strengthening of near-term policy mixes (Luderer et al., 2013; Kriegler et al., 2018b). Together with the decarbonisation of the supply side, ambitious policies targeting fuel switching and energy efficiency improvements on the demand side play a major role across mitigation pathways (Clarke et al., 2014; Kriegler et al., 2014b; Riahi et al., 2015; Kuramochi et al., 2017; Brown and Li, 2018; Rogelj et al., 2018; Wachsmuth and Duscha, 2018).

The combined evidence suggests that aggressive policies addressing energy efficiency are central in keeping 1.5°C within reach and lowering energy system and mitigation costs (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Grubler et al., 2018) (*high confidence*). Demand-side policies that increase energy efficiency or limit energy demand at a higher rate than historically observed are critical enabling factors reducing mitigation costs for stringent mitigation pathways across the board (Luderer et al., 2013; Rogelj et al., 2013b, 2015b; Clarke et al., 2014; Bertram et al., 2015a; Bataille et al., 2016b). Ambitious sector-specific mitigation policies in industry, transportation and residential sectors are needed in the short run for emissions to peak in 2030 (Méjean et al., 2018). Stringent demand-side policies (e.g., tightened efficiency standards for buildings and appliances) driving the expansion, efficiency and provision of high-quality energy services are essential to meet a 1.5˚C mitigation target while avoiding the need of CDR (Grubler et al., 2018). A 1.5˚C pathway for the transport sector is possible using a mix of additional and stringent policy actions preventing (or reducing) the need for transport, encouraging shifts towards efficient modes of transport, and improving vehicle-fuel efficiency (Ghota et al., 2018). Stringent demand-side policies also reduce the need for CCS (Wachsmuth and Duscha, 2018). Even in the presence of weak-near term policy frameworks, increased energy efficiency lowers mitigation costs noticeably compared to pathways with reference energy intensity (Bertram et al., 2015a). Horizontal issues in the literature relate to the rebound effect, the potential overestimation of the effectiveness of energy efficiency policy, and policies to counteract the rebound (Saunders, 2015; van den Bergh, 2017; Grubler et al., 2018) (Sections 2.4 and 4.4).

SSP-based modelling studies underline that socio-economic and climate policy assumptions strongly influence mitigation pathway characteristics and the economics of achieving a specific climate target (Bauer et al., 2017; Guivarch and Rogelj, 2017; Riahi et al., 2017; Rogelj et al., 2018) (*very high confidence*). SSP assumptions related to economic growth and energy intensity are critical determinants of projected CO_2 emissions (Marangoni et al., 2017). A multi-model inter-comparison study found that mitigation challenges in line with a 1.5˚C target vary substantially across SSPs and policy assumptions (Rogelj et al., 2018). Under SSP1-SPA1 (sustainability) and SSP2-SPA2 (middle-of-the-road), the majority of IAMs were capable of producing 1.5˚C pathways. On the contrary, none of the IAMs contained in the SR1.5 database could produce a 1.5°C pathway under SSP3-SPA3 assumptions. Preventing elements include, for instance, climate policy fragmentation, limited control of land-use emissions, heavy reliance on fossil fuels, unsustainable consumption and marked inequalities (Rogelj et al., 2018). Dietary aspects of the SSPs are also critical: climate-friendly diets were contained in 'sustainability' (SSP1) and meat-intensive diets in SSP3 and SSP5 (Popp et al., 2017). CDR requirements are reduced under 'sustainability' related assumptions (Strefler et al., 2018b). These are major policy-related factors for why SSP1-SPA1 translates into relatively low mitigation challenges whereas SSP3-SPA3 and SSP5-SPA5 entail futures that pose the highest socio-technical and economic challenges. SSPs/SPAs assumptions indicate that policy-driven pathways that encompass accelerated change away from fossil fuels, large-scale deployment of low-carbon energy supplies, improved energy efficiency and sustainable consumption lifestyles reduce the risks of climate targets becoming unreachable (Clarke et al., 2014; Riahi et al., 2015, 2017; Marangoni et al., 2017; Rogelj et al., 2017, 2018; Strefler et al., 2018b).

Policy assumptions that lead to weak or delayed mitigation action from what would be possible in a fully cooperative world, strongly influence the achievability of mitigation targets (Luderer et al., 2013; Rogelj et al., 2013; OECD, 2017; Holz et al., 2018a; Strefler et al., 2018b) (*high confidence*). Such regimes also include current NDCs (Fawcett et al., 2015; Aldy et al., 2016; Rogelj et al., 2016a, 2017; Hof et al., 2017; van Soest et al., 2017), which have been reported to make achieving a 2°C pathway unattainable without CDR (Strefler et al., 2018b). Not strengthening NDCs make it very challenging to keep 1.5°C within reach (see Section 2.3 and Cross-Chapter Box 11 in Chapter 4). One multi-model inter-comparison study (Luderer et al., 2016b, 2018) explored the effects on 1.5°C pathways assuming the implementation of current NDCs until 2030 and stringent reductions thereafter. It finds that delays in globally coordinated actions leads to various models reaching no 1.5°C-consistent pathways during the 21st century. Transnational emission reduction initiatives (TERIs) outside the UNFCCC have also been assessed and found to overlap (70–80%) with NDCs and be inadequate to bridge the gap between NDCs and a 2˚C pathway (Roelfsema et al., 2018). Weak and fragmented short-term policy efforts use up a large share of the long-term carbon budget before 2030–2050 (Bertram et al., 2015a; van Vuuren et al., 2016) and increase the need for the full portfolio of mitigation measures, including CDR (Clarke et al., 2014; Riahi et al., 2015; Xu and Ramanathan, 2017). Furthermore, fragmented policy scenarios also exhibit 'carbon leakage' via energy and capital markets (Arroyo-Currás et al., 2015; Kriegler et al., 2015b). A lack of integrated policy portfolios can increase the risks of trade-offs between mitigation approaches and sustainable development objectives (see Sections 2.5.3 and 5.4). However, more detailed analysis is needed about realistic (less disruptive) policy trajectories until 2030 that can strengthen near-term mitigation action and meaningfully decrease post-2030 challenges (see Section 4.4).

Whereas the policy frameworks and enabling conditions identified above pertain to the 'idealised' dimension of mitigation pathways, aspects related to 1.5°C mitigation pathways in practice are of prime importance. For example, issues related to second-best stringency levels, international cooperation, public acceptance, distributional consequences, multi-level governance, non-state actions, compliance levels, capacity building, rebound effects, linkages across highly heterogeneous policies, sustained behavioural change, finance and intra- and inter-generational issues need to be considered (Somanthan et al., 2014; Bataille et al., 2016a; Mundaca and Markandya, 2016; Baranzini et al., 2017; van den Bergh, 2017; Vogt-Schilb and Hallegatte, 2017; Chan et al., 2018; Holz et al., 2018a; Klinsky and Winkler, 2018; Michaelowa et al., 2018; Patterson et al., 2018) (see Section 4.4). Furthermore, policies interact with a wide portfolio of pre-existing policy instruments that address multiple areas (e.g., technology markets, economic growth, poverty alleviation, climate adaptation) and deal with various market failures (e.g., information asymmetries) and behavioural aspects (e.g., heuristics) that prevent or hinder mitigation actions (Kolstad et al., 2014; Mehling and Tvinnereim, 2018). The socio-technical transition literature points to multiple complexities in real-world settings that prevent reaching 'idealised' policy conditions but at the same time can still accelerate transformative change through other co-evolutionary processes of technology and society (Geels et al., 2017; Rockström et al., 2017). Such co-processes are complex and go beyond the role of policy (including carbon pricing) and comprise the role of citizens, businesses, stakeholder groups or governments, as well as the interplay of institutional and socio-political dimensions (Michaelowa et al., 2018; Veland et al., 2018). It is argued that large system transformations, similar to those in 1.5°C pathways, require prioritizing an evolutionary and behavioural framework in economic theory rather than an optimization or equilibrium framework as is common in current IAMs (Grubb et al., 2014; Patt, 2017). Accumulated know-how, accelerated innovation and public investment play a key role in (rapid) transitions (Geels et al., 2017; Michaelowa et al., 2018) (see Sections 4.2 and 4.4).

In summary, the emerging literature supports the AR5 on the need for integrated, robust and stringent policy frameworks targeting both the supply and demand-side of energy-economy systems (*high confidence*). Continuous ex-ante policy assessments provide learning opportunities for both policy makers and stakeholders.

[START CROSS CHAPTER BOX 5 HERE]

Cross-Chapter Box 5: Economics of 1.5°C Pathways and the Social Cost of Carbon

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Two approaches have been commonly used to assess alternative emissions pathways: **cost-effectiveness analysis (CEA)** and **cost-benefit analysis (CBA)**. **CEA** aims at identifying emissions pathways minimising the total mitigation costs of achieving a given warming or GHG limit (Clarke et al., 2014). **CBA** has the goal to identify the optimal emissions trajectory minimising the discounted flows of abatement expenditures and monetised climate change damages (Boardman, 2006; Stern, 2007). A third concept, the **Social Cost of Carbon (SCC)** measures the total net damages of an extra metric ton of CO_2 emissions due to the associated climate change (Nordhaus, 2014; Pizer et al., 2014; Rose et al., 2017a). Negative and positive impacts are monetised, discounted and the net value is expressed as an equivalent loss of consumption today. The SCC can be evaluated for any emissions pathway under policy consideration (Rose, 2012; NASEM, 2016, 2017).

Along the optimal trajectory determined by CBA, the SCC equals the discounted value of the marginal abatement cost of a metric ton of CO_2 emissions. Equating the present value of future damages and marginal abatement costs includes a number of critical value judgments in the formulation of the social welfare function (SWF), particularly in how non-market damages and the distribution of damages across countries and individuals and between current and future generations are valued (Kolstad et al., 2014). For example, since climate damages accrue to a larger extent in the farther future and can persist for many years, assumptions and approaches to determine the social discount rate (normative ‘prescriptive’ vs. positive ‘descriptive’) and social welfare function (e.g., discounted utilitarian SWF vs. undiscounted prioritarian SWF) can heavily influence CBA outcomes and associated estimates of SCC (Kolstad et al., 2014; Pizer et al., 2014; Adler and Treich, 2015; Adler et al., 2017; NASEM, 2017; Nordhaus, 2017; Rose et al., 2017a).

In CEA, the marginal abatement cost of carbon is determined by the climate goal under consideration. It equals the shadow price of carbon associated with the goal which in turn can be interpreted as the willingness to pay for imposing the goal as a political constraint. Emissions prices are usually expressed in carbon (equivalent) prices using the GWP-100 metric as the exchange rate for pricing emissions of non-CO_2 GHGs controlled under internationally climate agreements (like CH_4, N_2O and fluorinated gases, see Cross-Chapter Box 1.2)[13]. Since policy goals like the goals of limiting warming to 1.5°C or well below 2°C do not directly result from a money metric trade-off between mitigation and damages, associated shadow prices can differ from the SCC in a CBA. In CEA, value judgments are to a large extent concentrated in the choice of climate goal and related implications, while more explicit assumptions about social values are required to perform CBA. For example, assumptions about the social discount rate no longer affect the overall abatement levels now set by the climate goal, but the choice and timing of investments in individual measures to reach these levels.

Although CBA-based and CEA-based assessment are both subject to large uncertainty about socio-techno-economic trends, policy developments and climate response, the range of estimates for the SCC along an optimal trajectory determined by CBA is far higher than for estimates of the shadow price of carbon in CEA-based approaches. In CBA, the value judgments about inter- and intra-generational equity combined with uncertainties in the climate damage functions assumed, including their empirical basis, are important (Pindyck, 2013; Stern, 2013; Revesz et al., 2014). In a CEA-based approach, the value judgments about the aggregate welfare function matter less and uncertainty about climate response and impacts can be tied into various climate targets and related emissions budgets (Clarke et al., 2014).

The CEA- and CBA-based carbon cost estimates are derived with a different set of tools. They are all summarised as integrated assessment models (IAMs) but in fact are of very different nature (Weyant, 2017). Detailed process IAMs such as AIM (Fujimori, 2017), GCAM (Thomson et al., 2011; Calvin et al., 2017), IMAGE (van Vuuren et al., 2011b, 2017b), MESSAGE-GLOBIOM (Riahi et al., 2011; Havlík et al., 2014; Fricko et al., 2017), REMIND-MAgPIE (Popp et al., 2010; Luderer et al., 2013; Kriegler et al., 2017) and WITCH (Bosetti et al., 2006, 2008, 2009) include a process-based representation of energy and land systems, but in most cases lack a comprehensive representation of climate damages, and are typically used for CEA. Diagnostic analyses across CBA-IAMs indicate important dissimilarities in modelling assembly, implementation issues and behaviour (e.g., parametric uncertainty, damage responses, income sensitivity) that need to be recognised to better understand SCC estimates (Rose et al., 2017a).

CBA-IAMs such as DICE (Nordhaus and Boyer, 2000; Nordhaus, 2013, 2017), PAGE (Hope, 2006) and FUND (Tol, 1999; Anthoff and Tol, 2009) attempt to capture the full feedback from climate response to socio-economic damages in an aggregated manner, but are usually much more stylised than detailed process IAMs. In a nutshell, the methodological framework for estimating SCC involves projections of population growth, economic activity and resulting emissions; computations of atmospheric composition and global-mean temperatures as a result of emissions; estimations of physical impacts of climate changes; monetisation of impacts (positive and negative) on human welfare; and the discounting of the future monetary value of impacts to year of emission (Kolstad et al., 2014; Revesz et al., 2014; NASEM, 2017; Rose et al., 2017a). There has been a discussion in the literature to what extent CBA-IAMs underestimate the SCC due to, for example, a limited treatment or difficulties in addressing damages to human well-being, labour productivity, value of capital stock, ecosystem services and the risks of catastrophic climate change for future generations (Ackerman and Stanton, 2012; Revesz et al., 2014; Moore and Diaz, 2015; Stern, 2016). However, there has been progress in ‘bottom-up’ empirical analyses of climate damages (Hsiang et al., 2017), the insights of which could be integrated into these models (Dell et al., 2014). Most of the models used in Chapter 2 on 1.5°C mitigation pathways are detailed process IAMs and thus deal with CEA.

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[13] FOOTNOTE: Also other metrics to compare emissions have been suggested and adopted by governments nationally (Kandlikar, 1995; Marten et al., 2015; Shindell, 2015; Interagency Working Group on Social Cost of Greenhouse Gases, 2016).

An important question is how results from CEA- and CBA-type approaches can be compared and synthesised. Such synthesis needs to be done with care, since estimates of the shadow price of carbon under the climate goal and SCC estimates from CBA might not be directly comparable due to different tools, approaches and assumptions used to derive them. Acknowledging this caveat, the SCC literature has identified a range of factors, assumptions and value judgements that support SCC values above \$100 tCO_2^{-1} that are also found as net present values of the shadow price of carbon in 1.5°C pathways. These factors include accounting for tipping points in the climate system (Lemoine and Traeger, 2014; Cai et al., 2015; Lontzek et al., 2015), a low social discount rate (Nordhaus, 2005; Stern, 2007) and inequality aversion (Schmidt et al., 2013; Dennig et al., 2015; Adler et al., 2017).

The SCC and the shadow price of carbon are not merely theoretical concepts but used in regulation (Pizer et al., 2014; Revesz et al., 2014; Stiglitz et al., 2017). As stated by the report of the High-Level Commission on Carbon Pricing (Stiglitz et al., 2017), in the real world there is a distinction to be made between the implementable and efficient explicit carbon prices and the implicit (notional) carbon prices to be retained for policy appraisal and the evaluation of public investments, as is already done in some jurisdictions such as the USA, UK and France. Since 2008, the U.S. government has used SCC estimates to assess the benefits and costs related to CO_2 emissions resulting from federal policymaking (NASEM, 2017; Rose et al., 2017a).

The use of the SCC for policy appraisals is however not straightforward in an SDG context. There are suggestions that a broader range of polluting activities than only CO_2 emissions, for example emissions of air pollutants, and a broader range of impacts than only climate change, such as impacts on air quality, health and sustainable development in general (see Chapter 5 for a detailed discussion), would need to be included in social costs (Sarofim et al., 2017; Shindell et al., 2017a). Most importantly, a consistent valuation of the SCC in a sustainable development framework would require accounting for the SDGs in the social welfare formulation (see Chapter 5).

[END CROSS CHAPTER BOX 5 HERE]

2.5.2 Economic and financial implications of 1.5°C Pathways

2.5.2.1 Price of carbon emissions

The price of carbon assessed here is fundamentally different from the concepts of optimal carbon price in a cost-benefit analysis, or the social cost of carbon (see Cross-Chapter Box 5 in this Chapter and Section 3.5.2). Under a cost-effective analysis (CEA) modelling framework, prices for carbon (mitigation costs) reflect the stringency of mitigation requirements at the margin (i.e., cost of mitigating one extra unit of emission).

Based on data available for this special report, the price of carbon varies substantially across models and scenarios, and their value increase with mitigation efforts (see Figure 2.26) (*high confidence*). For instance, undiscounted values under a Higher-2˚C pathway range from 10–200 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2030, 45–960 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2050, 120–1000 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2070 and 160–2125 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2100. On the contrary, estimates for a Below-1.5˚C pathway range from 135–5500 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2030, 245–13000 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2050, 420–17500 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2070 and 690–27000 USD_{2010} $tCO_{2\text{-eq}}^{-1}$ in 2100. One can also observe that values for 1.5°C-low-OS pathway are relatively higher than 1.5°C-high-OS pathway in 2030, but the difference decreases over time. This is because in 1.5°C-high-OS pathways there is relatively less mitigation activity in the first half of the century, but more in the second half. *LED* exhibits the lowest values across the illustrative pathway archetypes. As a whole, the average discounted price of emissions across 1.5˚C- and 2˚C pathways differs by a factor of four across models (assuming a 5% annual discount rate). If values from 1.5˚C-high-OS pathways (with peak warming 0.1–0.4°C higher than 1.5°C) or pathways with very large land-use sinks are kept in the 1.5˚C pathway superclass, the differential value is reduced to a limited degree, from a factor 4 to a factor 3. The increase in carbon prices between 1.5°C- and 2°C-consistent pathways is based on a direct comparison of pathway pairs from the same model and the same study in which the 1.5°C-consistent pathway assumes a significantly smaller carbon budget compared to the 2°C-consistent pathway (e.g., 600 $GtCO_2$ smaller in the CD-LINKS and ADVANCE studies). This assumption is the main driver behind the increase in the price of carbon (Luderer et al., 2018; McCollum et al., 2018).[14] Considering incomplete and uncertain information, an optimal price of carbon of the magnitude estimated in modelling studies needs to be compared with what is politically and institutionally feasible (see Section 4.4.5.2).

The wide range of values depends on numerous aspects, including methodologies, projected energy service demands, mitigation targets, fuel prices and technology availability (Clarke et al., 2014; Kriegler et al., 2015b; Rogelj et al., 2015c; Riahi et al., 2017; Stiglitz et al., 2017) (*high confidence*). The characteristics of the technology portfolio, particularly in terms of investment costs and deployment rates play a key role (Luderer et al., 2013, 2016a; Clarke et al., 2014; Bertram et al., 2015a; Riahi et al., 2015; Rogelj et al., 2015c). Models that encompass a higher degree of technology granularity and that entail more flexibility regarding mitigation response, often produce relatively lower mitigation costs than those that show less flexibility from a technology perspective (Bertram et al., 2015a; Kriegler et al., 2015a). Pathways providing high estimates often have limited flexibility of substituting fossil fuels with low-carbon technologies and the associated need to compensate fossil-fuel emissions with CDR. Emission prices are also sensitive to the non-availability of BECCS (Bauer et al., 2018). Furthermore, and due to the treatment of future price anticipation, recursive-dynamic modelling approaches (with 'myopic anticipation') exhibit higher prices in the short term but modest increases in the long term compared to optimisation modelling frameworks with 'perfect foresight' that show exponential pricing trajectories (Guivarch and Rogelj, 2017). The chosen social discount rate in CEA studies (range of 2–8% per year in the reported data, varying over time and sectors) can also affect the choice and timing of investments in mitigation measures (Clarke et al., 2014; Kriegler et al., 2015b; Weyant, 2017). However, the impacts of varying discount rates on 1.5°C (and 2˚C) mitigation strategies can only be assessed to a limited degree. The above highlights the importance of sampling bias in pathway analysis ensembles towards outcomes derived from models which are more flexible, have more mitigation options and cheaper cost assumptions and thus can provide feasible pathways in contrast to other who are unable to do so (Tavoni and Tol, 2010; Clarke et al., 2014; Bertram et al., 2015a; Kriegler et al., 2015a; Guivarch and Rogelj, 2017). All CEA-based IAM studies reveal no unique carbon pricing path (Bertram et al., 2015a; Kriegler et al., 2015b; Akimoto et al., 2017; Riahi et al., 2017).

Socio-economic conditions and policy assumptions also influence the price of carbon (Bauer et al., 2017; Guivarch and Rogelj, 2017; Hof et al., 2017; Riahi et al., 2017; Rogelj et al., 2018) (*very high confidence*). A multi-model study (Riahi et al., 2017) estimated the average discounted price of carbon (2010-2100, 5% discount rate) for a 2˚C target to be nearly three times higher in the SSP5 marker than in the SSP1 marker. Another multi-model study (Rogelj et al., 2018) estimated average discounted carbon prices (2020-2100, 5%) to be 35–65% lower in SSP1 compared to SSP2 in 1.5˚C pathways. Delayed near-term mitigation policies and measures, including the limited extent of international global cooperation, increases total economic mitigation costs, and corresponding prices of carbon (Luderer et al., 2013; Clarke et al., 2014). This is because stronger efforts are required in the period after the delay to counterbalance the higher emissions in the near term. Staged accession scenarios also produce higher carbon prices than immediate action mitigation scenarios under the same stringency level of emissions (Kriegler et al., 2015b). In addition, the revenue recycling effect of carbon pricing can reduce mitigation costs by displacing distortionary taxes (Baranzini et al., 2017; OECD, 2017; McFarland et al., 2018; Sands, 2018; Siegmeier et al., 2018) and the reduction of capital tax (compared to a labour tax) can yield greater savings in welfare costs (Sands, 2018). The effect on public budgets is particularly important in the near term, however it can decline in the long term as carbon neutrality is achieved (Sands, 2018).

It has been long argued that carbon pricing (whether via a tax or cap-and-trade scheme) can theoretically achieve cost-effective emission reductions (Nordhaus, 2007; Stern, 2007; Aldy and Stavins, 2012; Goulder and Schein, 2013; Somanthan et al., 2014; Weitzman, 2014; Tol, 2017). Whereas the integrated assessment literature is mostly focused on the role of carbon pricing to reduce emissions (Clarke et al., 2014; Riahi et al., 2017; Weyant, 2017) there is an emerging body of studies (including bottom-up approaches) that focuses on the interaction and performance of various policy mixes (e.g., regulation, subsidies, standards). Assuming global implementation of a mix of regionally existing best practice policies (mostly regulatory policies in the electricity, industry, buildings, transport and agricultural sectors) and moderate carbon pricing (between 5–

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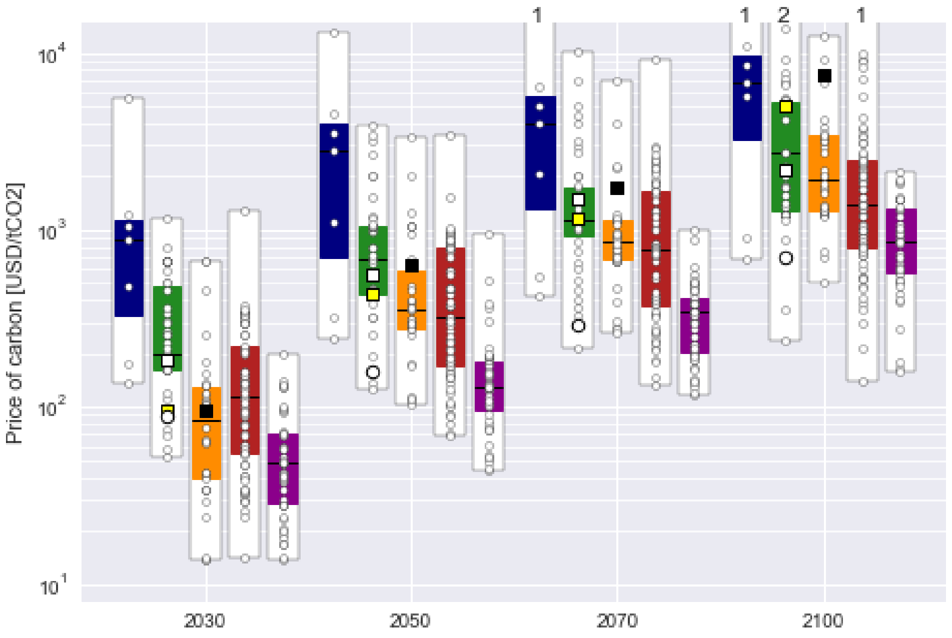
[14] FOOTNOTE: Unlike AR5, which only included cost-effective scenarios for estimating discounted average carbon prices for 2015-2100 (also using a 5% discount rate) (see Clarke et al., 2014, p.450), please note that values shown in Figure 2.26 (panel b) include delays or technology constraint cases (see Sections 2.1 and 2.3).

20 USD$_{2010}$ tCO$_2^{-1}$ in 2025 in most world regions and average prices around 25 USD$_{2010}$ tCO$_2^{-1}$ in 2030), early action mitigation pathways are generated that reduce global CO$_2$ emissions by an additional 10 GtCO$_2$e in 2030 compared to the NDCs (Kriegler et al., 2018b) (see Section 2.3.5). Furthermore, a mix of stringent energy efficiency policies (e.g., minimum performance standards, building codes) combined with a carbon tax (rising from 10 USD$_{2010}$ tCO$_2^{-1}$ in 2020 to 27 USD$_{2010}$ tCO$_2^{-1}$ in 2040) is more cost-effective than a carbon tax alone (from 20 to 53 USD$_{2010}$ tCO$_2^{-1}$) to generate a 1.5˚C pathway for the U.S. electric sector (Brown and Li, 2018). Likewise, a policy mix encompassing a moderate carbon price (7 USD$_{2010}$ tCO$_2^{-1}$ in 2015) combined with a ban on new coal-based power plants and dedicated policies addressing renewable electricity generation capacity and electric vehicles reduces efficiency losses compared with an optimal carbon pricing in 2030 (Bertram et al., 2015b). One study estimates the price of carbon in high energy-intensive pathways to be 25–50% higher than in low energy-intensive pathways that assume ambitious regulatory instruments, economic incentives (in addition to a carbon price) and voluntary initiatives (Méjean et al., 2018). A bottom-up approach shows that stringent minimum performance standards (MEPS) for appliances (e.g., refrigerators) can effectively complement carbon pricing, as tightened MEPS can achieve ambitious efficiency improvements that cannot be assured by carbon prices of 100 USD$_{2010}$ tCO$_2^{-1}$ or higher (Sonnenschein et al., 2018). The literature indicates that the pricing of emissions is relevant but needs to be complemented with other policies to drive the required changes in line with 1.5°C-consistent cost-effective pathways (Stiglitz et al., 2017; Mehling and Tvinnereim, 2018; Méjean et al., 2018; Michaelowa et al., 2018) (*low to medium evidence, high agreement*) (see Section 4.4.5).

In summary, new analyses are consistent with the AR5 and show that the price of carbon would need to increase significantly when a higher level of stringency is pursued (*high confidence*). Values vary substantially across models, scenarios and socio-economic, technology and policy assumptions. While the price of carbon is central to prompt mitigation pathways compatible with 1.5°C-consistent pathways, a complementary mix of stringent policies is required.



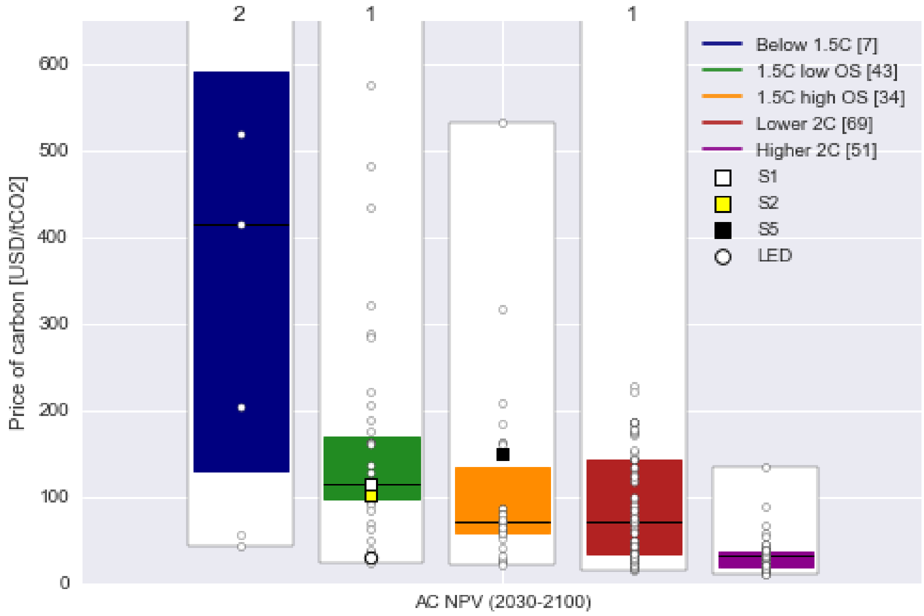


Figure 2.26: Global price of carbon emissions consistent with mitigation pathways. Panels show undiscounted price of carbon (2030-2100) (top panel) and average price of carbon (2030-2100) discounted at a 5% discount rate (lower panel). AC: Annually compounded. NPV: Net present value. Median values in floating black line. The number of pathways included in boxplots is indicated in the legend. Number of pathways outside the figure range is noted at the top.

2.5.2.2 Investments

Realising the transformations towards a 1.5°C world requires a major shift in investment patterns (McCollum et al., 2018). Literature on global climate-change mitigation investments is relatively sparse, with most detailed literature having focused on 2°C pathways (McCollum et al., 2013; Bowen et al., 2014; Gupta and Harnisch, 2014; Marangoni and Tavoni, 2014; OECD/IEA and IRENA, 2017).

Global energy-system investments in the year 2016 are estimated at approximately 1.7 trillion USD_{2010} (approximately 2.2% of global GDP and 10% of gross capital formation), of which 0.23 trillion USD_{2010} was for incremental end-use energy efficiency and the remainder for supply-side capacity installations (IEA, 2017c). There is some uncertainty surrounding this number because not all entities making investments report them publicly, and model-based estimates show an uncertainty range of about ± 15% (McCollum et al., 2018). Notwithstanding, the trend for global energy investments has been generally upward over the last two decades: increasing about threefold between 2000 and 2012, then levelling off for three years before declining in both 2015 and 2016 as a result of the oil price collapse and simultaneous capital cost reductions for renewables (IEA, 2017c).

Estimates of demand-side investments, either in total or for incremental efficiency efforts, are more uncertain, mainly due to a lack of reliable statistics and definitional issues about what exactly is counted towards a demand-side investment and what the reference should be for estimating incremental efficiency (McCollum et al., 2013). Grubler and Wilson (2014) use two working definitions (a broader and a narrower one) to provide a first-order estimate of historical end-use technology investments in total. The broad definition defines end-use technologies as the technological systems purchasable by final consumers in order to provide a useful service, for example, heating and air conditioning systems, cars, freezers, or aircraft. The narrow definition sets the boundary at the specific energy-using components or subsystems of the larger end-use technologies (e.g., compressor, car engine, heating element). Based on these two definitions, demand-side energy investments for the year 2005 were estimated about 1–3.5 trillion USD_{2010} (central estimate 1.7 trillion USD_{2010}) using the broad definition and 0.1–0.6 trillion USD_{2010} (central estimate 0.3 trillion USD_{2010}) using the narrower definition. Due to these definitional issues, demand-side investment projections are uncertain, often underreported, and difficult to compare. Global IAMs often do not fully and explicitly represent all the various measures that could improve end-use efficiency.

Research carried out by six global IAM teams found that 1.5°C-consistent climate policies would require a marked upscaling of energy system supply-side investments (resource extraction, power generation, fuel conversion, pipelines/transmission, and energy storage) between now and mid-century, reaching levels of between 1.6–3.8 trillion USD_{2010} yr^{-1} globally on average over the 2016-2050 timeframe (McCollum et al., 2018) (Figure 2.27). How these investment needs compare to those in a policy baseline scenario is uncertain: they could be higher, much higher, or lower. Investments in the policy baselines from these same models are 1.6–2.7 trillion USD_{2010} yr^{-1}. Much hinges on the reductions in energy demand growth embodied in the 1.5°C pathways, which require investing in energy efficiency. Studies suggest that annual supply-side investments by mid-century could be lowered by around 10% (McCollum et al., 2018) and in some cases up to 50% (Grubler et al., 2018) if strong policies to limit energy demand growth are successfully implemented. However, the degree to which these supply-side reductions would be partially offset by an increase in demand-side investments is unclear.

Some trends are robust across scenarios (Figure 2.27). First, pursuing 1.5°C mitigation efforts requires a major reallocation of the investment portfolio, implying a financial system aligned to mitigation challenges. The path laid out by countries' current NDCs until 2030 will not drive these structural changes; and despite increasing low-carbon investments in recent years (IEA, 2016b; Frankfurt School-UNEP Centre/BNEF, 2017), these are not yet aligned with 1.5°C. Specifically, annual investments in low-carbon energy are projected to average 0.8–2.9 trillion USD_{2010} yr^{-1} globally to 2050 in 1.5 °C pathways, overtaking fossil investments globally already by around 2025 (McCollum et al., 2018). The bulk of these investments are projected to be for clean electricity generation, particularly solar and wind power (0.09–1.0 trillion USD_{2010} yr^{-1} and 0.1–0.35 trillion USD_{2010} yr^{-1}, respectively) as well as nuclear power (0.1–0.25 trillion USD_{2010} yr^{-1}). The precise apportioning of these investments depends on model assumptions and societal preferences related to mitigation strategies and policy choices (see Sections 2.1 and 2.3). Investments for electricity transmission and distribution and storage are also scaled up in 1.5°C pathways (0.3–1.3 trillion USD_{2010} yr^{-1}), given their widespread electrification of the end-use sectors (see Section 2.4). Meanwhile, 1.5°C pathways see a reduction in annual investments for fossil-fuel extraction and unabated fossil electricity generation (to 0.3–0.85 trillion USD_{2010} yr^{-1} on average over the 2016–2050 period). Investments in unabated coal are halted by 2030 in most 1.5°C projections, while the literature is less conclusive for investments in unabated gas (McCollum et al., 2018). This illustrates how mitigation strategies vary between models, but in the real world should be considered in terms of their societal desirability (see Section 2.5.3). Furthermore, some fossil investments made over the next few years – or those made in the last few – will likely need to be retired prior to fully recovering their capital investment or before the end of their operational lifetime (Bertram et al., 2015a; Johnson et al., 2015; OECD/IEA and IRENA, 2017). How the pace of the energy transition will be affected by such dynamics, namely with respect to politics and society, is not well captured by global IAMs at present. Modelling studies have, however, shown how the reliability of institutions influences investment risks and hence climate mitigation investment decisions (Iyer et al., 2015), finding that a lack of regulatory credibility or policy commitment fails to stimulate low-carbon investments (Bosetti and Victor, 2011; Faehn and Isaksen, 2016).

Low-carbon supply-side investment needs are projected to be largest in OECD countries and those of developing Asia. The regional distribution of investments in 1.5°C pathways estimated by the multiple models in (McCollum et al., 2018) are the following (average over 2016-2050 timeframe): 0.30-1.3 trillion USD_{2010} yr^{-1}(ASIA), 0.35–0.85 trillion USD_{2010} yr^{-1} (OECD), 0.08–0.55 trillion USD_{2010} yr^{-1} (MAF), 0.07–0.25 trillion USD_{2010} yr^{-1} (LAM), and 0.05–0.15 trillion USD_{2010} yr^{-1} (REF) (regions are defined consistent with their use in AR5 WGIII, see Table A.II.8 in Krey et al., 2014b).

Until now, IAM investment analyses of 1.5 °C pathways have focused on middle-of-the-road socioeconomic and technological development futures (SSP2) (Fricko et al., 2017). Consideration of a broader range of development futures would yield different outcomes in terms of the magnitudes of the projected investment levels. Sensitivity analyses indicate that the magnitude of supply-side investments as well as the investment portfolio do not change strongly across the SSPs for a given level of climate policy stringency (McCollum et al., 2018). With only one dedicated multi-model comparison study published, there is *limited to medium evidence* available. For some features, there is *high agreement* across modelling frameworks leading, for example, to *medium to high confidence* that limiting global temperature increase to 1.5°C will require a major reallocation of the investment portfolio. Given the limited amount of sensitivity cases available compared to the default SSP2 assumptions, *medium confidence* can be assigned to the specific energy and climate mitigation investment estimates reported here.

Assumptions in modelling studies indicate a number of challenges. For instance, access to finance and mobilisation of funds are critical (Fankhauser et al., 2016; OECD, 2017). In turn, policy efforts need to be effective in re-directing financial resources (UNEP, 2015; OECD, 2017) and reduce transaction costs for bankable mitigation projects (i.e. projects that have adequate future cash-flow, collateral, etc. so lenders are willing to finance it), particularly on the demand side (Mundaca et al., 2013; Brunner and Enting, 2014; Grubler et al., 2018). Assumptions also imply that policy certainty, regulatory oversight mechanisms and fiduciary duty need to be robust and effective to safeguard credible and stable financial markets and de-risk mitigation investments in the long term (Clarke et al., 2014; Mundaca et al., 2016; EC, 2017; OECD, 2017). Importantly, the different time horizons that actors have in the competitive finance industry are typically not explicitly captured by modelling assumptions (Harmes, 2011). See Section 4.4.5 for details of climate finance in practice.

In summary and despite inherent uncertainties, the emerging literature indicates a gap between current investment patterns and those compatible with 1.5°C (or 2°C) pathways (*limited to medium evidence, high agreement*). Estimates and assumptions from modelling frameworks suggest a major shift in investment patterns and entail a financial system effectively aligned with mitigation challenges (*high confidence*).

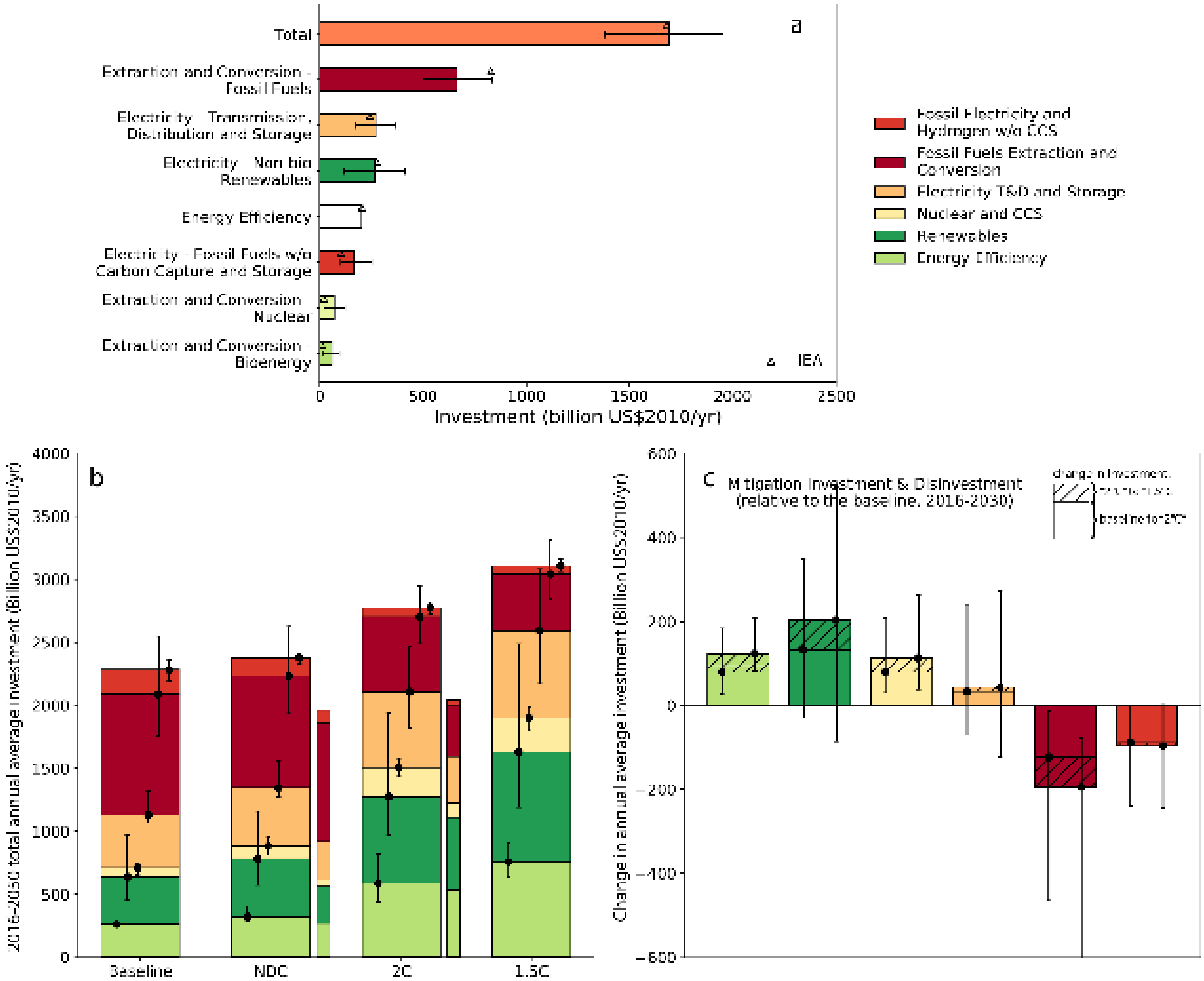


Figure 2.27: Historical and projected global energy investments. (a) Historical investment estimates across six global models from (McCollum et al., 2018) (bars = model means, whiskers full model range) compared to historical estimates from IEA (International Energy Agency (IEA) 2016) (triangles). (b) Average annual investments over the 2016–2050 period in no-climate policy 'baselines', scenarios which implement the NDCs ('NDC'), scenarios consistent with the Lower-2°C pathway class ('2°C'), and scenarios in line with the 1.5°C-low-OS pathway class ('1.5°C'). Whiskers show the range of models; wide bars show the multi-model means; narrow bars represent analogous values from individual IEA

scenarios (OECD/IEA and IRENA, 2017). (c) Average annual mitigation investments and disinvestments for the 2016–2030 periods relative to the baseline. The solid bars show the values for '2°C' pathways, while the hatched areas show the additional investments for the pathways labelled with '1.5°C'. Whiskers show the full range around the multi-model means. T&D stands for transmission and distribution, and CCS stands for carbon capture and storage. Global cumulative carbon dioxide emissions, from fossil fuels and industrial processes (FF&I) but excluding land use, over the 2016-2100 timeframe range from 880 to 1074 $GtCO_2$ (multi-model mean: 952 $GtCO_2$) in the '2°C' pathway and from 206 to 525 $GtCO_2$ (mean: 390 $GtCO_2$) in the '1.5°C' pathway.

2.5.3 Sustainable development features of 1.5°C pathways

Potential synergies and trade-offs between 1.5°C mitigation pathways and different sustainable development (SD) dimensions (see Cross-Chapter Box 4) are an emerging field of research. Section 5.4 assesses interactions between individual mitigation measures with other societal objectives, as well as the Sustainable Development Goals (SGDs) (Table 5.1). This section synthesized the Chapter 5 insights to assess how these interactions play out in integrated 1.5°C pathways, and the four illustrative pathway archetypes of this chapter in particular (see Section 2.1). Information from integrated pathways is combined with the interactions assessed in Chapter 5 and aggregated for each SDG, with a level of confidence attributed to each interaction based on the amount and agreement of the scientific evidence (see Chapter 5).

Figure 2.28 shows how the scale and combination of individual mitigation measures (i.e., their mitigation portfolios) influence the extent of synergies and trade-offs with other societal objectives. All pathways generate multiple synergies with SD dimensions and can advance several other SDGs simultaneously. Some, however, show higher risks for trade-offs. An example is increased biomass production and its potential to increase pressure on land and water resources, food production, biodiversity, and reduced air-quality when combusted inefficiently. At the same time, mitigation actions in energy-demand sectors and behavioural response options with appropriate management of rebound effects can advance multiple SDGs simultaneously, more so than energy supply-side mitigation actions (see Section 5.4, Table 5.1 and Figure 5.3 for more examples). Of the four pathway archetypes used in this chapter (*S1*, *S2*, *S5*, and *LED*), the *S1* and *LED* pathways show the largest number of synergies and least number of potential trade-offs, while for the *S5* pathway most potential trade-offs are identified. In general, pathways with emphasis on demand reductions, with policies that incentivise behavioural change, sustainable consumption patterns, healthy diets and relatively low use of CDR (or only afforestation) show relatively more synergies with individual SDGs than others.

There is *robust evidence* and *high agreement* in the pathway literature that multiple strategies can be considered to limit warming to 1.5°C (see Sections 2.1.3, 2.3 and 2.4). Together with the extensive evidence on the existence of interactions of mitigation measures with other societal objectives (Section 5.4), this results in *high confidence* that the choice of mitigation portfolio or strategy can markedly affect the achievement of other societal objectives. For instance, action on SLCFs has been suggested to facilitate the achievement of SDGs (Shindell et al., 2017b) and to reduce regional impacts, e.g., from black carbon sources on snow and ice loss in the Arctic and alpine regions (Painter et al., 2013), with particular focus on the warming sub-set of SLCFs. Reductions in both surface aerosols and ozone through methane reductions provide health and ecosystem co-benefits (Jacobson, 2002, 2010; Anenberg et al., 2012; Shindell et al., 2012; Stohl et al., 2015; Collins et al., 2018). Public health benefits of stringent mitigation pathways in line with 1.5°C-consistent pathways can be sizeable. For instance, a study examining a more rapid reduction of fossil-fuel usage to achieve 1.5°C relative to 2°C, similar to that of other recent studies (Grubler et al., 2018; van Vuuren et al., 2018), found that improved air quality would lead to more than 100 million avoided premature deaths over the 21st century (Shindell et al., 2018). These benefits are assumed to be in addition to those occurring under 2°C pathways (e.g., Silva et al., 2016), and could in monetary terms offset a large portion to all of the initial mitigation costs (West et al., 2013; Shindell et al., 2018). However, some sources of SLCFs with important impacts for public health (e.g., traditional biomass burning) are only mildly affected by climate policy in the available integrated pathways and are more strongly impacted by baseline assumptions about future societal development and preferences, and technologies instead (Rao et al., 2016, 2017).

At the same time, the literature on climate-SDG interactions is still an emergent field of research and hence there is *low to medium confidence* in the precise magnitude of the majority of these interactions. Very limited literature suggests that achieving co-benefits are not automatically assured but result from conscious and carefully coordinated policies and implementation strategies (Shukla and Chaturvedi, 2012; Clarke et al., 2014; McCollum et al., 2018). Understanding these mitigation-SDG interactions is key for selecting mitigation options that maximise synergies and minimize trade-offs towards the 1.5°C and sustainable development objectives (van Vuuren et al., 2015; Hildingsson and Johansson, 2016; Jakob and Steckel, 2016; von Stechow et al., 2016; Delponte et al., 2017).

In summary, the combined evidence indicates that the chosen mitigation portfolio can distinctly have an impact on the achievement of other societal policy objectives (*high confidence*); however, there is uncertainty regarding the specific extent of climate-SDG interactions.

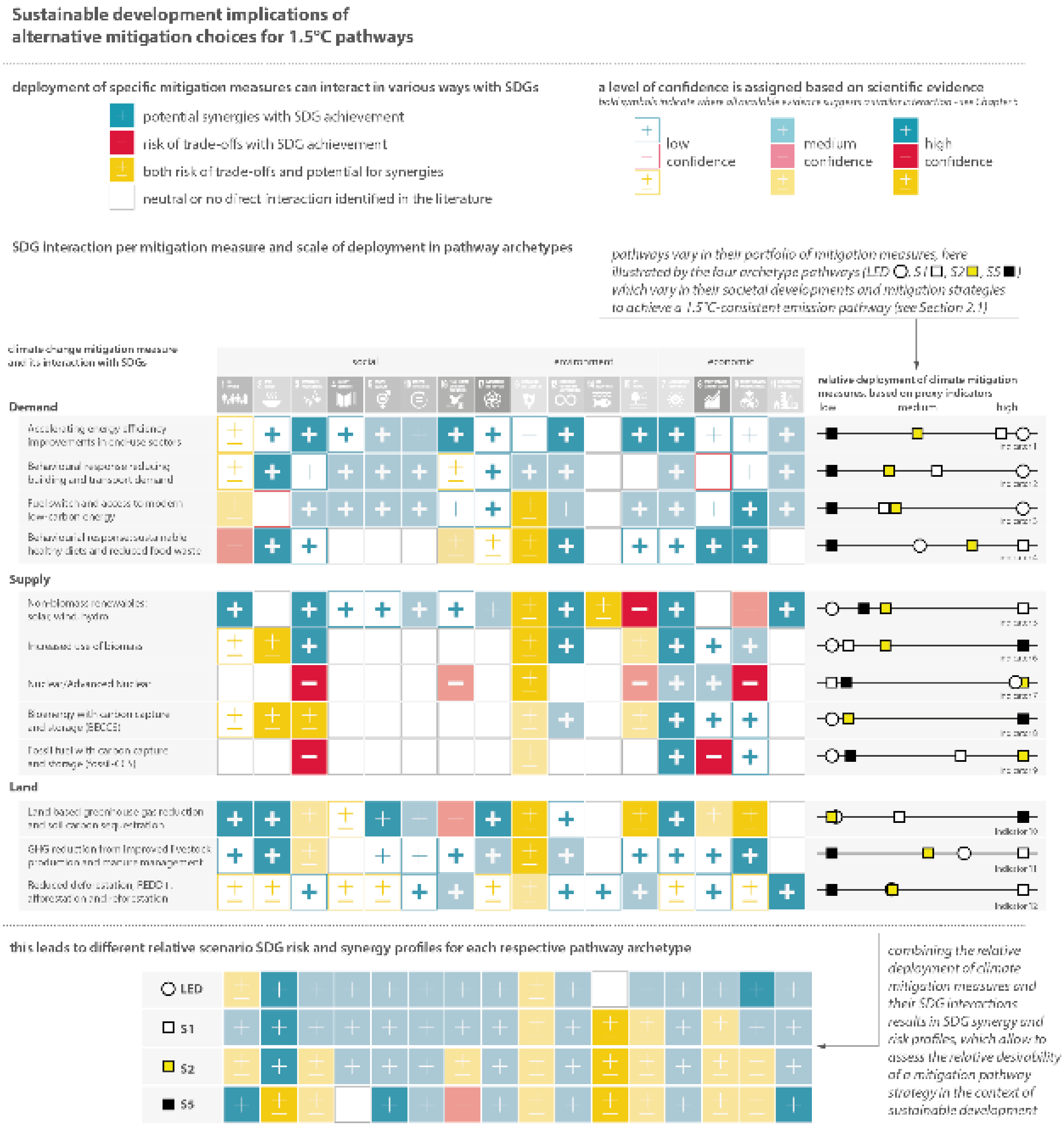


Figure 2.28: Interactions of individual mitigation measures and alternative mitigations portfolios for 1.5°C with Sustainable Development Goals (SDGs). The assessment of interactions between mitigation measures and individual SDGs is based on the assessment of Section 5.4. Proxy indicators and synthesis method are described in Annex 2.A.5.

2.6 Knowledge gaps

This section summarises the knowledge gaps articulated in earlier sections of the chapter.

2.6.1 Geophysical understanding

Knowledge gaps are associated with the carbon-cycle response, the role of non-CO_2 emissions and on the evaluation of an appropriate historic baseline.

Quantifying how the carbon cycle responds to negative emissions is an important knowledge gap for strong mitigation pathways (Section 2.2). Earth-system feedback uncertainties are important to consider for the longer-term response, particularly in how permafrost melting might affect the carbon budget (Section 2.2). Future research and ongoing observations over the next years will provide a better indication as to how the 2006-2015 base period compares with the long-term trends and might at present bias the carbon budget estimates.

The future emissions of short-lived climate forcers and their temperature response are a large source of uncertainty in 1.5°C pathways, having a greater relative uncertainty than in higher CO_2 emission pathways. Their global emissions, their sectorial and regional disaggregation and their climate response are generally less well quantified than for CO_2 (Sections 2.2 and 2.3). Emissions from the agricultural sector including land-use based mitigation options in 1.5°C pathways constitute the main source of uncertainty here and are an important gap in understanding the potential achievement of stringent mitigation scenarios (Sections 2.3 and 2.4). This also includes uncertainties surrounding the mitigation potential of the long-lived GHG nitrous oxide. (Sections 2.3 and 2.4)

There is considerable uncertainty in how future emissions of aerosol precursors will affect the effective radiative forcing from aerosol-cloud interaction. The potential future warming from mitigation of these emissions reduces remaining carbon budgets and increases peak temperatures (Section 2.2). The potential co-benefits of mitigating air pollutants and how the reduction in air pollution may affect the carbon sink are also important sources of uncertainty (Sections 2.2 and 2.5).

The pathway classification employed in this Chapter employs results from the MAGICC model with its AR5 parameter sets. The alternative representation of the relationship between emissions and effective radiative forcing and response in the FAIR model would lead to a different classification that would make 1.5°C targets more achievable (Section 2.2 and Annex 2.A.1). Such a revision would significantly alter the temperature outcomes for the pathways and, if the result is found to be robust, future research and assessments would need to adjust their classifications accordingly. Any possible high bias in the MAGICC response may be partly or entirely offset by missing Earth system feedbacks that are not represented in either climate emulator that would act to increase the temperature response (Section 2.2). For this assessment report, any possible bias in MAGICC setup applied in this and earlier reports is not established enough in the literature to change the classification approach. However, we only place *medium confidence* in the classification adopted by the chapter.

2.6.2 Integrated assessment approaches

IAMs attempt to be as broad as possible in order to explore interactions between various societal subsystems, like the economy, land, and energy system. They hence include stylised and simplified representations of these subsystems. Climate damages, avoided impacts and societal co-benefits of the modelled transformations remain largely unaccounted for and are important knowledge gaps. Furthermore, rapid technological changes and uncertainties about input data present continuous challenges.

The IAMs used in this report do not account for climate impacts (Section 2.1), and similarly, none of the Gross Domestic Product (GDP) projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth (Section 2.3). Although some IAMs do allow for climate impact feedbacks in their modelling frameworks, particularly in their land components, such feedbacks were by design excluded in pathways developed in the context of the SSP framework. The SSP framework aims at providing an integrative framework for the assessment of climate change adaptation and mitigation. IAMs are typically developed to inform the mitigation component of this question, while the assessment of impacts is carried out by specialized impact models. However, the use of a consistent set of socio-economic drivers embodied by the SSPs allows for an integrated assessment of climate change impacts and mitigation challenges at a later stage. Further integration of these two strands of research will allow a better understanding of climate impacts on mitigation studies.

Many of the IAMs that contributed mitigation pathways to this assessment include a process-based description of the land system in addition to the energy system and several have been extended to cover air pollutants and water use. These features make them increasingly fit to explore questions beyond those that touch upon climate mitigation only. The models do not, however, fully account for all constraints that could affect realization of pathways (Section 2.1).

While the representation of renewable energy resource potentials, technology costs and system integration in IAMs has been updated since AR5, bottom-up studies find higher mitigation potentials in the industry, buildings, and transport sector in that realized by selected pathways from IAMs, indicating the possibility to strengthen sectorial decarbonisation strategies compared to the IAM 1.5°C pathways assessed in this chapter (Section 2.1).

Studies indicate that a major shift in investment patterns is required to limit global warming to 1.5°C. This assessment would benefit from a more explicit representation and understanding of the financial sector within the modelling approaches. Assumptions in modelling studies imply low-to-zero transaction costs for market agents and that regulatory oversight mechanisms and fiduciary duty need to be highly robust to guarantee stable and credible financial markets in the long term. This area can be subject to high uncertainty, however. The heterogeneity of actors (e.g., banks, insurance companies, asset managers, or credit rating agencies) and financial products also needs to be taken into account, as does the mobilisation of capital and financial flows between countries and regions (Section 2.5).

The literature on interactions between 1.5˚C mitigation pathways and SDGs is an emergent field of research (Section 2.3.5, 2.5 and Chapter 5). Whereas the choice of mitigation strategies can noticeably affect the attainment of various societal objectives, there is uncertainty regarding the extent of the majority of identified interactions. Understanding climate-SDG interactions helps the choice of mitigation options that minimize trade-offs and risks and maximise synergies towards sustainable development objectives and the 1.5°C goal (Section 2.5).

2.6.3 Carbon Dioxide Removal (CDR)

Most 1.5°C and 2°C pathways are heavily reliant on CDR at a speculatively large scale before mid-century. There are a number of knowledge gaps associated which such technologies. Chapter 4 performs a detailed assessment of CDR technologies.

There is uncertainty in the future deployment of CCS given the limited pace of current deployment, the evolution of CCS technology that would be associated with deployment, and the current lack of incentives for large-scale implementation of CCS (Section 4.2.7). Technologies other than BECCS and afforestation have yet to be comprehensively assessed in integrated assessment approaches. No proposed technology is close to deployment at scale and regulatory frameworks are not established. This limits how they can be realistically implemented within IAMs. (Section 2.3)

Evaluating the potential from BECCS is problematic due to large uncertainties in future land projections due to differences in modelling approaches in current land-use models which are at least as great as the differences attributed to climate scenario variations. (Section 2.3)

There is substantial uncertainty about the adverse effects of large-scale CDR deployment on the environment and societal sustainable development goals. It is not fully understood how land use and land management choices for large-scale BECCS will affect various ecosystem services and sustainable development, and further translate into indirect impacts on climate including GHG emissions other than $CO_{2.}$ (Section 2.3, Section 2.5.3)

Frequently Asked Questions

FAQ 2.1: What kind of pathways limit warming to 1.5°C and are we on track?

***Summary**: There is no definitive way to limit global temperature rise to 1.5°C above pre-industrial levels. This Special Report identifies two main conceptual pathways to illustrate different interpretations. One stabilises global temperature at, or just below, 1.5°C. Another sees global temperature temporarily exceed 1.5°C before coming back down. Countries' pledges to reduce their emissions are currently not in line with limiting global warming to 1.5°C.*

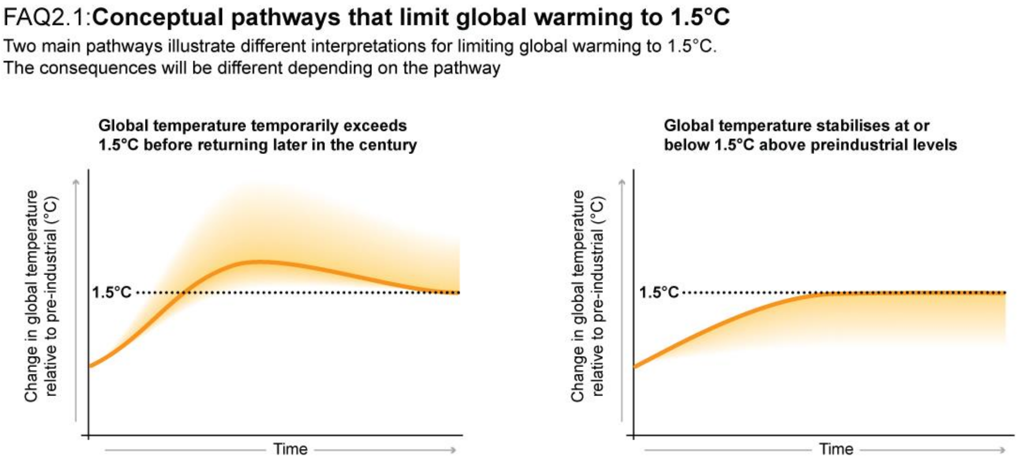
Scientists use computer models to simulate the emissions of greenhouse gases that would be consistent with different levels of warming. The different possibilities are often referred to as 'greenhouse gas emission pathways'. There is no single, definitive pathway to limiting warming to 1.5°C.

This IPCC special report identifies two main pathways that explore global warming of 1.5°C. The first involves global temperature stabilising at or below before 1.5°C above preindustrial levels. The second pathway sees warming exceed 1.5°C around mid-century, remain above 1.5°C for a maximum duration of a few decades, and return to below 1.5°C before 2100. The latter is often referred to as an 'overshoot' pathway. Any alternative situation in which global temperature continues to rise, exceeding 1.5°C permanently until the end of the 21st century, is not considered to be a 1.5°C pathway.

The two types of pathway have different implications for greenhouse gas emissions, as well as for climate change impacts and for achieving sustainable development. For example, the larger and longer an 'overshoot', the greater the reliance on practices or technologies that remove CO_2 from the atmosphere, on top of reducing the sources of emissions (mitigation). Such ideas for CO_2 removal have not been proven to work at scale and, therefore, run the risk of being less practical, effective or economical than assumed. There is also the risk that the use of CO_2 removal techniques ends up competing for land and water and if these trade-offs are not appropriately managed, they can adversely affect sustainable development. Additionally, a larger and longer overshoot increases the risk for irreversible climate impacts, such as the onset of the collapse of polar ice shelves and accelerated sea level rise.

Countries that formally accept or 'ratify' the Paris Agreement submit pledges for how they intend to address climate change. Unique to each country, these pledges are known as Nationally Determined Contributions (NDCs). Different groups of researchers around the world have analysed the combined effect of adding up all the NDCs. Such analyses show that current pledges are not on track to limit global warming to 1.5°C above pre-industrial levels. If current pledges for 2030 are achieved but no more, researchers find very few (if any) ways to reduce emissions after 2030 sufficiently quickly to limit warming to 1.5°C. This, in turn, suggests that with the national pledges as they stand, warming would exceed 1.5°C, at least for a period of time, and practices and technologies that remove CO_2 from the atmosphere at a global scale would be required to return warming to 1.5°C at a later date.

A world that is consistent with holding warming to 1.5°C would see greenhouse gas emissions rapidly decline in the coming decade, with strong international cooperation and a scaling up of countries' combined ambition beyond current NDCs. In contrast, delayed action, limited international cooperation, and weak or fragmented policies that lead to stagnating or increasing greenhouse gas emissions would put the possibility of limiting global temperature rise to 1.5°C above pre-industrial levels out of reach.



FAQ2.1, Figure 1: Two main pathways for limiting global temperature rise to 1.5°C above pre-industrial levels are discussed in this Special Report. These are: stabilising global temperature at, or just below, 1.5°C (left) and global temperature temporarily exceeding 1.5°C before coming back down later in the century (right). Temperatures shown are relative to pre-industrial but pathways are illustrative only, demonstrating conceptual not quantitative characteristics.

FAQ 2.2: What do energy supply and demand have to do with limiting warming to 1.5°C?

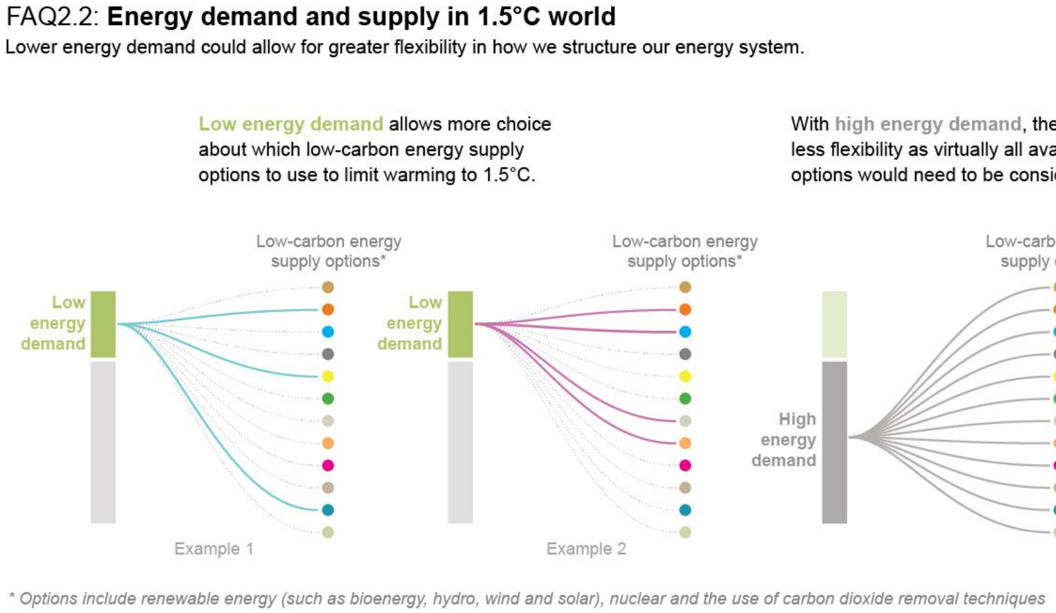
***Summary**: Limiting global warming to 1.5°C above pre-industrial levels would require major reductions in greenhouse gas emissions in all sectors. But different sectors are not independent of each other and making changes in one can have implications for another. For example, if we as a society use a lot of energy, then this could mean we have less flexibility in the choice of mitigation options available to limit warming to 1.5°C. If we use less energy, the choice of possible actions is greater. For example we could be less reliant on technologies that remove carbon dioxide (*CO_2*) from the atmosphere.*

To stabilise global temperature at any level, 'net' CO_2 emissions would need to be reduced to zero. This means the amount of CO_2 entering the atmosphere must equal the amount that is removed. Achieving a balance between CO_2 'sources' and 'sinks' is often referred to as 'net zero' emissions or 'carbon neutrality'. The implication of net zero emissions is that the concentration of CO_2 in the atmosphere would slowly decline over time until a new equilibrium is reached, as CO_2 emissions from human activity are redistributed and taken up by the oceans and the land biosphere. This would lead to a near-constant global temperature over many centuries.

Warming will not be limited to 1.5°C or 2°C unless transformations in a number of areas achieve the required greenhouse gas emissions reductions. Emissions would need to decline rapidly across all of society's main sectors, including buildings, industry, transport, energy, and agriculture, forestry and other land use (AFOLU). Actions that can reduce emissions include, for example, phasing out coal in the energy sector, increasing the amount of energy produced from renewable sources, electrifying transport, and reducing the 'carbon footprint' of the food we consume.

The above are examples of 'supply-side' actions. Broadly speaking, these are actions that can reduce greenhouse gas emissions through the use of low-carbon solutions. A different type of action can reduce how much energy human society uses, while still ensuring increasing levels of development and well-being. Known as 'demand-side' actions, this category includes improving energy efficiency in buildings and reducing consumption of energy- and greenhouse-gas intensive products through behavioural and lifestyle changes, for example. Demand and supply-side measures are not an either-or question, they work in parallel with each other. But emphasis can be given to one or the other.

Making changes in one sector can have consequences for another, as they are not independent of each other. In other words, the choices that we make now as a society in one sector can either restrict or expand our options later on. For example, a high demand for energy could mean we would need to deploy almost all known options to reduce emissions in order to limit global temperature rise to 1.5°C above pre-industrial levels, with the potential for adverse side-effects. For example, a high-demand pathway increases our reliance on practices and technologies that remove CO_2 from the atmosphere. As of yet, such techniques have not been proven to work on a large scale and, depending on how they are implemented, could compete for land and water. By leading to lower overall energy demand, effective demand-side measures could allow for greater flexibility in how we structure our energy system. However, demand-side measures are not easy to implement and barriers have prevented the most efficient practices being used in the past.



FAQ2.2: **Energy demand and supply in 1.5°C world**

Lower energy demand could allow for greater flexibility in how we structure our energy system.

Low energy demand allows more choice about which low-carbon energy supply options to use to limit warming to 1.5°C.

With high energy demand, there is less flexibility as virtually all available options would need to be considered.

* Options include renewable energy (such as bioenergy, hydro, wind and solar), nuclear and the use of carbon dioxide removal techniques

FAQ2.2, Figure 1: Having a lower energy demand increases the flexibility in choosing options for supplying energy. A larger energy demand means many more low carbon energy supply options would need to be used.

References

Ackerman, F. and E.A. Stanton, 2012: Climate Risks and Carbon Prices: Revising the Social Cost of Carbon. *Economics: The Open-Access, Open-Assessment E-Journal*, **6(2012-10)**, 1, doi:10.5018/economics-ejournal.ja.2012-10.

Adler, M.D. and N. Treich, 2015: Prioritarianism and Climate Change. *Environmental and Resource Economics*, **62(2)**, 279-308, doi:10.1007/s10640-015-9960-7.

Adler, M.D. et al., 2017: Priority for the worse-off and the social cost of carbon. *Nature Clim. Change*, **7(6)**, 443-449, doi:10.1038/nclimate3298.

Akimoto, K., F. Sano, and T. Tomoda, 2017: GHG emission pathways until 2300 for the 1.5 °C temperature rise target and the mitigation costs achieving the pathways. *Mitigation and Adaptation Strategies for Global Change*, 1-14, doi:10.1007/s11027-017-9762-z.

Alcalde, J. et al., 2018: Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature Communications* (in press), doi:10.1038/s41467-018-04423-1.

Aldy, J.E. and R.N. Stavins, 2012: The Promise and Problems of Pricing Carbon. *The Journal of Environment & Development*, **21(2)**, 152-180, doi:10.1177/1070496512442508.

Aldy, J.E. et al., 2016: Economic tools to promote transparency and comparability in the Paris Agreement. *Nature Climate Change*, **6(11)**, 1000-1004, doi:10.1038/nclimate3106.

Allen, M.R. et al., 2009: Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458(7242)**, 1163-1166, doi:10.1038/nature08019.

Allen, M.R. et al., 2016: New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nature Climate Change*, **6(May)**, 1-5, doi:10.1038/nclimate2998.

Allen, M.R. et al., 2018: A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *npj Climate and Atmospheric Science* (in press).

Allwood, J.M., M.F. Ashby, T.G. Gutowski, and E. Worrell, 2013: Material efficiency: providing material services with less material production. *Phil. Trans. R. Soc. A*, **371(1986)**, 20120496, doi:10.1098/rsta.2012.0496.

Anderson, K. and G. Peters, 2016: The trouble with negative emissions. *Science*, **354(6309)**, 182-183, doi:10.1126/science.aah4567.

Anenberg, S.C. et al., 2012: Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environmental Health Perspectives*, **120(6)**, 831-839, doi:10.1289/ehp.1104301.

Anthoff, D. and R.S.J. Tol, 2009: The impact of climate change on the balanced growth equivalent: An application of FUND. *Environmental and Resource Economics*, **43(3)**, 351-367, doi:10.1007/s10640-009-9269-5.

Armour, K.C., 2017: Energy budget constraints on climate sensitivity in light of inconstant climate feedbacks. *Nature Clim. Change*, **7(5)**, 331-335, doi:10.1038/nclimate3278.

Arneth, A. et al., 2010: Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience*, **3(8)**, 525-532, doi:10.1038/ngeo905.

Arroyo-Currás, T. et al., 2015: Carbon leakage in a fragmented climate regime: The dynamic response of global energy markets. *Technological Forecasting & Social Change*, **90**, 192-203, doi:10.1016/j.techfore.2013.10.002.

Bachu, S., 2015: Review of CO_2 storage efficiency in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **40**, 188-202, doi:10.1016/j.ijggc.2015.01.007.

Bachu, S. et al., 2007a: *Phase II Final Report from the Task Force for Review and Identification of Standards for* CO_2 *Storage Capacity Estimation*. Estimation of CO_2 Storage Capacity in Geological Media - Phase 2, 43 pp.

Bachu, S. et al., 2007b: CO_2 storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control*, **1(4)**, 430-443, doi:10.1016/S1750-5836(07)00086-2.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924-929, doi:10.1038/nclimate2353.

Banerjee, R. et al., 2012: GEA Chapter 8 - Energy End Use: Industry. In: *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 513-574.

Baranzini, A. et al., 2017: Carbon pricing in climate policy: seven reasons, complementary instruments, and political economy considerations. *Wiley Interdisciplinary Reviews: Climate Change*, **8(4)**, e462, doi:10.1002/wcc.462.

Bataille, C., H. Waisman, M. Colombier, L. Segafredo, and J. Williams, 2016a: The Deep Decarbonization Pathways Project (DDPP): insights and emerging issues. *Climate Policy*, **16(sup1)**, S1-S6, doi:10.1080/14693062.2016.1179620.

Bataille, C. et al., 2016b: The need for national deep decarbonization pathways for effective climate policy. *Climate Policy*, **16(sup1)**, S7-S26, doi:10.1080/14693062.2016.1173005.

Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives. *Global Environmental Change*, **42**, 316-330, doi:10.1016/j.gloenvcha.2016.07.006.

Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF 33 model comparison. *Climatic Change* (in press), doi:10.1007/s10584-018-2226-y.

Beck, S. and M. Mahony, 2017: The IPCC and the politics of anticipation. *Nature Climate Change*, **7(5)**, 311-313, doi:10.1038/nclimate3264.

Bentham, M., T. Mallows, J. Lowndes, and A. Green, 2014: CO_2 STORage evaluation database (CO_2 Stored). The UK's online storage atlas. *Energy Procedia*, **63**, 5103-5113, doi:10.1016/j.egypro.2014.11.540.

Benveniste, H. et al., 2018: Impacts of nationally determined contributions on 2030 global greenhouse gas emissions: Uncertainty analysis and distribution of emissions. *Environmental Research Letters*, **13(1)**, 014022, doi:10.1088/1748-9326/aaa0b9.

Berger, A. et al., 2017a: Nuclear energy and bio energy carbon capture and storage, keys for obtaining 1.5°C mean surface temperature limit. *International Journal of Global Energy Issues*, **40(3/4)**, 240, doi:10.1504/IJGEI.2017.086622.

Berger, A. et al., 2017b: How much can nuclear energy do about global warming? *International Journal of Global Energy Issues*, **40(1/2)**, 43, doi:10.1504/IJGEI.2017.080766.

Bertram, C., G. Luderer, A. Popp, J.C. Minx, and W. Lamb, 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environ. Res. Lett* (in press), doi: 10.1088/1748-9326/aac3ec.

Bertram, C. et al., 2015a: Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technological Forecasting and Social Change*, **90(PA)**, 62-72, doi:10.1016/j.techfore.2013.10.001.

Bertram, C. et al., 2015b: Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change*, **5(3)**, 235-239, doi:10.1038/nclimate2514.

Bindoff, N. et al., 2013: Detection and Attribution of Climate Change: from Global to Regional. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 867-952.

Blanco, G. et al., 2014: Drivers, Trends and Mitigation. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 351-412.

Boardman, A.E., 2006: *Cost-Benefit Analysis: Concepts and Practice*. Pearson/Prentice Hall, 560 pp.

Bodirsky, B.L. et al., 2012: N2O emissions from the global agricultural nitrogen cycle-current state and future scenarios. *Biogeosciences*, **9(10)**, 4169-4197, doi:10.5194/bg-9-4169-2012.

Bodirsky, B.L. et al., 2014: Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature Communications*, **5**, doi:10.1038/ncomms4858.

Bond, T.C. et al., 2013: Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, **118(11)**, 5380-5552, doi:10.1002/jgrd.50171.

Bonsch, M. et al., 2014: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11-24, doi:10.1111/gcbb.12226.

Bosetti, V. and D.G. Victor, 2011: Politics and Economics of Second-Best Regulation of Greenhouse Gases: The Importance of Regulatory Credibility. *The Energy Journal*, **32(1)**, 1-24.

Bosetti, V., C. Carraro, E. Massetti, and M. Tavoni, 2008: International energy R&D spillovers and the economics of greenhouse gas atmospheric stabilization. *Energy Economics*, **30(6)**, 2912-2929, doi:10.1016/j.eneco.2008.04.008.

Bosetti, V., C. Carraro, A. Sgobbi, and M. Tavoni, 2009: Delayed action and uncertain stabilisation targets. How much will the delay cost? *Climatic Change*, **96(3)**, 299-312, doi:10.1007/s10584-009-9630-2.

Bosetti, V., C. Carraro, M. Galeotti, E. Massetti, and M. Tavoni, 2006: WITCH - A world induced technical change hybrid model. *The Energy Journal, Special Issue. Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down*, 13-38.

Bosetti, V. et al., 2015: Sensitivity to energy technology costs: A multi-model comparison analysis. *Energy Policy*, **80**, 244-263, doi:10.1016/j.enpol.2014.12.012.

Boucher, O. and G.A. Folberth, 2010: New Directions: Atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment*, **44(27)**, 3343-3345, doi:10.1016/J.ATMOSENV.2010.04.032.

Bowen, A., E. Campiglio, and M. Tavoni, 2014: A macroeconomic perspective on climate change mitigation: Meeting the financing challenge. *Climate Change Economics*, **05(01)**, 1440005, doi:10.1142/S2010007814400053.

Bowerman, N.H.A., D.J. Frame, C. Huntingford, J.A. Lowe, and M.R. Allen, 2011: Cumulative carbon emissions, emissions floors and short-term rates of warming: implications for policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369(1934)**, 45-66, doi:10.1098/rsta.2010.0288.

Bowerman, N.H.A. et al., 2013: The role of short-lived climate pollutants in meeting temperature goals. *Nature Climate Change*, **3(12)**, 1021-1024, doi:10.1038/nclimate2034.

Boysen, L.R., W. Lucht, and D. Gerten, 2017a: Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Global Change Biology*, **23(10)**, 4303-4317, doi:doi:10.1111/gcb.13745.

Boysen, L.R., W. Lucht, D. Gerten, and V. Heck, 2016: Impacts devalue the potential of large-scale terrestrial CO_2 removal through biomass plantations. *Environmental Research Letters*, **11(9)**, 1-10, doi:10.1088/1748-9326/11/9/095010.

Boysen, L.R. et al., 2017b: The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, **5(5)**, 463-474, doi:10.1002/2016EF000469.

Breyer, C. et al., 2017: On the role of solar photovoltaics in global energy transition scenarios. *Progress in Photovoltaics: Research and Applications*, **25(8)**, 727-745, doi:10.1002/pip.2885.

Brown, M.A. and Y. Li, 2018: Carbon Pricing and Energy Efficiency: Pathways to Deep Decarbonization of the U.S. Electric Sector. *Energy Efficiency* (in press), doi:10.1007/s12053-018-9686-9.

Brown, P.T. and K. Caldeira, 2017: Greater future global warming inferred from Earth's recent energy budget. *Nature*, **552(7683)**, 45-50, doi:10.1038/nature24672.

Bruckner, T., I.A. Bashmakov, and Y. Mulugetta, 2014: Energy Systems. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 511-598.

Brunner, S. and K. Enting, 2014: Climate finance: A transaction cost perspective on the structure of state-to-state transfers. *Global Environmental Change*, **27**, 138-143.

Brynolf, S., M. Taljegard, M. Grahn, and J. Hansson, 2018: Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews*, **81**, 1887-1905, doi:https://doi.org/10.1016/j.rser.2017.05.288.

Buck, H.J., 2016: Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change*, 1-13, doi:10.1007/s10584-016-1770-6.

Burke, E.J., I.P. Hartley, and C.D. Jones, 2012: Uncertainties in the global temperature change caused by carbon release from permafrost thawing. *Cryosphere*, **6(5)**, 1063-1076, doi:10.5194/tc-6-1063-2012.

Burke, E.J. et al., 2017: Quantifying uncertainties of permafrost carbon-climate feedbacks. *Biogeosciences*, **14(12)**, 3051-3066, doi:10.5194/bg-14-3051-2017.

Burns, W. and S. Nicholson, 2017: Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *Journal of Environmental Studies and Sciences*, **7(4)**, 527-534, doi:10.1007/s13412-017-0445-6.

Cadule, P., L. Bopp, and P. Friedlingstein, 2009: A revised estimate of the processes contributing to global warming due to climate-carbon feedback. *Geophysical Research Letters*, **36(14)**, doi:10.1029/2009GL038681.

Cai, Y., K.L. Judd, T.M. Lenton, T.S. Lontzek, and D. Narita, 2015: Environmental tipping points significantly affect the cost-benefit assessment of climate policies. *Proceedings of the National Academy of Sciences*, **112(15)**, 4606-4611, doi:10.1073/pnas.1503890112.

Calvin, K. et al., 2014: Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Climatic Change*, **123(3-4)**, 691-704, doi:10.1007/s10584-013-0897-y.

Calvin, K. et al., 2017: The SSP4: A world of deepening inequality. *Global Environmental Change*, **42**, 284-296, doi:10.1016/j.gloenvcha.2016.06.010.

Canadell, J.G. and M.R. Raupach, 2008: Managing Forests for Climate Change Mitigation. *Science*, **320(5882)**, 1456-1457, doi:10.1126/SCIENCE.1155458.

Carslaw, K.S. et al., 2013: Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature*, **503(7474)**, doi:10.1038/nature12674.

Ceppi, P. and J.M. Gregory, 2017: Relationship of tropospheric stability to climate sensitivity and Earth's observed radiation budget. *Proceedings of the National Academy of Sciences of the United States of America*, 201714308, doi:10.1073/pnas.1714308114.

Chan, S., P. Ellinger, and O. Widerberg, 2018: Exploring national and regional orchestration of non-state action for a < 1.5 °C world. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 135-152, doi:10.1007/s10784-018-9384-2.

Chen, C. and M. Tavoni, 2013: Direct air capture of CO_2 and climate stabilization: A model based assessment. *Climatic Change*, **118(1)**, 59-72, doi:10.1007/s10584-013-0714-7.

Choi, Y.S., D. Young, S. Nešić, and L.G.S. Gray, 2013: Wellbore integrity and corrosion of carbon steel in CO_2 geologic storage environments: A literature review. *International Journal of Greenhouse Gas Control*, **16**, S70 - S77, doi:https://doi.org/10.1016/j.ijggc.2012.12.028.

Clack, C.T.M. et al., 2017: Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar.. *Proceedings of the National Academy of Sciences of the United States of America*, **114(26)**, 6722-6727, doi:10.1073/pnas.1610381114.

Clarke, L. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413-510.

Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029-1136.

Collins, W.J. et al., 2018: Increased importance of methane reduction for a 1.5 degree target. *Environmental Research Letters***, 13(5)**, 054003, doi:10.1088/1748-9326/aab89c.

Comyn-Platt, E. et al., 2018: Natural CH4 release and permafrost thaw lower CO_2 emissions to achieve 1.5 and 2°C targets. *Nat. Geosci.* (in press).

Cox, P.M., C. Huntingford, and M.S. Williamson, 2018: Emergent constraint on equilibrium climate sensitivity from global temperature variability. *Nature***, 553(7688)**, 319-322, doi:10.1038/nature25450.

Crespo Cuaresma, J., 2017: Income projections for climate change research: A framework based on human capital dynamics. *Global Environmental Change***, 42**, 226-236, doi:10.1016/j.gloenvcha.2015.02.012.

Creutzig, F., 2016: Evolving Narratives of Low-Carbon Futures in Transportation. *Transport Reviews***, 36(3)**, 341-360, doi:10.1080/01441647.2015.1079277.

Creutzig, F. et al., 2012: Reconciling top-down and bottom-up modelling on future bioenergy deployment. *Nature Climate Change***, 2(5)**, 320-327, doi:10.1038/nclimate1416.

Creutzig, F. et al., 2015: Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy***, 7(5)**, 916-944, doi:10.1111/gcbb.12205.

Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy***, 2(9)**, 17140, doi:10.1038/nenergy.2017.140.

Davis, S.C. et al., 2013: Management swing potential for bioenergy crops. *GCB Bioenergy***, 5(6)**, 623-638, doi:10.1111/gcbb.12042.

Davis, S.J. and K. Caldeira, 2010: Consumption-based accounting of CO_2 emissions. *Proceedings of the National Academy of Sciences of the United States of America***, 107(12)**, 5687-92, doi:10.1073/pnas.0906974107.

de Richter, R., T. Ming, P. Davies, W. Liu, and S. Caillol, 2017: Removal of non-CO_2 greenhouse gases by large-scale atmospheric solar photocatalysis. *Progress in Energy and Combustion Science***, 60**, 68-96, doi:10.1016/j.pecs.2017.01.001.

de Vries, W., M. Posch, D. Simpson, and G.J. Reinds, 2017: Modelling long-term impacts of changes in climate, nitrogen deposition and ozone exposure on carbon sequestration of European forest ecosystems. *Science of the Total Environment***, 605-606**, 1097-1116, doi:10.1016/j.scitotenv.2017.06.132.

Dell, M., B.F. Jones, and B.A. Olken, 2014: What Do We Learn from the Weather ? The New Climate-Economy Literature. *Journal of Economic Literature***, 52(3)**, 740-798.

Dellink, R., J. Chateau, E. Lanzi, and B. Magné, 2017: Long-term economic growth projections in the Shared Socioeconomic Pathways. *Global Environmental Change***, 42**, 1-15, doi:10.1016/j.gloenvcha.2015.06.004.

Delponte, I., I. Pittaluga, and C. Schenone, 2017: Monitoring and evaluation of Sustainable Energy Action Plan: Practice and perspective. *Energy Policy***, 100**, 9-17, doi:10.1016/j.enpol.2016.10.003.

den Elzen, M.G.J., D.P. van Vuuren, and J. van Vliet, 2010: Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Climatic Change***, 99(1)**, 313-320, doi:10.1007/s10584-010-9798-5.

den Elzen, M.G.J. et al., 2016: Contribution of the G20 economies to the global impact of the Paris agreement climate proposals. *Climatic Change***, 137(3-4)**, 655-665, doi:10.1007/s10584-016-1700-7.

Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences***, 112(52)**, 15827-15832, doi:10.1073/pnas.1513967112.

DOE/NETL, 2013: *Cost and performance of PC and IGCC plants for a range of carbon dioxide capture: revision 1*. DOE/NETL-2011/1498, National Energy Technology Laboratory (NETL), 518 pp.

Doelman, J.C. et al., 2018: Exploring SSP land-use dynamics using the IMAGE model: Regional and gridded scenarios of land-use change and land-based climate change mitigation. *Global Environmental Change***, 48**, 119-135, doi:https://doi.org/10.1016/j.gloenvcha.2017.11.014.

Dooley, J.J., 2013: Estimating the supply and demand for deep geologic CO_2 storage capacity over the course of the 21st century: A meta-analysis of the literature. *Energy Procedia***, 37**, 5141-5150, doi:10.1016/j.egypro.2013.06.429.

Dooley, K. and S. Kartha, 2018: Land-based negative emissions: risks for climate mitigation and impacts on sustainable development. *International Environmental Agreements: Politics, Law and Economics***, 18(1)**, 79-98, doi:10.1007/s10784-017-9382-9.

Duce, R.A. et al., 2008: Impacts of Atmospheric Anthropogenic Nitrogen on the Open Ocean. *Science***, 320(5878)**, 893-897.

EC, 2017: *High-Level Expert Group on Sustainable Finance interim report - Financing a sustainable European economy*. European Commission, Brussels, Belgium, 72 pp.

Edenhofer, O., J.C. Steckel, M. Jakob, and C. Bertram, 2018: Reports of coal's terminal decline may be exaggerated. *Environ. Res. Lett***, 13**, 024019.

Erb, K.H., H. Haberl, and C. Plutzar, 2012: Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy***, 47**, 260-269, doi:10.1016/j.enpol.2012.04.066.

Erb, K.H. et al., 2016a: Biomass turnover time in terrestrial ecosystems halved by land use. *Nature Geoscience*, **9(9)**, 674-678, doi:10.1038/ngeo2782.

Erb, K.H. et al., 2016b: Exploring the biophysical option space for feeding the world without deforestation. *Nature Communications*, **7**, 11382, doi:10.1038/ncomms11382.

Erb, K.H. et al., 2018: Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature*, **553**, 73-76.

Erickson, P., S. Kartha, M. Lazarus, and K. Tempest, 2015: Assessing carbon lock-in. *Environmental Research Letters*, **10(8)**, 84023.

Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614-12,623, doi:10.1002/2016GL071930.

Faehn, T. and E. Isaksen, 2016: Diffusion of Climate Technologies in the Presence of Commitment Problems. *The Energy Journal*, **37(2)**, 155-180, doi:10.5547/01956574.37.2.tfae.

Fankhauser, S., A. Sahni, A. Savvas, and J. Ward, 2016: Where are the gaps in climate finance? *Climate and Development*, **8(3)**, 203-206, doi:10.1080/17565529.2015.1064811.

FAOSTAT, 2017: Database Collection of the Food and Agriculture Organization of the United Nations. http://www.fao.org/faostat

Fawcett, A.A. et al., 2015: Can Paris pledges avert severe climate change? *Science*, **350(6265)**, 1168-1169, doi:10.1126/science.aad5761.

Forster, P.M., 2016: Inference of Climate Sensitivity from Analysis of Earth's Energy Budget. *Annual Review of Earth and Planetary Sciences*, **44(1)**, 85-106, doi:10.1146/annurev-earth-060614-105156.

Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, 105004, doi:10.1088/1748-9326/aa8c83.

Frank, S. et al., 2018: Structural change as a key component for agricultural non-CO_2 mitigation efforts. *Nature Communications*, **9(1)**, 1060, doi:10.1038/s41467-018-03489-1.

Frankfurt School-UNEP Centre/BNEF, 2017: Global Trends in Renewable Energy Investment 2017. , 90.

Fricko, O. et al., 2016: Energy sector water use implications of a 2 °C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.

Fricko, O. et al., 2017: The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change*, **42**, 251-267, doi:10.1016/j.gloenvcha.2016.06.004.

Friedlingstein, P. et al., 2014a: Persistent growth of CO_2 emissions and implications for reaching climate targets. *Nature Geoscience*, **7(10)**, 709-715, doi:10.1038/ngeo2248.

Friedlingstein, P. et al., 2014b: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. *Journal of Climate*, **27(2)**, 511-526, doi:10.1175/JCLI-D-12-00579.1.

Frölicher, T.L. and F. Joos, 2010: Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model. *Climate Dynamics*, **35(7)**, 1439-1459, doi:10.1007/s00382-009-0727-0.

Fuglestvedt, J.S. et al., 2010: Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment*, **44(37)**, 4648-4677, doi:10.1016/j.atmosenv.2009.04.044.

Fujimori, S., 2017: SSP3: AIM Implementation of Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 268-283, doi:10.1016/j.gloenvcha.2016.06.009.

Fujimori, S. et al., 2016: Implication of Paris Agreement in the context of long-term climate mitigation goals. *SpringerPlus*, **5(1)**, 1620, doi:10.1186/s40064-016-3235-9.

Fuss, S. et al., 2014: Betting on negative emissions. *Nature Climate Change*, **4(10)**, 850-853, doi:10.1038/nclimate2392.

Fuss, S. et al., 2016: Research priorities for negative emissions. *Environmental Research Letters*, **11(11)**, doi:10.1088/1748-9326/11/11/115007.

Fuss, S. et al., 2018: Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Reviews* (in press), doi:10.1088/1748-9326/aabf9f.

Geden, O., 2015: Policy: Climate advisers must maintain integrity. *Nature*, **521(7550)**, 27-28, doi:10.1038/521027a.

Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**.

Gerber, P.J. et al., 2013: *Tackling Climate Change through Livestock: A global assessment of emissions and mitigation opportunities*. 115 pp.

Gernaat, D.E.H.J. et al., 2015: Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change*, **33**, 142-153, doi:10.1016/j.gloenvcha.2015.04.010.

Ghan, S.J. et al., 2013: A simple model of global aerosol indirect effects. *Journal of Geophysical Research: Atmospheres*, **118(12)**, 6688-6707, doi:10.1002/jgrd.50567.

Ghota, S., C. Huizenga, K. Peet, N. Medimorec, and S. Bakker, 2018: Decarbonising Transport to Achieve Paris Agreement Targets. *Energy Efficiency* (in press).

Giannakidis, G., K. Karlsson, M. Labriet, and B. Ó Gallachóir (eds.), 2018: *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development*. Springer International Publishing, 423 pp.

Gillett, N.P., V.K. Arora, D. Matthews, and M.R. Allen, 2013: Constraining the Ratio of Global Warming to Cumulative CO_2 Emissions Using CMIP5 Simulations. *Journal of Climate*, **26(18)**, 6844-6858, doi:10.1175/JCLI-D-12-00476.1.

Gillett, N.P., V.K. Arora, K. Zickfeld, S.J. Marshall, and W.J. Merryfield, 2011: Ongoing climate change following a complete cessation of carbon dioxide emissions. *Nature Geoscience*, **4(2)**, 83-87, doi:10.1038/ngeo1047.

Global CCS Institute, 2016: *The Global Status of CCS: 2016 Summary Report*. 28 pp.

González-Eguino, M., A. Olabe, and T. Ribera, 2017: New Coal-Fired Plants Jeopardise Paris Agreement. *Sustainability*, **9(2)**.

Goodwin, P., S. Brown, I.D. Haigh, R.J. Nicholls, and J.M. Matter, 2018a: Adjusting Mitigation Pathways to Stabilize Climate at 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future*, 0-3, doi:10.1002/2017EF000732.

Goodwin, P. et al., 2018b: Pathways to 1.5 and 2 °C warming based on observational and geological constraints. *Nature Geoscience*, **11(1)**, 1-22, doi:10.1038/s41561-017-0054-8.

Gough, C. and P. Upham, 2011: Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases: Science and Technology*, **1(4)**, 324-334, doi:10.1002/ghg.34.

Goulder, L. and A. Schein, 2013: Carbon Taxes vs. Cap and Trade: A Critical Review. *Climate Change Economics*, **04(03)**, 1350010, doi:10.1142/S2010007813500103.

Grassi, G. et al., 2017: The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, **7(3)**, 220-226, doi:10.1038/nclimate3227.

Greene, C.H. et al., 2017: Geoengineering, Marine Microalgae, and Climate Stabilization in the 21st Century. *Earth's Future*, doi:10.1002/2016EF000486.

Gregory, J.M. and T. Andrews, 2016: Variation in climate sensitivity and feedback parameters during the historical period. *Geophysical Research Letters*, **43(8)**, 3911-3920, doi:10.1002/2016GL068406.

Gren, I.M. and A.Z. Aklilu, 2016: Policy design for forest carbon sequestration: A review of the literature. *Forest Policy and Economics*, **70**, 128-136, doi:https://doi.org/10.1016/j.forpol.2016.06.008.

Griscom, B.W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, **114(44)**, 11645-11650, doi:10.1073/pnas.1710465114.

Grubb, M., J.C. Hourcade, and K. Neuhoff, 2014: *Planetary economics: energy, climate change and the three domains of sustainable development*. Routledge Earthscan, Oxon, New York, 520 pp.

Grubler, A. and C. Wilson, 2014: *Energy Technology Innovation - Learning from Historical Succeses and Failures*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 400 pp.

Grubler, A. et al., 2018: A Global Scenario of Low Energy Demand for Sustainable Development below 1.5°C without Negative Emission Technologies. *Nature Energy* (in press).

Guivarch, C. and J. Rogelj, 2017: *Carbon price variations in 2°C scenarios explored*. 15 pp.

Güneralp, B. et al., 2017: Global scenarios of urban density and its impacts on building energy use through 2050. *Proceedings of the National Academy of Sciences*, **114(34)**, 8945-8950, doi:10.1073/pnas.1606035114.

Gupta, S. and J. Harnisch, 2014: Cross-cutting Investment and Finance Issues. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Inter- governmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1207-1246.

Haberl, H., 2015: Competition for land: A sociometabolic perspective. *Ecological Economics*, **119**, 424-431, doi:https://doi.org/10.1016/j.ecolecon.2014.10.002.

Haberl, H. et al., 2011: Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, **35(12)**, 4753-4769, doi:https://doi.org/10.1016/j.biombioe.2011.04.035.

Haberl, H. et al., 2013: Bioenergy: how much can we expect for 2050? *Environmental Research Letters*, **8(3)**, 031004, doi:10.1088/1748-9326/8/3/031004.

Harmes, A., 2011: The Limits of Carbon Disclosure: Theorizing the Business Case for Investor Environmentalism. *Global Environmental Politics*, **11(2)**, 98-119.

Hartmann, J. et al., 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification. *Reviews of Geophysics*, **51(2)**, 113-149, doi:10.1002/rog.20004.

Hauglustaine, D.A., Y. Balkanski, and M. Schulz, 2014: A global model simulation of present and future nitrate aerosols and their direct radiative forcing of climate. *Atmos. Chem. Phys*, **14**, 11031-11063, doi:10.5194/acp-14-11031-2014.

Havlik, P. et al., 2013: Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions. *American Journal of Agricultural Economics*, **95(2)**, 442-448, doi:10.1093/ajae/aas085.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **111(10)**, 3709-14, doi:10.1073/pnas.1308044111.

Heck, V., D. Gerten, W. Lucht, and L.R. Boysen, 2016: Is extensive terrestrial carbon dioxide removal a 'green' form of geoengineering? A global modelling study. *Global and Planetary Change*, **137**, 123-130, doi:10.1016/j.gloplacha.2015.12.008.

Heck, V., D. Gerten, W. Lucht, and A. Popp, 2018: Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, **8(2)**, 151-155, doi:10.1038/s41558-017-0064-y.

Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, **81**, 205-226, doi:10.1016/j.techfore.2013.05.006.

Herrero, M. et al., 2016: Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, **6(5)**, 452-461, doi:10.1038/nclimate2925.

Herrington, T. and K. Zickfeld, 2014: Path independence of climate and carbon cycle response over a broad range of cumulative carbon emissions. *Earth System Dynamics*, **5**, 409-422, doi:10.5194/esd-5-409-2014.

Herzog, H., K. Caldeira, and J. Reilly, 2003: An Issue of Permanence: Assessing the Effectiveness of Temporary Carbon Storage. *Climate Change*, **59**, 293-310.

Hildingsson, R. and B. Johansson, 2016: Governing low-carbon energy transitions in sustainable ways: Potential synergies and conflicts between climate and environmental policy objectives. *Energy Policy*, **88**, 245-252, doi:10.1016/J.ENPOL.2015.10.029.

Hoesly, R.M. et al., 2018: Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, **11(1)**, 369-408, doi:10.5194/gmd-11-369-2018.

Hof, A.F. et al., 2017: Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2 °C and 1.5 °C. *Environmental Science & Policy*, **71**, 30-40, doi:10.1016/j.envsci.2017.02.008.

Höglund-Isaksson, L. et al., 2017: Cost estimates of the Kigali Amendment to phase-down hydrofluorocarbons. *Environmental Science & Policy*, **75**, 138-147, doi:10.1016/j.envsci.2017.05.006.

Holz, C., S. Kartha, and T. Athanasiou, 2018a: Fairly sharing 1.5: national fair shares of a 1.5C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 117-134, doi:10.1007/s10784-017-9371-z.

Holz, C., L. Siegel, E. Johnston, A.P. Jones, and J. Sterman, 2018b: Ratcheting ambition to limit warming to 1.5°C - trade-offs between emission reductions and carbon dioxide removal. *Environmental Research Letters* (in press), doi:10.1088/1748-9326/aac0c1.

Honegger, M. and D. Reiner, 2018: The political economy of negative emissions technologies: consequences for international policy design. *Climate Policy*, **18(3)**, 306-321, doi:10.1080/14693062.2017.1413322.

Hong, S., C.J.A. Bradshaw, and B.W. Brook, 2015: Global zero-carbon energy pathways using viable mixes of nuclear and renewables. *Applied Energy*, **143**, 451-459, doi:10.1016/J.APENERGY.2015.01.006.

Hope, C., 2006: The Marginal Impact of CO_2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern. *The Integrated Assessment Journal*, **6(1)**, 16-56.

Hristov, A.N. et al., 2015: An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production.. *Proceedings of the National Academy of Sciences of the United States of America*, **112(34)**, 10663-8, doi:10.1073/pnas.1504124112.

Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356(6345)**, 1362 LP - 1369.

Humpenöder, F. et al., 2014: Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environmental Research Letters*, **9(6)**, 64029, doi:10.1088/1748-9326/9/6/064029.

Humpenöder, F. et al., 2017: Large-scale bioenergy production: How to resolve sustainability trade-offs? *Environmental Research Letters*, doi:10.1088/1748-9326/aa9e3b.

Huntingford, C. and J. Lowe, 2007: "Overshoot" Scenarios and Climate Change. *Science*, **316(5826)**, 829, doi:10.1126/science.316.5826.829b.

IEA, 2014: *Energy Technology Perspectives 2014*. International Energy Agency (IEA), Paris, France, 382 pp.

IEA, 2015a: *Energy and Climate Change. World Energy Outlook Special Report*. International Energy Agency (IEA), 200 pp.

IEA, 2015b: *Energy Technology Perspectives 2015*. International Energy Agency (IEA), Paris, France, 418 pp.

IEA, 2016a: *Energy Technology Perspectives 2016*. International Energy Agency (IEA), Paris, France, 418 pp.

IEA, 2016b: *World Energy Investment 2016*. IEA/OECD, Paris, 177 pp.

IEA, 2017a: *Energy Technology Perspectives 2017: Catalyzing Energy Technology Transformations*. International Energy Agency (IEA), Paris, France, France, 443 pp.

IEA, 2017b: *Renewables Information - Overview (2017 edition)*. International Energy Agency (IEA), Paris, 11 pp.

IEA, 2017c: *World Energy Investment 2017*. International Energy Agency (IEA), Paris, France, 191 pp.

IEA, 2017d: World Energy Outlook 2017. , 782.

IEA, 2017e: *World Energy Statistics 2017*. International Energy Agency (IEA).

IEAGHG, 2006: *Near zero emission technology for* CO_2 *capture from power plant*. IEA Greenhouse Gas R&D Programme, Cheltenham, UK, 114 pp.

Ilyina, T., D. Wolf-Gladrow, G. Munhoven, and C. Heinze, 2013: Assessing the potential of calcium-based artificial ocean alkalinization to mitigate rising atmospheric CO_2 and ocean acidification. *Geophysical Research Letters*,

40(22), 5909-5914, doi:10.1002/2013GL057981.

Interagency Working Group on Social Cost of Greenhouse Gases, 2016: *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866*. 35 pp.

IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

IPCC, 2013a: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambirdge University Press, Cambride, United Kingdom and New York, USA, 1535 pp.

IPCC, 2013b: Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2014a: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. 151 pp.

IPCC, 2014b: Summary for Policymakers. In: *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-30.

IPCC/TEAP, 2005: Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons. Cambridge University Press, Cambridge, UK and New York, NY, USA, 485 pp.

Irlam, L., 2017: *Global Costs of Carbon Capture and Storage*. Global CCS Institute, 14 pp.

Iyer, G.C. et al., 2015: Improved representation of investment decisions in assessments of CO_2 mitigation. *Nature Climate Change*, **5(5)**, 436-440, doi:10.1038/nclimate2553.

Jackson, R.B. et al., 2017: Warning signs for stabilizing global CO 2 emissions. *Environmental Research Letters*, **12(11)**, 110202, doi:10.1088/1748-9326/aa9662.

Jacobson, M.Z., 2002: Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. *Journal of Geophysical Research*, **107(D19)**, 4410, doi:10.1029/2001JD001376.

Jacobson, M.Z., 2010: Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. *Journal of Geophysical Research*, **115(D14)**, D14209, doi:10.1029/2009JD013795.

Jacobson, M.Z., 2017: Roadmaps to Transition Countries to 100% Clean, Renewable Energy for All Purposes to Curtail Global Warming, Air Pollution, and Energy Risk. *Earth's Future*, **5(10)**, 948-952, doi:10.1002/2017EF000672.

Jacobson, M.Z. et al., 2017: 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule*, **1(1)**, 108-121, doi:10.1016/j.joule.2017.07.005.

Jakob, M. and J.C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environmental Research Letters*, **11(10)**, 104010, doi:10.1088/1748-9326/11/10/104010.

Jakob, M. et al., 2014: Feasible mitigation actions in developing countries. *Nature Climate Change*, **4(11)**, 961-968, doi:10.1038/nclimate2370.

Jie Di, H. and K. Cameron, 2016: Inhibition of nitrification to mitigate nitrate leaching and nitrous oxide emissions in grazed grassland: A review. *Journal of Soils and Sediments*, **16**, 1401-1420, doi:10.1007/s11368-016-1403-8.

Johnson, N. et al., 2015: Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, **90**, 89-102, doi:10.1016/j.techfore.2014.02.028.

Jones, A., J.M. Haywood, and C.D. Jones, 2018: Can reducing black carbon and methane below RCP2.6 levels keep global warming below 1.5 °C? *Atmospheric Science Letters*, doi:10.1002/asl.821.

Jones, C.D. et al., 2016: Simulating the Earth system response to negative emissions. *Environmental Research Letters*, **11(9)**, 95012, doi:10.1088/1748-9326/11/9/095012.

Jones, D.G. et al., 2015: Developments since 2005 in understanding potential environmental impacts of CO_2 leakage from geological storage. *International Journal of Greenhouse Gas Control*, **40**, 350-377, doi:10.1016/J.IJGGC.2015.05.032.

Joshi, V. and S. Kumar, 2015: Meat Analogues: Plant based alternatives to meat products- A review. *International journal of food fermentation and technology*, **5(2)**, 107-119.

Kandlikar, M., 1995: The relative role of trace gas emissions in greenhouse abatement policies. *Energy Policy*, **23(10)**, 879-883, doi:10.1016/0301-4215(95)00108-U.

KC, S. and W. Lutz, 2017: The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Global Environmental Change*, **42**, 181-192, doi:10.1016/j.gloenvcha.2014.06.004.

Kearns, J. et al., 2017: Developing a consistent database for regional geologic CO_2 storage capacity worldwide. *Energy*

*Procedia***, 114**, 4697-4709, doi:10.1016/j.egypro.2017.03.1603.

Keith, D.W. and J.S. Rhodes, 2002: Bury, Burn or Both: A Two-for-One Deal on Biomass Carbon and Energy. *Climatic Change***, 54(3)**, 375-377, doi:10.1023/A:1016187420442.

Keith, D.W., M. Ha-Duong, and J.K. Stolaroff, 2006: Climate Strategy with CO_2 Capture from the Air. *Climatic Change***, 74(1-3)**, 17-45, doi:10.1007/s10584-005-9026-x.

Kheshgi, H.S., 1995: Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy***, 20(9)**, 915-922, doi:10.1016/0360-5442(95)00035-F.

Kim, S.H., K. Wada, A. Kurosawa, and M. Roberts, 2014: Nuclear energy response in the EMF27 study. *Climatic Change***, 123(3-4)**, 443-460, doi:10.1007/s10584-014-1098-z.

Klein, D. et al., 2014: The value of bioenergy in low stabilization scenarios: An assessment using REMIND-MAgPIE. *Climatic Change***, 123(3-4)**, 705-718, doi:10.1007/s10584-013-0940-z.

Klimont, Z. et al., 2017: Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics***, 17(14)**, 8681-8723, doi:10.5194/acp-17-8681-2017.

Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C world, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, doi:10.1098/rsta.2016.0461.

Knutti, R. and J. Rogelj, 2015: The legacy of our CO_2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change***, 133(3)**, 361-373, doi:10.1007/s10584-015-1340-3.

Knutti, R., M.A.A. Rugenstein, and G.C. Hegerl, 2017: Beyond equilibrium climate sensitivity. *Nature Geoscience***, 10(10)**, 727-736, doi:10.1038/ngeo3017.

Kolstad, C. et al., 2014: Social, Economic and Ethical Concepts and Methods. In: *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207-282.

Krasting, J.P., J.P. Dunne, E. Shevliakova, and R.J. Stouffer, 2014: Trajectory sensitivity of the transient climate response to cumulative carbon emissions. *Geophysical Research Letters***, 41(7)**, 2520-2527, doi:10.1002/(ISSN)1944-8007.

Krause, A. et al., 2017: Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. *Biogeosciences***, 14(21)**, 4829-4850, doi:10.5194/bg-14-4829-2017.

Kraxner, F. et al., 2013: Global bioenergy scenarios - Future forest development, land-use implications, and trade-offs. *Biomass and Bioenergy***, 57**, 86-96, doi:10.1016/j.biombioe.2013.02.003.

Kreidenweis, U. et al., 2016: Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environmental Research Letters***, 11(8)**, 85001, doi:10.1088/1748-9326/11/8/085001.

Kretzschmar, J. et al., 2017: Comment on "Rethinking the Lower Bound on Aerosol Radiative Forcing". *Journal of Climate***, 30(16)**, 6579-6584, doi:10.1175/JCLI-D-16-0668.1.

Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014a: Getting from here to there - energy technology transformation pathways in the EMF27 scenarios. *Climatic Change***, 123**, 369-382, doi:10.1007/s10584-013-0947-5.

Krey, V. et al., 2014b: Annex II: Metrics & Methodology. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1281-1328.

Kriegler, E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein, 2013a: Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change***, 118(1)**, doi:10.1007/s10584-012-0681-4.

Kriegler, E. et al., 2012: The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. *Global Environmental Change***, 22(4)**, 807-822, doi:10.1016/j.gloenvcha.2012.05.005.

Kriegler, E. et al., 2013b: What Does the 2°C Target Imply for a Global Climate Agreement in 2020? The Limits Study on Durban Platform Scenarios. *Climate Change Economics***, 04(04)**, 1340008, doi:10.1142/S2010007813400083.

Kriegler, E. et al., 2014a: A new scenario framework for climate change research: the concept of shared climate policy assumptions. *Climatic Change***, 122(3)**, 401-414, doi:10.1007/s10584-013-0971-5.

Kriegler, E. et al., 2014b: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change***, 123(3-4)**, 353-367, doi:10.1007/s10584-013-0953-7.

Kriegler, E. et al., 2015a: Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change***, 90(PA)**, 45-61, doi:10.1016/j.techfore.2013.09.020.

Kriegler, E. et al., 2015b: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change***, 90(PA)**, 24-44, doi:10.1016/j.techfore.2013.09.021.

Kriegler, E. et al., 2016: Will economic growth and fossil fuel scarcity help or hinder climate stabilization?: Overview of the RoSE multi-model study. *Climatic Change*, **136(1)**, 7-22, doi:10.1007/s10584-016-1668-3.

Kriegler, E. et al., 2017: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, **42**, 297-315, doi:10.1016/j.gloenvcha.2016.05.015.

Kriegler, E. et al., 2018a: Pathways limiting warming to 1.5°C: A tale of turning around in no time? *Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences*, **376**, 20160457.

Kriegler, E. et al., 2018b: Short term policies to keep the door open for Paris climate goals. *Environ. Res. Lett* (in press), doi:10.1088/1748-9326/aac4f1.

Kuramochi, T. et al., 2017: Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, **18(3)**, 1-19, doi:10.1080/14693062.2017.1397495.

Lamarque, J.F. et al., 2011: Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways. *Climatic Change*, **109(1-2)**, 191-212, doi:10.1007/s10584-011-0155-0.

Lambin, E.F. and P. Meyfroidt, 2011: Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences of the United States of America*, **108(9)**, 3465-72, doi:10.1073/pnas.1100480108.

Le Quéré, C. et al., 2018: Global Carbon Budget 2017. *Earth System Science Data*, **10(1)**, 405-448, doi:10.5194/essd-10-405-2018.

Lehtilä, A. and T. Koljonen, 2018: Pathways to Post-fossil Economy in a Well Below 2 ℃ World. In: *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development* [Giannakidis, G., K. Karlsson, M. Labriet, and B. Gallachóir (eds.)]. Springer International Publishing, Cham, pp. 33-49.

Leimbach, M., E. Kriegler, N. Roming, and J. Schwanitz, 2017: Future growth patterns of world regions - A GDP scenario approach. *Global Environmental Change*, **42**, 215-225, doi:10.1016/j.gloenvcha.2015.02.005.

Lemoine, D. and C. Traeger, 2014: Watch Your Step: Optimal Policy in a Tipping Climate. *American Economic Journal: Economic Policy*, **6(1)**, 137-166, doi:10.1257/pol.6.1.137.

Lenton, A., R.J. Matear, D.P. Keller, V. Scott, and N.E. Vaughan, 2018: Assessing carbon dioxide removal through global and regional ocean alkalinization under high and low emission pathways. *Earth System Dynamics*, **9(2)**, 339-357, doi:10.5194/esd-9-339-2018.

Lewis, N. and J.A. Curry, 2015: The implications for climate sensitivity of AR5 forcing and heat uptake estimates. *Climate Dynamics*, **45(3-4)**, 1009-1023, doi:10.1007/s00382-014-2342-y.

Lewis, N. and J. Curry, 2018: The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *Journal of Climate*, JCLI-D-17-0667.1, doi:10.1175/JCLI-D-17-0667.1.

Liu, J., T.W. Hertel, F. Taheripour, T. Zhu, and C. Ringler, 2014: International trade buffers the impact of future irrigation shortfalls. *Global Environmental Change*, **29**, 22-31, doi:10.1016/J.GLOENVCHA.2014.07.010.

Liu, J.Y. et al., 2017: Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C. *Carbon Management* (in press).

Löffler, K. et al., 2017: Designing a Model for the Global Energy System-GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies*, **10(10)**, 1468, doi:10.3390/en10101468.

Lontzek, T.S., Y. Cai, K.L. Judd, and T.M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, **5(5)**, 441-444.

Lowe, J.A. and D. Bernie, 2018: The impact of Earth system feedbacks on carbon budgets and climate response. *Philosophical Transactions of the Royal Society A - Mathematical Physical and Engineering Sciences*, doi:10.1098/rsta.2017.0263.

Lowe, J.A. et al., 2009: How difficult is it to recover from dangerous levels of global warming? *Environmental Research Letters*, **4(1)**, 014012, doi:10.1088/1748-9326/4/1/014012.

Lucon, O. et al., 2014: Buildings. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 671-738.

Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016a: Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change*, **136(1)**, 127-140, doi:10.1007/s10584-013-0899-9.

Luderer, G. et al., 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters*, **8(3)**, 034033, doi:10.1088/1748-9326/8/3/034033.

Luderer, G. et al., 2014: The role of renewable energy in climate stabilization: results from the {EMF}27 scenarios. *Climatic Change*, **123(3-4)**, 427-441, doi:10.1007/s10584-013-0924-z.

Luderer, G. et al., 2016b: *Deep Decarbonization towards 1.5°C - 2°C stabilization: Policy findings from the ADVANCE project*. 42 pp.

Luderer, G. et al., 2017: Assessment of wind and solar power in global low-carbon energy scenarios: An introduction. *Energy Economics*, **64**, 542-551, doi:10.1016/J.ENECO.2017.03.027.

Luderer, G. et al., 2018: Residual fossil CO_2 emissions in 1.5-2°C pathways. *Nature Climate Change* (in press), doi:10.1038/s41558-018-0198-6.

Lutz, W. and S. KC, 2011: Global Human Capital: Integrating Education and Population. *Science*, **333(6042)**, 587-592, doi:10.1126/science.1206964.

MacDougall, A.H., K. Zickfeld, R. Knutti, and H.D. Matthews, 2015: Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO 2 forcings. *Environmental Research Letters*, **10(12)**, 125003, doi:10.1088/1748-9326/10/12/125003.

Madeira, M.S. et al., 2017: Microalgae as feed ingredients for livestock production and meat quality: A review. *Livestock Science*, **205**, 111-121, doi:10.1016/j.livsci.2017.09.020.

Mahowald, N.M. et al., 2017: Aerosol Deposition Impacts on Land and Ocean Carbon Cycles. *Current Climate Change Reports*, **3(1)**, 16-31, doi:10.1007/s40641-017-0056-z.

Malavelle, F.F. et al., 2017: Strong constraints on aerosol-cloud interactions from volcanic eruptions. *Nature*, **546(7659)**, 485-491, doi:10.1038/nature22974.

Marangoni, G. and M. Tavoni, 2014: The Clean Energy R&D Strategy for 2°C. *Climate Change Economics*, **05(01)**, 1440003, doi:10.1142/S201000781440003X.

Marangoni, G. et al., 2017: Sensitivity of projected long-term CO_2 emissions across the Shared Socioeconomic Pathways. *Nature Climate Change*, **7(January)**, 113-119, doi:10.1038/nclimate3199.

Marcucci, A., S. Kypreos, and E. Panos, 2017: The road to achieving the long-term Paris targets: Energy transition and the role of direct air capture. *Climatic Change*, **144(2)**, 181-193, doi:10.1007/s10584-017-2051-8.

Marten, A.L., E.A. Kopits, C.W. Griffiths, S.C. Newbold, and A. Wolverton, 2015: Incremental CH4 and N2O mitigation benefits consistent with the US Government's SC-CO_2 estimates. *Climate Policy*, **15(2)**, 272-298, doi:10.1080/14693062.2014.912981.

Marvel, K., G.A. Schmidt, R.L. Miller, and L.S. Nazarenko, 2016: Implications for climate sensitivity from the response to individual forcings. *Nature Clim. Change*, **6(4)**, 386-389, doi:10.1038/NCLIMATE2888.

Masui, T. et al., 2011: An emission pathway for stabilization at 6 Wm-2 radiative forcing. *Climatic Change*, **109(1)**, 59-76, doi:10.1007/s10584-011-0150-5.

Matter, J.M. et al., 2016: Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions. *Science*, **352(6291)**, 1312 LP - 1314.

Matthews, H.D. and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, **35(4)**, 1-5, doi:10.1029/2007GL032388.

Matthews, H.D. and K. Zickfeld, 2012: Climate response to zeroed emissions of greenhouse gases and aerosols. *Nature Climate Change*, **2(5)**, 338-341, doi:10.1038/NCLIMATE1424.

Matthews, H.D., N.P. Gillett, P.A. Stott, and K. Zickfeld, 2009: The proportionality of global warming to cumulative carbon emissions. *Nature*, **459(7248)**, 829-832, doi:10.1038/nature08047.

Matthews, H.D. et al., 2017: Estimating Carbon Budgets for Ambitious Climate Targets. *Current Climate Change Reports*, **3**, 69-77, doi:10.1007/s40641-017-0055-0.

Mazzotti, M. et al., 2005: Mineral carbonation and industrial uses of carbon dioxide. In: *IPCC Special Report on Carbon dioxide Capture and Storage* [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 319-338.

McCollum, D.L., V. Krey, and K. Riahi, 2011: An integrated approach to energy sustainability. *Nature Climate Change*, **1(9)**, 428-429, doi:10.1038/nclimate1297.

McCollum, D.L., W. Zhou, C. Bertram, H.S. de Boer, and V. Bosetti, 2018: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, doi:10.1038/s41560-018-0179-z.

McCollum, D.L. et al., 2013: Energy Investments Under Climate Policy: A Comparison of Global Models. *Clim. Change Econ.*, **4(4)**, doi:10.1142/s2010007813400101.

McCollum, D.L. et al., 2017: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, **55**, 322-342, doi:10.1016/j.trd.2016.04.003.

McFarland, J.R., A.A. Fawcett, A.C. Morris, J.M. Reilly, and P.J. Wilcoxen, 2018: Overview of the EMF 32 Study on U.S. Carbon Tax Scenarios. *Climate Change Economics*, **09(01)**, 1840002, doi:10.1142/S201000781840002X.

McLeod, E. et al., 2011: A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment*, **9(10)**, 552-560, doi:10.1890/110004.

Mehling, M. and E. Tvinnereim, 2018: Carbon Pricing and the 1.5°C Target: Near-Term Decarbonisation and the Importance of an Instrument Mix. *Carbon & Climate Law Review*, **12(1)**, 50-61, doi:https://doi.org/10.21552/cclr/2018/1/9.

Meinshausen, M., S.C.B. Raper, and T.M.L. Wigley, 2011a: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. *Atmospheric Chemistry and Physics*, **11(4)**, 1417-1456, doi:10.5194/acp-11-1417-2011.

Meinshausen, M. et al., 2009: Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature*, **458(7242)**, 1158-1162, doi:10.1038/nature08017.

Meinshausen, M. et al., 2011b: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109(1-2)**, 213-241, doi:10.1007/s10584-011-0156-z.

Méjean, A., C. Guivarch, J. Lefèvre, and M. Hamdi-Cherif, 2018: The transition in energy demand sectors to limit global warming to 1.5°C. *Energy Efficiency* (in press), doi: 10.1007/s12053-018-9682-0.

Mengis, N., A. Partanen, J. Jalbert, and H.D. Matthews, 2018: 1.5 °C carbon budget dependent on carbon cycle uncertainty and future non-CO_2 forcing. *Scientific Reports*, **8(1)**, 5831, doi:10.1038/s41598-018-24241-1.

Michaelowa, A., M. Allen, and F. Sha, 2018: Policy instruments for limiting global temperature rise to 1.5°C - can humanity rise to the challenge? *Climate Policy*, **18(3)**, 275-286, doi:10.1080/14693062.2018.1426977.

Millar, R.J. and P. Friedlingstein, 2018: The utility of the historical record for assessing the transient climate response to cumulative emissions. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160449, doi:10.1098/rsta.2016.0449.

Millar, R.J. et al., 2017: Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nature Geoscience*, **10(10)**, 741-747, doi:10.1038/ngeo3031.

Minx, J.C., W.F. Lamb, M.W. Callaghan, L. Bornmann, and S. Fuss, 2017: Fast growing research on negative emissions. *Environmental Research Letters*, **12(3)**, 035007, doi:10.1088/1748-9326/aa5ee5.

Minx, J.C., W.F. Lamb, M.W. Callaghan, S. Fuss, and J. Hilaire, 2018: Negative emissions: Part 1 - research landscape and synthesis. *Environmental Research Reviews* (in press), doi:doi.org/10.1088/1748-9326/aabf9b.

Moore, F.C. and D.B. Diaz, 2015: Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change*, **5(January)**, 127-132, doi:10.1038/nclimate2481.

Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science and Policy*, **64**, 48-58, doi:10.1016/j.envsci.2016.06.007.

Muller, A. et al., 2017: Strategies for feeding the world more sustainably with organic agriculture. *Nature Communications*, **8(1)**, 1290, doi:10.1038/s41467-017-01410-w.

Mundaca, L. and A. Markandya, 2016: Assessing regional progress towards a Green Energy Economy. *Applied Energy*, **179**, 1372-1394, doi:10.1016/j.apenergy.2015.10.098.

Mundaca, L., M. Mansoz, L. Neij, and G. Timilsina, 2013: Transaction costs analysis of low-carbon technologies. *Climate Policy*, **13(4)**, 490-513, doi:10.1080/14693062.2013.781452.

Mundaca, L., L. Neij, A. Markandya, P. Hennicke, and J. Yan, 2016: Towards a Green Energy Economy? Assessing policy choices, strategies and transitional pathways. *Applied Energy*, **179**, 1283-1292, doi:10.1016/j.apenergy.2016.08.086.

Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-740.

Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990-2015. *Atmospheric Chemistry and Physics*, **17(4)**, 2709-2720, doi:10.5194/acp-17-2709-2017.

Narayan, C., P.M. Fernandes, J. van Brusselen, and A. Schuck, 2007: Potential for CO_2 emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol. *Forest Ecology and Management*, **251(3)**, 164-173, doi:10.1016/j.foreco.2007.06.042.

NASEM, 2016: *Assessment of Approaches to Updating the Social Cost of Carbon: Phase 1 Report on a Near-Term Update*. The National Academies Press, Washington DC, USA.

NASEM, 2017: *Valuing Climate Damages: Updating estimation of the social costs of carbon dioxide*. National Academies of Sciences, Engineering, and Medicine (NASEM), The National Academies Press, Washington DC, USA.

Naudts, K. et al., 2016: Europe's forest management did not mitigate climate warming. *Science*, **351(6273)**, 597-600, doi:10.1126/science.aad7270.

Nelson, G.C. et al., 2014: Climate change effects on agriculture: economic responses to biophysical shocks.. *Proceedings of the National Academy of Sciences of the United States of America*, **111(9)**, 3274-9, doi:10.1073/pnas.1222465110.

Nemet, G.F. et al., 2018: Negative emissions - Part 3: Innovation and upscaling. *Environmental Research Letters* (in press), 1-51, doi:10.1088/1748-9326/aabff4.

NETL, 2015: Carbon Storage Atlas - Fifth Edition (Atlas V). U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL).

Nicol, A. et al., 2013: Induced seismicity; observations, risks and mitigation measures at CO_2 storage sites. *Energy Procedia*, **37**, 4749-4756, doi:10.1016/j.egypro.2013.06.384.

Nohara, D. et al., 2015: Examination of a climate stabilization pathway via zero-emissions using Earth system models. *Environmental Research Letters*, **10(9)**, 095005, doi:10.1088/1748-9326/10/9/095005.

Nordhaus, W.D., 2005: A Review of The Stern Review on the Economics of Climate Change. *Journal of Economic Literature*, **XLV**, 686-702.

Nordhaus, W.D., 2007: To Tax or Not to Tax: Alternative Approaches to Slowing Global Warming. *Review of Environmental Economics and Policy*, **1(1)**, 26-44, doi:10.1093/reep/rem008.

Nordhaus, W.D., 2013: The Climate Casino: Risk, Uncertainty, and Economics for a Warming World. Yale University Press, 392 pp.

Nordhaus, W.D., 2014: Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists*, **1(1-2)**, 273-312, doi:10.1086/676035.

Nordhaus, W.D., 2017: Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences*, **114(7)**, 1518-1523, doi:10.1073/pnas.1609244114.

Nordhaus, W.D. and J. Boyer, 2000: *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA, USA and London, UK, 244 pp.

NRC, 2015: *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. The National Academies Press, Washington, DC.

Obersteiner, M. et al., 2001: Managing Climate Risk. *Science*, **294(5543)**, 786-787, doi:10.1126/science.294.5543.786b.

Obersteiner, M. et al., 2016: Assessing the land resource-food price nexus of the Sustainable Development Goals. *Science Advances*, **2(9)**, doi:10.1126/sciadv.1501499.

Obersteiner, M. et al., 2018: How to spend a dwindling greenhouse gas budget. *Nature Climate Change*, **8(1)**, 7-10, doi:10.1038/s41558-017-0045-1.

OECD, 2017: *Investing in Climate, Investing in Growth*. OECD Publishing, Paris, France, 314 pp.

OECD/IEA and IRENA, 2017: *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*. OECD/IEA and IRENA, 204 pp.

Ogawa, T., S. Nakanishi, T. Shidahara, T. Okumura, and E. Hayashi, 2011: Saline-aquifer CO_2 sequestration in Japan-methodology of storage capacity assessment. *International Journal of Greenhouse Gas Control*, **5(2)**, 318-326, doi:10.1016/j.ijggc.2010.09.009.

O'Neill, B.C. et al., 2014: A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, **122(3)**, 387-400, doi:10.1007/s10584-013-0905-2.

O'Neill, B.C. et al., 2017: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169-180, doi:10.1016/j.gloenvcha.2015.01.004.

Painter, T.H. et al., 2013: End of the Little Ice Age in the Alps forced by industrial black carbon. *Proceedings of the National Academy of Sciences of the United States of America*, **110(38)**, 15216-21, doi:10.1073/pnas.1302570110.

Patt, A., 2017: Beyond the tragedy of the commons: Reframing effective climate change governance. *Energy Research & Social Science*, **34**, 1-3, doi:10.1016/J.ERSS.2017.05.023.

Patterson, J.J. et al., 2018: Political feasibility of 1.5°C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*, **31**, 1-9, doi:10.1016/j.cosust.2017.11.002.

Paustian, K. et al., 2016: Climate-smart soils. *Nature*, **532**, 49, doi:10.1038/nature17174.

Pawar, R.J. et al., 2015: Recent advances in risk assessment and risk management of geologic CO_2 storage. *International Journal of Greenhouse Gas Control*, **40**, 292-311, doi:10.1016/J.IJGGC.2015.06.014.

Pehl, M. et al., 2017: Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, **2(12)**, 939-945, doi:10.1038/s41560-017-0032-9.

Peters, G.P., 2016: The 'best available science' to inform 1.5 °C policy choices. *Nature Climate Change*, **6(7)**, 646-649, doi:10.1038/nclimate3000.

Pietzcker, R.C. et al., 2017: System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Economics*, **64**, 583-599, doi:10.1016/j.eneco.2016.11.018.

Pikaar, I. et al., 2018: Decoupling livestock from land use through industrial feed production pathways. *Environmental Science & Technology* (in press).

Pindyck, R.S., 2013: Climate Change Policy: What Do the Models Tell Us? *Journal of Economic Literature*, **51(3)**, 1-23, doi:10.1257/jel.51.3.860.

Pizer, W. et al., 2014: Using and improving the social cost of carbon. *Science*, **346(6214)**, 1189-1190, doi:10.1126/science.1259774.

Popp, A., H. Lotze-Campen, and B. Bodirsky, 2010: Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. *Global Environmental Change*, **20(3)**, 451-462, doi:10.1016/j.gloenvcha.2010.02.001.

Popp, A. et al., 2014a: Land-use protection for climate change mitigation. *Nature Climate Change*, **4(12)**, 1095-1098, doi:10.1038/nclimate2444.

Popp, A. et al., 2014b: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3-4)**, 495-509, doi:10.1007/s10584-013-0926-x.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002.

Post, M.J., 2012: Cultured meat from stem cells: Challenges and prospects. *Meat Science*, **92(3)**, 297-301, doi:https://doi.org/10.1016/j.meatsci.2012.04.008.

Prestele, R. et al., 2016: Hotspots of uncertainty in land-use and land-cover change projections: a global-scale model comparison. *Global Change Biology*, **22(12)**, 3967-3983, doi:10.1111/gcb.13337.

Proistosescu, C. and P.J. Huybers, 2017: Slow climate mode reconciles historical and model-based estimates of climate sensitivity. *Science Advances*, **3(7)**.

Psarras, P. et al., 2017: Slicing the pie: how big could carbon dioxide removal be? *Wiley Interdisciplinary Reviews: Energy and Environment*, **6(5)**, e253, doi:10.1002/wene.253.

Purohit, P. and L. Höglund-Isaksson, 2017: Global emissions of fluorinated greenhouse gases 2005-2050 with abatement potentials and costs. *Atmospheric Chemistry and Physics*, **17(4)**, 2795-2816, doi:10.5194/acp-17-2795-2017.

Rao, S. et al., 2016: A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environmental Research Letters*, **11(12)**, 124013, doi:10.1088/1748-9326/11/12/124013.

Rao, S. et al., 2017: Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change*, **42**, 346-358, doi:10.1016/j.gloenvcha.2016.05.012.

Rau, G.H., 2011: CO_2 Mitigation via Capture and Chemical Conversion in Seawater. *Environmental Science & Technology*, **45(3)**, 1088-1092, doi:10.1021/es102671x.

Revesz, R. et al., 2014: Global warming: Improve economic models of climate change. *Nature*, **508(7495)**, 173-175, doi:10.1038/508173a.

Riahi, K. et al., 2011: RCP 8.5 - A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, **109(1)**, 33, doi:10.1007/s10584-011-0149-y.

Riahi, K. et al., 2012: Chapter 17 - Energy Pathways for Sustainable Development. In: *Global Energy Assessment - Toward a Sustainable Future*. pp. 1203-1306.

Riahi, K. et al., 2015: Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, **90(PA)**, 8-23, doi:10.1016/j.techfore.2013.09.016.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009.

Ricke, K.L., R.J. Millar, and D.G. MacMartin, 2017: Constraints on global temperature target overshoot. *Scientific Reports*, **7(1)**, 1-7, doi:10.1038/s41598-017-14503-9.

Riis, F. and E. Halland, 2014: CO_2 storage atlas of the Norwegian Continental shelf: Methods used to evaluate capacity and maturity of the CO_2 storage potential. *Energy Procedia*, **63**, 5258-5265, doi:10.1016/j.egypro.2014.11.557.

Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science*, **355(6331)**, 1269-1271, doi:10.1126/science.aah3443.

Roelfsema, M., M. Harmsen, J.J.G. Olivier, A.F. Hof, and D.P. van Vuuren, 2018: Integrated assessment of international climate mitigation commitments outside the UNFCCC. *Global Environmental Change*, **48**, 67-75, doi:10.1016/J.GLOENVCHA.2017.11.001.

Rogelj, J., D.L. McCollum, B.C. O'Neill, and K. Riahi, 2013a: 2020 emissions levels required to limit warming to below 2 C. *Nature Climate Change*, **3(4)**, 405-412, doi:10.1038/nclimate1758.

Rogelj, J., M. Meinshausen, J. Sedláček, and R. Knutti, 2014a: Implications of potentially lower climate sensitivity on climate projections and policy. *Environmental Research Letters*, **9(3)**, 031003, doi:10.1088/1748-9326/9/3/031003.

Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013b: Probabilistic cost estimates for climate change mitigation. *Nature*, **493(7430)**, 79-83, doi:10.1038/nature11787.

Rogelj, J., M. Meinshausen, M. Schaeffer, R. Knutti, and K. Riahi, 2015a: Impact of short-lived non-CO_2 mitigation on carbon budgets for stabilizing global warming. *Environmental Research Letters*, **10(7)**, 075001, doi:10.1088/1748-9326/10/7/075001.

Rogelj, J. et al., 2011: Emission pathways consistent with a 2 °C global temperature limit. *Nature Climate Change*, **1(8)**, 413-418, doi:10.1038/nclimate1258.

Rogelj, J. et al., 2014b: Disentangling the effects of CO_2 and short-lived climate forcer mitigation. *Proceedings of the National Academy of Sciences*, **111(46)**, 16325-16330, doi:10.1073/pnas.1415631111.

Rogelj, J. et al., 2015b: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, **5(6)**, 519-527, doi:10.1038/nclimate2572.

Rogelj, J. et al., 2015c: Mitigation choices impact carbon budget size compatible with low temperature goals. *Environmental Research Letters*, **10(7)**, 075003, doi:10.1088/1748-9326/10/7/075003.

Rogelj, J. et al., 2015d: Zero emission targets as long-term global goals for climate protection. *Environmental Research Letters*, **10(10)**, 105007, doi:10.1088/1748-9326/10/10/105007.

Rogelj, J. et al., 2016a: Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, **534(7609)**, 631-639, doi:10.1038/nature18307.

Rogelj, J. et al., 2016b: Differences between carbon budget estimates unravelled. *Nature Climate Change*, **6(3)**, 245-252, doi:10.1038/nclimate2868.

Rogelj, J. et al., 2017: Understanding the origin of Paris Agreement emission uncertainties. *Nature Communications*, **8**, 15748, doi:10.1038/ncomms15748.

Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, **8(4)**, 325-332, doi:10.1038/s41558-018-0091-3.

Rose, S.K., 2012: The role of the social cost of carbon in policy. *Wiley Interdisciplinary Reviews: Climate Change*, **3(2)**, 195-212, doi:10.1002/wcc.163.

Rose, S.K., D.B. Diza, and G.J. Blanford, 2017a: Undesterstanding the Social Cost of Carbon: A Model diagnostic and Inter-comparison Study. *Climate Change Economics*, **08(02)**, 1750009, doi:10.1142/S2010007817500099.

Rose, S.K., R. Richels, G. Blanford, and T. Rutherford, 2017b: The Paris Agreement and next steps in limiting global warming. *Climatic Change*, **142(1-2)**, 1-16, doi:10.1007/s10584-017-1935-y.

Rose, S.K. et al., 2014a: Bioenergy in energy transformation and climate management. *Climatic Change*, **123(3-4)**, 477-493, doi:10.1007/s10584-013-0965-3.

Rose, S.K. et al., 2014b: Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios. *Climatic Change*, **123(3-4)**, 511-525, doi:10.1007/s10584-013-0955-5.

Rugenstein, M.A.A. et al., 2016: Multiannual Ocean-Atmosphere Adjustments to Radiative Forcing. *Journal of Climate*, **29(15)**, 5643-5659, doi:10.1175/JCLI-D-16-0312.1.

Samset, B.H. et al., 2016: Fast and slow precipitation responses to individual climate forcers: A PDRMIP multimodel study. *Geophysical Research Letters*, **43(6)**, 2782-2791, doi:10.1002/2016GL068064.

Samset, B.H. et al., 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical Research Letters*, **45(2)**, 1020-1029, doi:10.1002/2017GL076079.

Sand, M. et al., 2015: Response of Arctic temperature to changes in emissions of short-lived climate forcers. *Nature Climate Change*, **6(3)**, 286-289, doi:10.1038/nclimate2880.

Sanderson, B.M., B.C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris temperature targets? *Geophysical Research Letters*, **43(13)**, 7133-7142, doi:10.1002/2016GL069563.

Sands, R.D., 2018: U.S. Carbon Tax Scenarios and Bioenergy. *Climate Change Economics*, **09(01)**, 1840010, doi:10.1142/S2010007818400109.

Sarofim, M.C., S.T. Waldhoff, and S.C. Anenberg, 2017: Valuing the Ozone-Related Health Benefits of Methane Emission Controls. *Environmental and Resource Economics*, **66(1)**, 45-63, doi:10.1007/s10640-015-9937-6.

Saunders, H.D., 2015: Recent Evidence for Large Rebound: Elucidating the Drivers and their Implications for Climate Change Models. *The Energy Journal*, **36(1)**, 23-48.

Schädel, C. et al., 2014: Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data. *Global Change Biology*, **20(2)**, 641-652, doi:10.1111/gcb.12417.

Schädel, C. et al., 2016: Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nature Climate Change*, **6(10)**, 950-953, doi:10.1038/nclimate3054.

Schleussner, C.F. et al., 2016: Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*, **6**, 827-835, doi:10.1038/nclimate3096.

Schmidt, M.G.W., H. Held, E. Kriegler, and A. Lorenz, 2013: Climate Policy Under Uncertain and Heterogeneous Climate Damages. *Environmental and Resource Economics*, **54(1)**, 79-99, doi:10.1007/s10640-012-9582-2.

Schmitz, C. et al., 2012: Trading more food: Implications for land use, greenhouse gas emissions, and the food system. *Global Environmental Change*, **22(1)**, 189-209, doi:10.1016/J.GLOENVCHA.2011.09.013.

Schneider, T. et al., 2017: Climate goals and computing the future of clouds. *Nature Climate Change*, **7(1)**, 3-5, doi:10.1038/nclimate3190.

Schneider von Deimling, T. et al., 2012: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences*, **9(2)**, 649-665, doi:10.5194/bg-9-649-2012.

Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences*, **12(11)**, 3469-3488, doi:10.5194/bg-12-3469-2015.

Schuiling, R.D. and P. Krijgsman, 2006: Enhanced Weathering: An Effective and Cheap Tool to Sequester CO_2. *Climatic Change*, **74(1-3)**, 349-354, doi:10.1007/s10584-005-3485-y.

Schurer, A.P. et al., 2018: Interpretations of the Paris climate target. *Nature Geoscience*, **11(4)**, 220-221, doi:10.1038/s41561-018-0086-8.

Schuur, E.A.G. et al., 2015: Climate change and the permafrost carbon feedback. *Nature*, **520(7546)**, 171-179, doi:10.1038/nature14338.

Scott, C.E. et al., 2017: Substantial large-scale feedbacks between natural aerosols and climate. *Nature Geoscience*, 1, doi:10.1038/s41561-017-0020-5.

Scott, V., R.S. Haszeldine, S.F.B. Tett, and A. Oschlies, 2015: Fossil fuels in a trillion tonne world. *Nature Climate Change*, **5(5)**, 419-423, doi:10.1038/nclimate2578.

Searle, S.Y. and C.J. Malins, 2014: Will energy crop yields meet expectations? *Biomass and Bioenergy*, **65**, 3-12, doi:10.1016/J.BIOMBIOE.2014.01.001.

Séférian, R., M. Rocher, C. Guivarch, and J. Colin, 2018: Constraints on biomass energy deployment in mitigation pathways: the case of water limitation. *Environmental Research Letters*, 1-32, doi:10.1088/1748-9326/aabcd7.

Seto, K.C. et al., 2016: Carbon lock-in: Types, causes, and policy implications. *Annual Review of Environment and Resources*, **41**, 425-452.

Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. LBNL-1003671, 58 pp.

Shearer, C., N. Mathew-Shah, L. Myllyvirta, A. Yu, and T. Nace, 2018: *Boom and Bust 2018: Tracking the global coal plant pipeline*. Coalswarm, Sierra Club, Greenpeace, 16 pp.

Shell International B.V., 2018: *Shell Scenarios: Sky - Meeting the Goals of the Paris Agreement*. Shell International B.V. 36 pp.

Sherwood, S.C., S. Bony, and J.L. Dufresne, 2014: Spread in model climate sensitivity traced to atmospheric convective mixing. *Nature*, **505(7481)**, 37-42, doi:10.1038/nature12829.

Shindell, D.T., 2015: The social cost of atmospheric release. *Climatic Change*, **130(2)**, 313-326, doi:10.1007/s10584-015-1343-0.

Shindell, D.T. and G. Faluvegi, 2010: The net climate impact of coal-fired power plant emissions. *Atmospheric Chemistry and Physics*, **10(7)**, 3247-3260, doi:10.5194/acp-10-3247-2010.

Shindell, D.T., Y. Lee, and G. Faluvegi, 2016: Climate and health impacts of US emissions reductions consistent with 2C. *Nature Climate Change*, **6**, 503-509.

Shindell, D.T., J.S. Fuglestvedt, and W.J. Collins, 2017a: The social cost of methane: theory and applications. *Faraday Discussions*, **200**, 429-451, doi:10.1039/C7FD00009J.

Shindell, D.T., G. Faluvegi, L. Rotstayn, and G. Milly, 2015: Spatial patterns of radiative forcing and surface temperature response. *Journal of Geophysical Research: Atmospheres*, **120(11)**, 5385-5403, doi:10.1002/2014JD022752.

Shindell, D.T., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8(4)**, 291-295, doi:10.1038/s41558-018-0108-y.

Shindell, D.T. et al., 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science*, **335(6065)**, 183-189, doi:10.1126/science.1210026.

Shindell, D.T. et al., 2017b: A climate policy pathway for near- and long-term benefits. *Science*, **356(6337)**, 493-494, doi:10.1126/science.aak9521.

Shukla, P.R. and V. Chaturvedi, 2012: Low carbon and clean energy scenarios for India: Analysis of targets approach. *Energy Economics*, **34(Suppl.3)**, S487-S495, doi:10.1016/j.eneco.2012.05.002.

Siegmeier, J. et al., 2018: The fiscal benefits of stringent climate change mitigation: an overview. *Climate Policy*, **18(3)**, 352-367, doi:10.1080/14693062.2017.1400943.

Silva, R.A. et al., 2016: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmospheric Chemistry and Physics*, doi:10.5194/acp-16-9847-2016.

Sims, R. et al., 2014: Transport. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 599-670.

Smith, C.J. et al., 2018: FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development* (in press), doi:10.5194/gmd-2017-266.

Smith, L.J. and M.S. Torn, 2013: Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change*, **118(1)**, 89-103, doi:10.1007/s10584-012-0682-3.

Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, **22(3)**, 1315-1324, doi:10.1111/gcb.13178.

Smith, P. and M. Bustamante, 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 811-922.

Smith, P. et al., 2013: How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology*, **19(8)**, 2285-2302, doi:10.1111/gcb.12160.

Smith, P. et al., 2015: Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, **6(1)**, 42-50, doi:10.1038/nclimate2870.

Snopkowski, K., M.C. Towner, M.K. Shenk, and H. Colleran, 2016: Pathways from education to fertility decline: a multi-site comparative study. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, **371(1692)**, 20150156, doi:10.1098/rstb.2015.0156.

Socolow, R. et al., 2011: *Direct Air Capture of* CO_2 *with Chemicals: A Technology Assessment for the APS Panel on Public Affairs*. American Physical Society, 100 pp.

Somanthan, E. et al., 2014: National and Sub-national Policies and Institutions. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1141-1206.

Sonnenschein, J., R. van Buskirk, J. Luth Richter, and C. Dalhammar, 2018: Minimum energy performance standards for the 1.5°C target: an effective complement to carbon pricing? *Energy Efficiency* (in press), doi:10.1007/s12053-018-9669-x.

Spencer, T., R. Pierfederici, H. Waisman, and M. Colombier, 2015: *Beyond the Numbers. Understanding the Transformation Induced by INDCs*. Study N°05/15, MILES Project Consortium, Paris, 80 pp.

Springmann, M., H.C.J. Godfray, M. Rayner, and P. Scarborough, 2016: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences of the United States of America*, **113(15)**, 4146-4151, doi:10.1073/pnas.1523119113.

Steckel, J.C., O. Edenhofer, and M. Jakob, 2015: Drivers for the renaissance of coal. *Proceedings of the National Academy of Sciences*, **112(29)**, E3775--E3781, doi:10.1073/pnas.1422722112.

Stehfest, E. et al., 2009: Climate benefits of changing diet. *Climatic Change*, **95(1-2)**, 83-102, doi:10.1007/s10584-008-9534-6.

Stern, N., 2007: *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, United Kingdom, 692 pp.

Stern, N., 2013: The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature*, **51(3)**, 838-859, doi:10.1257/jel.51.3.838.

Stern, N., 2016: Current climate models are grossly misleading. *Nature*, **530**, 407-409, doi:10.1038/530407a.

Stevanović, M. et al., 2017: Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices. *Environmental Science & Technology*, **51(1)**, 365-374, doi:10.1021/acs.est.6b04291.

Stiglitz, J.E. et al., 2017: *Report of the High-Level Commission on Carbon Prices*. Carbon Pricing Leadership Coalition, 68 pp.

Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33-115.

Stohl, A. et al., 2015: Evaluating the climate and air quality impacts of short-lived pollutants. *Atmospheric Chemistry and Physics*, **15(18)**, 10529-10566, doi:10.5194/acp-15-10529-2015.

Strapasson, A. et al., 2017: On the global limits of bioenergy and land use for climate change mitigation. *GCB Bioenergy*, **9(12)**, 1721-1735, doi:10.1111/gcbb.12456.

Strefler, J., T. Amann, N. Bauer, E. Kriegler, and J. Hartmann, 2018a: Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, **13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.

Strefler, J., N. Bauer, E. Kriegler, A. Popp, and O. Giannousakis, Anastasis Edenhofer, 2018b: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett*, **13**, 044015.

Su, X. et al., 2017: Emission pathways to achieve 2.0°C and 1.5°C climate targets. *Earth's Future*, **5(6)**, 592-604, doi:10.1002/2016EF000492.

Subbarao, G. et al., 2013: Potential for biological nitrification inhibition to reduce nitrification and N2O emissions in pasture crop-livestock systems. *animal*, **7(s2)**, 322-332, doi:10.1017/S1751731113000761.

Subharat, S. et al., 2016: Vaccination of Sheep with a Methanogen Protein Provides Insight into Levels of Antibody in Saliva Needed to Target Ruminal Methanogens. *PLOS ONE*, **11(7)**, e0159861, doi:10.1371/journal.pone.0159861.

Szulczewski, M.L., C.W. MacMinn, and R. Juanes, 2014: Theoretical analysis of how pressure buildup and CO_2 migration can both constrain storage capacity in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **23**, 113-118, doi:10.1016/j.ijggc.2014.02.006.

Tachiiri, K., T. Hajima, and M. Kawamiya, 2015: Increase of uncertainty in transient climate response to cumulative carbon emissions after stabilization of atmospheric CO_2 concentration. *Environmental Research Letters*, **10(12)**, 125018, doi:10.1088/1748-9326/10/12/125018.

Tan, I., T. Storelvmo, and M.D. Zelinka, 2016: Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, **352(6282)**, 224-227, doi:10.1126/science.aad5300.

Tavoni, M. and R.S.J. Tol, 2010: Counting only the hits? The risk of underestimating the costs of stringent climate policy. *Climatic Change*, **100(3-4)**, 769-778, doi:10.1007/s10584-010-9867-9.

The Royal Society, 2009: *Geoengineering the climate: science, governance and uncertainty*.

Thomson, A.M. et al., 2011: RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*, **109(1-2)**, 77-94, doi:10.1007/s10584-011-0151-4.

Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515(7528)**, 518-522, doi:10.1038/nature13959.

Tokarska, K.B. and N.P. Gillett, 2018: Cumulative carbon emissions budgets consistent with 1.5 °C global warming. *Nature Climate Change*, **8(4)**, 296-299, doi:10.1038/s41558-018-0118-9.

Tokarska, K.B., N.P. Gillett, V.K. Arora, W.G. Lee, and K. Zickfeld, 2018: The influence of non-CO_2 forcings on cumulative carbon emissions budgets. *Environmental Research Letters*, **13(3)**, 034039, doi:10.1088/1748-9326/aaafdd.

Tol, R.S.J., 1999: Spatial and Temporal Efficiency in Climate Policy: Applications of FUND. *Environmental and Resource Economics*, **14(1)**, 33-49.

Tol, R.S.J., 2017: The structure of the climate debate. *Energy Policy*, **104**, 431-438, doi:10.1016/J.ENPOL.2017.01.005.

Tuomisto, H.L. and M.J. Teixeira de Mattos, 2011: Environmental Impacts of Cultured Meat Production. *Environmental Science & Technology*, **45(14)**, 6117-6123, doi:10.1021/es200130u.

UNEP, 2015: *Aligning the Financial System with Sustainable Development: Pathways to Scale*. United Nations

Environment Programme (UNEP), Geneva, 26 pp.

UNEP, 2016: *The Emissions Gap Report 2016: A UNEP Synthesis Report*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 85 pp.

UNEP, 2017: *The Emissions Gap Report 2017: A UN Environment Synthesis Report*. 116 pp.

UNFCCC, 2016: *Aggregate effect of the intended nationally determined contributions: an update*. FCCC/CP/2016/2, The Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), Bonn, Germany, 75 pp.

Unruh, G.C. and J. Carrillo-Hermosilla, 2006: Globalizing carbon lock-in. *Energy Policy*, **34(10)**, 1185-1197, doi:10.1016/j.enpol.2004.10.013.

Unruh, J.D., 2011: Tree-Based Carbon Storage in Developing Countries: Neglect of the Social Sciences. *Society & Natural Resources*, **24(2)**, 185-192, doi:10.1080/08941920903410136.

US EPA, 2013: *Global Mitigation of Non-*CO_2 *Greenhouse Gases: 2010-2030. Report No. EPA-430-R-13-011*. United States Environmental Protection Agency (US EPA), Washington DC, USA, 410 pp.

Valin, H. et al., 2013: Agricultural productivity and greenhouse gas emissions: trade-offs or synergies between mitigation and food security? *Environmental Research Letters*, **8(3)**, 035019, doi:10.1088/1748-9326/8/3/035019.

van den Bergh, J.C.J.M., 2017: Rebound policy in the Paris Agreement: instrument comparison and climate-club revenue offsets. *Climate Policy*, **17(6)**, 801-813, doi:10.1080/14693062.2016.1169499.

van Sluisveld, M.A.E., S.H. Martínez, V. Daioglou, and D.P. van Vuuren, 2016: Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **102**, 309-319, doi:10.1016/J.TECHFORE.2015.08.013.

van Soest, H.L. et al., 2017: Low-emission pathways in 11 major economies: comparison of cost-optimal pathways and Paris climate proposals. *Climatic Change*, **142(3-4)**, 491-504, doi:10.1007/s10584-017-1964-6.

van Vuuren, D.P. and K. Riahi, 2011: The relationship between short-term emissions and long-term concentration targets. *Climatic Change*, **104(3)**, 793-801, doi:10.1007/s10584-010-0004-6.

van Vuuren, D.P., A.F. Hof, M.A.E. van Sluisveld, and K. Riahi, 2017a: Open discussion of negative emissions is urgently needed. *Nature Energy*, **2(12)**, 902-904, doi:10.1038/s41560-017-0055-2.

van Vuuren, D.P. et al., 2007: Stabilizing greenhouse gas concentrations at low levels: An assessment of reduction strategies and costs. *Climatic Change*, **81(2)**, 119-159, doi:10.1007/s10584-006-9172-9.

van Vuuren, D.P. et al., 2011a: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5-31, doi:10.1007/s10584-011-0148-z.

van Vuuren, D.P. et al., 2011b: RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change*, **109(1)**, 95-116, doi:10.1007/s10584-011-0152-3.

van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303-323, doi:10.1016/J.TECHFORE.2015.03.005.

van Vuuren, D.P. et al., 2016: Carbon budgets and energy transition pathways. *Environmental Research Letters*, **11(7)**, 075002, doi:10.1088/1748-9326/11/7/075002.

van Vuuren, D.P. et al., 2017b: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, **42**, 237-250, doi:10.1016/j.gloenvcha.2016.05.008.

van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391-397, doi:10.1038/s41558-018-0119-8.

Vangkilde-Pedersen, T. et al., 2009: Assessing European capacity for geological storage of carbon dioxide-the EU GeoCapacity project. *Energy Procedia*, **1(1)**, 2663-2670, doi:10.1016/j.egypro.2009.02.034.

Veland, S. et al., 2018: Narrative matters for sustainability: the transformative role of storytelling in realizing 1.5°C futures. *Current Opinion in Environmental Sustainability*, **31**, 41-47, doi:10.1016/J.COSUST.2017.12.005.

Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123**, 200-209, doi:10.1016/j.atmosenv.2015.10.071.

Vogt-Schilb, A. and S. Hallegatte, 2017: Climate policies and nationally determined contributions: reconciling the needed ambition with the political economy. *Wiley Interdisciplinary Reviews: Energy and Environment*, **6(6)**, 1-23, doi:10.1002/wene.256.

Voigt, C. et al., 2017a: Warming of subarctic tundra increases emissions of all three important greenhouse gases - carbon dioxide, methane, and nitrous oxide. *Global Change Biology*, **23(8)**, 3121-3138, doi:10.1111/gcb.13563.

Voigt, C. et al., 2017b: Increased nitrous oxide emissions from Arctic peatlands after permafrost thaw. *Proceedings of the National Academy of Sciences*, **114(24)**, 6238-6243, doi:10.1073/pnas.1702902114.

von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annual Review of Environment and Resources*, **40(1)**, 363-394, doi:10.1146/annurev-environ-021113-095626.

von Stechow, C. et al., 2016: 2 °C and SDGs: united they stand, divided they fall? *Environmental Research Letters*, **11(3)**, 034022, doi:10.1088/1748-9326/11/3/034022.

Vrontisi, Z., G. Luderer, B. Saveyn, K. Keramidas, and L.A. Reis, 2018: Enhancing global climate policy ambition towards a 1.5°C stabilization: a short-term multi-model assessment. *Environ. Res. Lett*, **13**, 044039.

Wachsmuth, J. and V. Duscha, 2018: Achievability of the Paris targets in the EU-the role of demand-side-driven mitigation in different types of scenarios. *Energy Efficiency*, 1-19, doi:10.1007/s12053-018-9670-4.

Walsh, M.J. et al., 2016: Algal food and fuel coproduction can mitigate greenhouse gas emissions while improving land and water-use efficiency. *Environmental Research Letters*, **11(11)**, 114006.

Wang, X. et al., 2016: Taking account of governance: Implications for land-use dynamics, food prices, and trade patterns. *Ecological Economics*, **122**, 12-24, doi:10.1016/J.ECOLECON.2015.11.018.

Warwick, P.D., M.K. Verma, P.A. Freeman, M.D. Corum, and S.H. Hickman, 2014: U.S. geological survey carbon sequestration - geologic research and assessments. *Energy Procedia*, **63**, 5305-5309, doi:10.1016/j.egypro.2014.11.561.

Wedlock, D.N., P.H. Janssen, S.C. Leahy, D. Shu, and B.M. Buddle, 2013: Progress in the development of vaccines against rumen methanogens. *animal*, **7(s2)**, 244-252, doi:10.1017/S1751731113000682.

Wei, N. et al., 2013: A preliminary sub-basin scale evaluation framework of site suitability for onshore aquifer-based CO_2 storage in China. *International Journal of Greenhouse Gas Control*, **12**, 231-246, doi:10.1016/j.ijggc.2012.10.012.

Weindl, I. et al., 2015: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environmental Research Letters*, **10(9)**, 094021, doi:10.1088/1748-9326/10/9/094021.

Weindl, I. et al., 2017: Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics. *Global and Planetary Change*, **159**, 1-10, doi:10.1016/j.gloplacha.2017.10.002.

Weitzman, M.L., 2014: Can Negotiating a Uniform Carbon Price Help to Internalize the Global Warming Externality? *Journal of the Association of Environmental and Resource Economists*, **1(1/2)**, 29-49, doi:10.1086/676039.

Werner, C., H.P. Schmidt, D. Gerten, W. Lucht, and C. Kammann, 2018: Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °C. *Environmental Research Letters*, **13(4)**, 044036, doi:10.1088/1748-9326/aabb0e.

West, J.J. et al., 2013: Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nature Climate Change*, **3(10)**, 885-889, doi:10.1038/nclimate2009.

Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, **11(1)**, 115-137, doi:10.1093/reep/rew018.

Weyant, J.P., F.C. Chesnaye, and G.J. Blanford, 2006: Overview of EMF-21: Multigas Mitigation and Climate Policy. *The Energy Journal*, **27**, 1-32, doi:10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-1.

Wiebe, K. et al., 2015: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, **10(8)**, 085010, doi:10.1088/1748-9326/10/8/085010.

Wigley, T.M.L., R. Richels, and J. Edmonds, 2007: Overshoot Pathways to CO_2 stabilization in a multi-gas context. In: *Human Induced Climate Change: An Interdisciplinary Perspective* [Schlesinger, M.E., H.S. Kheshgi, J. Smith, F.C. de la Chesnaye, J.M. Reilly, T. Wilson, and C. Kolstad (eds.)]. Cambridge University Press, Cambridge, pp. 84-92.

Williams, P.J.L.B. and L.M.L. Laurens, 2010: Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics. *Energy & Environmental Science*, **3(5)**, 554, doi:10.1039/b924978h.

Williamson, P., 2016: Emissions reduction: Scrutinize CO_2 removal methods. *Nature*, **530(153)**, 153-155, doi:10.1038/530153a.

Williamson, P. and R. Bodle, 2016: *Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework*. CBD Technical Series No. 84, Secretariat of the Convention on Biological Diversity, Montreal, QC, Canada, 158 pp.

Wise, M., K. Calvin, P. Kyle, P. Luckow, and J. Edmonds, 2014: Economic and physical modeling of land use in GCAM 3.0 and an application to agricultural productivity, land, and terrestrial carbon. *Climate Change Economics*, **05(02)**, 1450003, doi:10.1142/S2010007814500031.

Woolf, D., J.E. Amonette, F.A. Street-Perrott, J. Lehmann, and S. Joseph, 2010: Sustainable biochar to mitigate global climate change. *Nature Communications*, **1(5)**, 1-9, doi:10.1038/ncomms1053.

Xiao, X. and K. Jiang, 2017: Prospect of and preliminary feasibility study on China's nuclear power under the Global 1.5°C Target. *Advances in Climate Change Research* (in press), doi:10.1016/j.accre.2018.05.002.

Xu, Y. and V. Ramanathan, 2017: Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proceedings of the National Academy of Sciences of the United States of America*, **114(39)**, 10315-10323, doi:10.1073/pnas.1618481114.

Yeh, S. et al., 2016: Detailed assessment of global transport-energy models' structures and projections. *Transportation Research Part D: Transport and Environment*, **55**, 294-309, doi:10.1016/j.trd.2016.11.001.

Zeman, F.S. and K. Lackner, 2004: Capturing carbon dioxide directly from the atmosphere. *World Resource Review*, **16(2)**, 157-172.

Zeman, F.S. and D.W. Keith, 2008: Carbon Neutral Hydrocarbons. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences*, **366(1882)**, 3901-3918, doi:10.1098/rsta.2008.0143.

Zhai, C., J.H. Jiang, and H. Su, 2015: Long-term cloud change imprinted in seasonal cloud variation: More evidence of high climate sensitivity. *Geophysical Research Letters*, **42(20)**, 8729-8737, doi:10.1002/2015GL065911.

Zhang, R., S. Fujimori, and T. Hanaoka, 2018: The contribution of transport policies to the mitigation potential and cost of 2°C and 1.5°C goals. *Environmental Research Letters*, **13(5)**, 054008.

Zickfeld, K. and T. Herrington, 2015: The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission. *Environmental Research Letters*, **10(3)**, 031001, doi:10.1088/1748-9326/10/3/031001.

Zickfeld, K., A.H. MacDougall, and H.D. Matthews, 2016: On the proportionality between global temperature change and cumulative CO_2 emissions during periods of net negative CO_2 emissions. *Environmental Research Letters*, **11(5)**, 055006, doi:10.1088/1748-9326/11/5/055006.

Zickfeld, K., M. Eby, H.D. Matthews, and A.J. Weaver, 2009: Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **106(38)**, 16129-16134, doi:10.1073/pnas.0805800106.

Zomer, R.J., D.A. Bossio, R. Sommer, and L.V. Verchot, 2017: Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. *Scientific Reports*, **7(1)**, 15554.

Zomer, R.J. et al., 2016: Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports*, **6**, 29987.

Table of Content

Chapter 2 – Technical Annex - Part 1 - Mitigation pathways compatible with 1.5°C in the context of sustainable development

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2.A.1 Geophysical relationships and constraints

2.A.1.1 Reduced complexity climate models

The 'Model for the Assessment of Greenhouse Gas Induced Climate Change' (MAGICC6, Meinshausen et al., 2011a), is a reduced complexity carbon-cycle, atmospheric composition and climate model that has been widely used in prior IPCC Assessments and policy literature. This model is used with its parameter set as identical to that employed in AR5 for backwards compatibility. This model has been shown to match temperature trends very well compared to CMIP5 models (Collins et al., 2013; Clarke et al., 2014).

The 'Finite Amplitude Impulse Response' (FAIRv1.3, Smith et al., 2018) model is similar to MAGICC but has even simpler representations of the carbon cycle and some atmospheric chemistry. Its parameter sets are based on AR5 physics with updated methane radiative forcing (Etminan et al., 2016). The FAIR model is a reasonable fit to CMIP5 model for lower emission pathways but underestimates the temperature response compared to CMIP5 models for RCP8.5 (Smith et al., 2018). It has been argued that its near-term temperature trends are more realistic than MAGICC (Leach et al., 2018).

The MAGICC model is used in this report to classify the different pathways in terms of temperature thresholds and its results are averaged with the FAIR model to support the evaluation of the non-CO_2 forcing contribution to the remaining carbon budget. The FAIR model is less established in the literature but can be seen as being more up to date in regards to its radiative forcing treatment. It is used in this report to help assess the uncertainty in the pathway classification approach and also used to support the carbon budget evaluation (Section 2.2 and 2.A.1.2).

The section analyses geophysical differences between FAIR and MAGICC to help provide confidence in the assessed climate response findings of the main report (Sections 2.2 and 2.3).

There are structural choices in how the models relate emissions to concentrations and effective radiative forcing. There are also differences in their ranges of climate sensitivity, their choice of carbon-cycle parameters, and how they are constrained, even though both models are consistent with AR5 ranges. Overall their temperature trends are similar for the range of emission trajectories (Figure 2.1 of the main report). However, differences exist in their near-term trends, with MAGICC exhibiting stronger warming trends than FAIR (see Figure 2.A.1). Leach et al. (2018) also note that that MAGICC warms more strongly than current warming rates. By adjusting FAIR parameters to match those in MAGICC, more than half the difference in mean near-term warming trends can be traced to parameter choices. The remaining differences are due to choices regarding model structure (Figure 2.A.1).

A structural difference exists in the way the models transfer from the historical period to the future. The setup of MAGICC used for AR5 uses a parametrisation that is constrained by observations of hemispheric temperatures and ocean heat uptake, as well as assessed ranges of radiative forcing consistent with AR4 (Meinshausen et al., 2009). From 1765 to 2005 the setup used for AR5 bases forcing on observed concentrations and uses emissions from 2006. It also ramps down the magnitude of volcanic forcing from 1995 to 2000 to give zero forcing in future scenarios, and solar forcing is fixed at 2009 values in the future. In contrast, FAIR produces a constrained set of parameters from emissions runs over the historic period (1765-2017) using both natural and anthropogenic forcings, and then uses this set to run the emissions model with only anthropogenic emissions for the full period of analysis (1765-2110). Structural choices in how aerosol, CH_4 and N_2O are implemented in the model are apparent (see Figure 2.A.2). As well as a weaker CH_4 radiative forcing, MAGICC also has a stronger total aerosol effective radiative forcing that is close to the AR4 best estimate of -1.2 Wm^{-2} for the total aerosol radiative forcing (Forster et al., 2007). As a result its forcing is larger than either FAIR or the AR5 best estimate (Figure 2.A.2), although its median aerosol forcing is well within the IPCC range (Myhre et al., 2013). The difference in N_2O forcings between the models result both from a slightly downwards-revised radiative forcing estimate for N_2O in (Etminan et al., 2016) and the treatment of how the models account for natural emissions and atmospheric lifetime of N_2O. The stronger aerosol forcing and its stronger recovery in MAGICC has the largest effect on near-term trends, with CH_4 and N_2O also contributing to stronger warming trends in the MAGICC model.

TCRE differences between the models are an informative illustration of their parametric differences. (Figure 2.A.3). In their setups used in this report, FAIR has a TCRE median of 0.38°C (5–95% range of 0.25 to 0.57°C) per 1000 GtO_2 and MAGICC a TCRE median of 0.47°C (5–95% range of 0.13 to 1.02°C) per 1000 $GtCO_2$. When directly used for the estimation of carbon budgets, this would make the remaining carbon budgets considerably larger in FAIR compared to MAGICC. As a result, rather than to use their budgets directly, this report bases its budget estimate on the AR5 TCRE *likely* (greater than 16–84%) range of 0.2 to 0.7°C per 1000 $GtCO_2$ (Collins et al., 2013) (see Section 2.A.1.2).

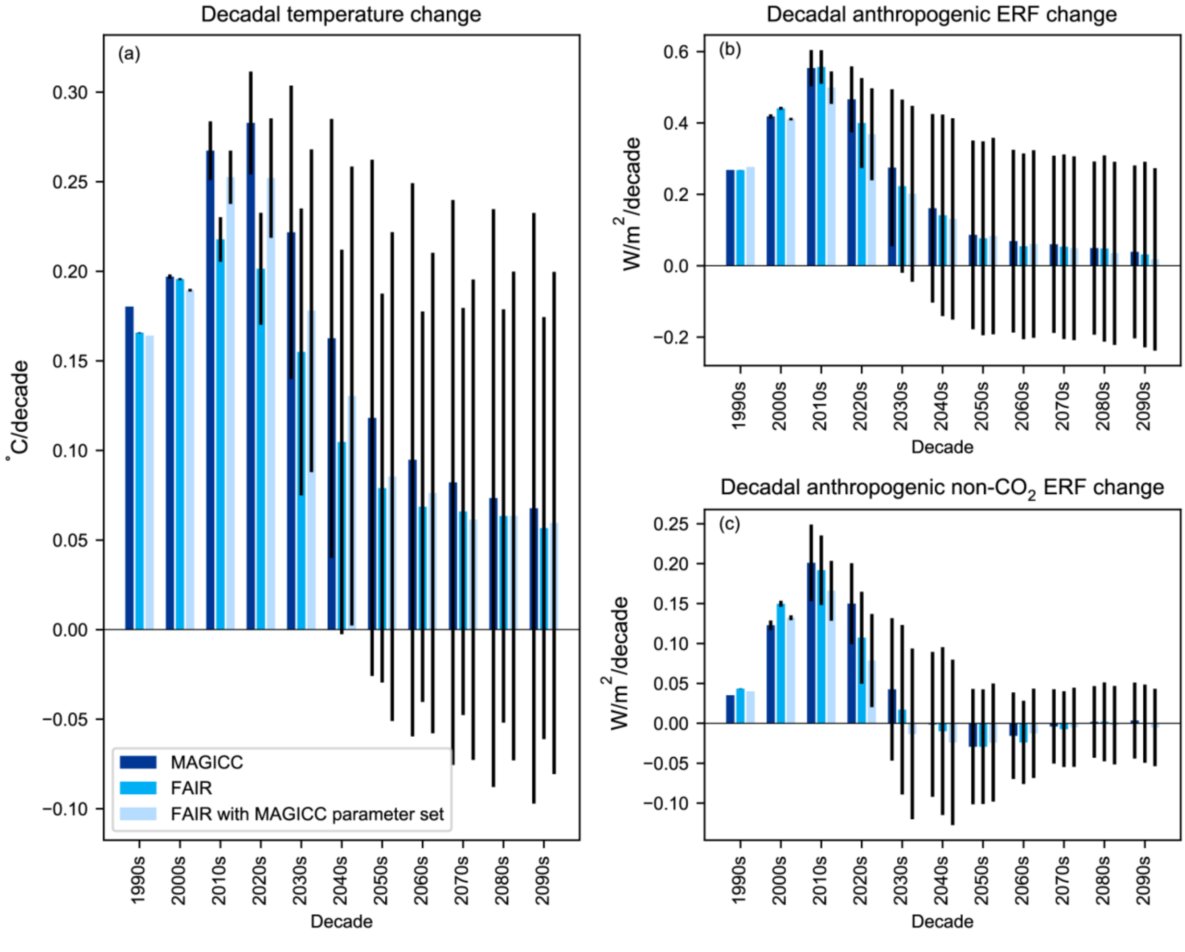

Figure 2.A.1: Warming rates per decade for MAGICC (dark blue), FAIR (sky blue) and FAIR matching the MAGICC parameter set (light blue) for the scenario dataset used in this report. Bars represent the mean of regression slopes taken over each decade (years 0 to 9) for scenario median temperature changes, over all scenarios. The black bars show the standard deviation over the set of scenarios.

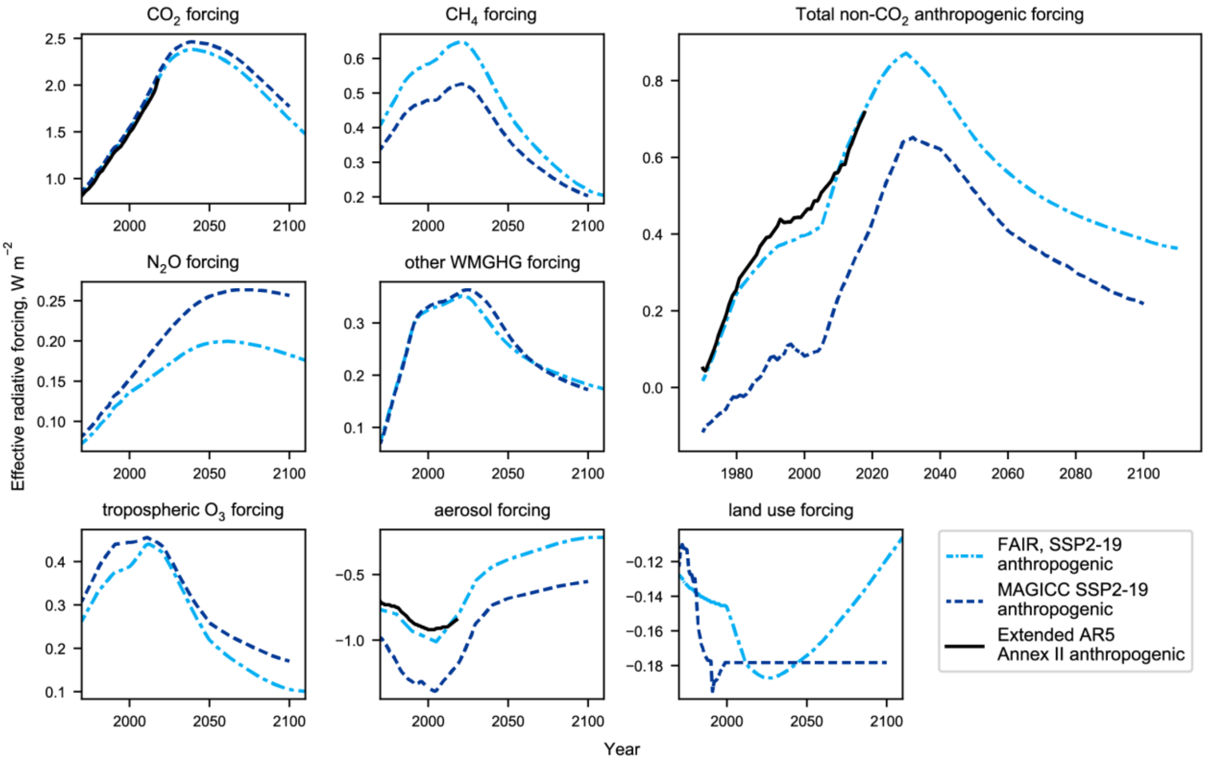

Figure 2.A.2: Time series of MAGICC (dark blue dashed) and FAIR (sky blue dash-dotted) effective radiative forcing for an example emission scenario for the main forcing agents where the models exhibit differences. AR5 data is from Myhre et al. (2013), extended from 2011 until the end of 2017 with greenhouse gas data from NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/), updated radiative forcing approximations for greenhouse gases (Etminan et al., 2016) and extended aerosol forcing following (Myhre et al., 2017).

The summary assessment is that both models exhibit plausible temperature responses to emissions. It is too premature to say that either model may be biased. As MAGICC is more established in the literature than FAIR and has been tested against CMIP5 models, the classification of scenarios used in this report is based on MAGICC temperature projections. There is *medium confidence* in this classification and the likelihoods used at the boundaries could prove to underestimate the probability of staying below given temperatures thresholds if near-term temperatures in the applied setup of MAGICC turn out to be warming too strongly. However, neither model accounts for possible permafrost melting in their setup used for this report (although MAGICC does have a setting that would allow them to be included (Schneider von Deimling et al., 2012, 2015)), so biases in MAGICC could cancel in terms of their effect on long-term temperature targets. The veracity of these reduced complexity climate models is a substantial knowledge gap in the overall assessment of pathways and their temperature thresholds.

The differences between FAIR and MAGICC have a substantial effect on their remaining carbon budgets (see Figure 2.A.3), and the strong near-term warming in the specific MAGICC setup applied here (Leach et al., 2018) may bias its results to smaller remaining budgets (green line on Figure 2.A.3). Likewise, the relatively small TCRE in FAIR (compared to AR5) might bias its results to higher remaining budgets (orange line on Figure 2.A.3). Rather than using the entire model response, only the contribution of non-CO$_2$ warming from each model is used, using the method discussed next.

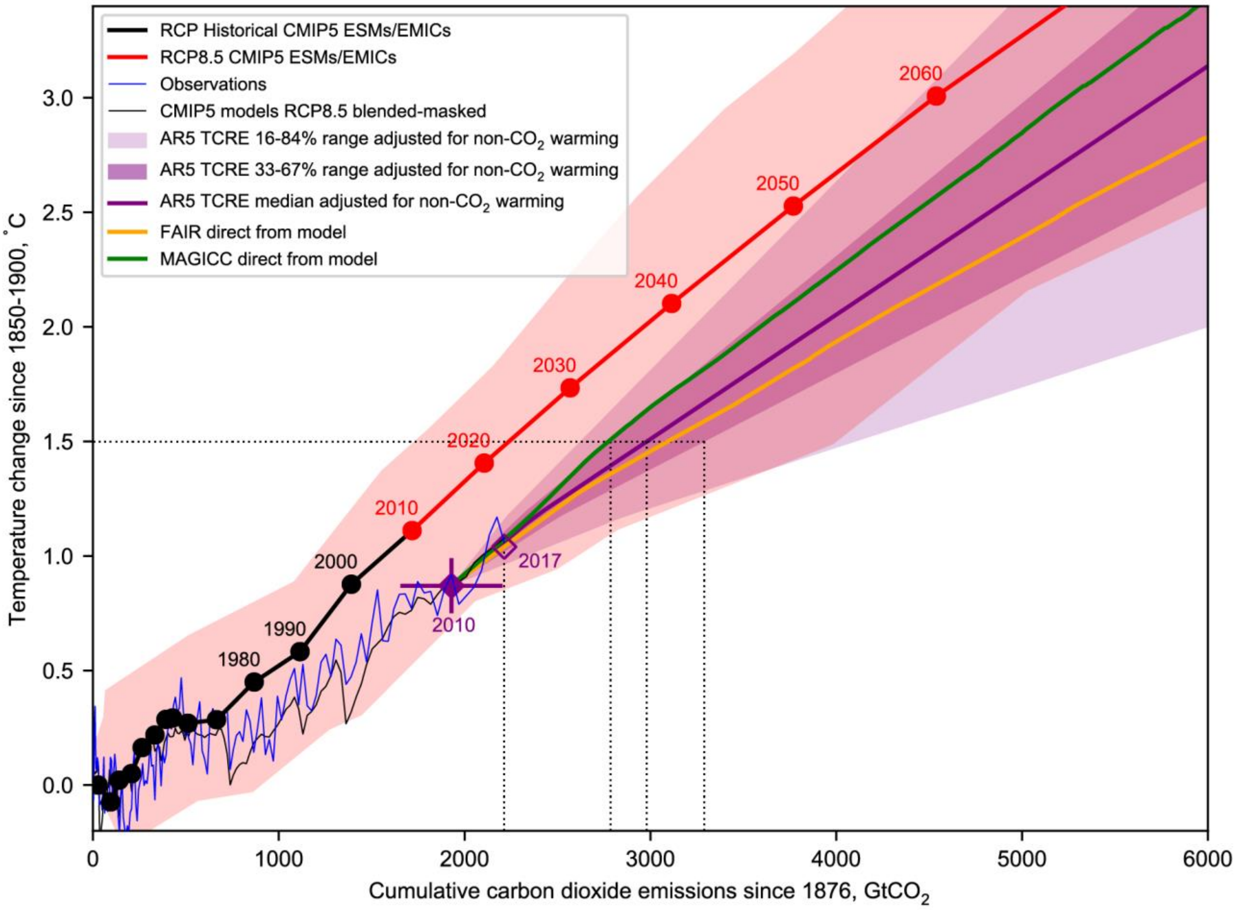

Figure 2.A.3: This figure follows Figure 2.3 of the main report with two extra lines on each showing FAIR (orange) and MAGICC (green) results separately. These additional lines show the full model response averaged across all scenarios and geophysical parameters.

2.A.1.2 *Methods for assessing remaining carbon budgets*

First, the basis for the median remaining carbon budget estimate is described based on MAGICC and FAIR non-CO_2 warming contributions. This is then compared to a simple analysis approach. Lastly, the uncertainty analysis is detailed.

2.A.1.2.1 Median remaining carbon budget basis

This assessment employs historical net cumulative CO_2 emissions reported by the Global Carbon Project (Le Quéré et al., 2018). They report 2170±240 $GtCO_2$ emitted between 1 January 1876 and 31 December 2016. Annual CO_2 emissions for 2017 are estimated at about 41±4 $GtCO_2$/yr (Le Quéré et al., 2018) (Version 1.3 accessed 22 May 2018). From 1 Jan 2011 until 31 December 2017, an additional 290 $GtCO_2$ (270-310 $GtCO_2$, 1σ range) has been emitted (Le Quéré et al., 2018).

In WG1 AR5, TCRE was assessed to have a likely range of 0.22°C to 0.68°C per 1000 $GtCO_2$. The middle of this range (0.45°C per 1000 $GtCO_2$) is taken to be the best estimate, although no best estimate was explicitly defined (Collins et al., 2013; Stocker et al., 2013).

TCRE is diagnosed from integrations of climate models forced with CO_2 emissions only. However, also the influence of other climate forcers on global temperatures should also be taken into account (see Figure 3 in Knutti and Rogelj (2015).

The Reference Non-CO_2 Temperature Contribution (RNCTC) is defined as the median future warming due to non-CO_2 radiative forcing until the time of net-zero CO_2 emissions. The RNCTC is then removed from pre-defined levels of future peak warming (ΔT_{peak}) between 0.3 to 1.2 °C. The CO_2-only carbon budget is subsequently computed for this revised set of warming levels ($\Delta T_{\text{peak}} - RNCTC$).

In FAIR, the RNCTC is defined as the difference in temperature between two experiments, one where all anthropogenic emissions are included and one where only CO_2 emissions are included, using the constrained parameter set. Parallel integrations with matching physical parameters are performed for the suite of 205 scenarios in which CO_2 emissions become net zero during the 21st century. The non-CO_2 warming from a 2006-2015 average baseline is evaluated at the time in which CO_2 emissions become net zero. A linear regression between peak temperature relative to 2006-2015 and non-CO_2 warming relative to 2006-2015 at the time of net zero emissions is performed over the set of 205 scenarios (Figure 2.A.4). The RNCTC acts to reduce the ΔT_{peak} by an amount of warming caused by non-CO_2 agents, which also takes into account warming effects of non-CO_2 forcing on the carbon-cycle response . In the MAGICC model the non-CO_2 temperature contribution is computed from the non-CO_2 effective radiative forcing time series for the same 205 scenarios, using the AR5 impulse response function (Myhre et al., 2013). As in FAIR, the RNCTC is then calculated from a linear regression of non-CO_2 temperature change against peak temperature.

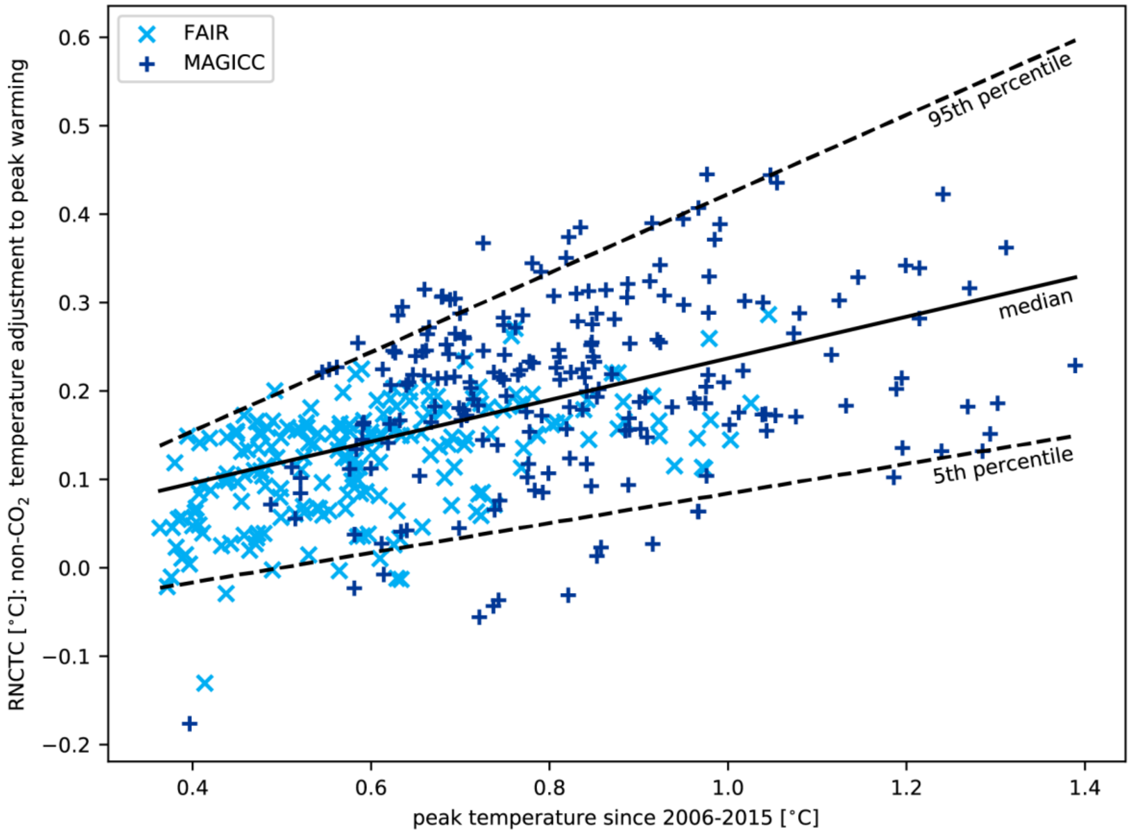

Figure 2.A.4: Relationship of RNCTC with peak temperature in the FAIR and MAGICC models. The black line is the linear regression relationship between peak temperature and RNCTC. The dashed lines show the quantile regressions at the 5th and 95th percentile.

Table 2.A.1 presents the CO_2 only budgets for different levels of future warming assuming both a normal and a log-normal TCRE distribution, where the overall distribution matches the AR5 *likely* TCRE range of 0.2° to 0.7°C per 1000 $GtCO_2$. Table 2.A.2 presents the RNCTC values for different levels of future warming and how they affect the remaining carbon budget for the individual models assuming the normal distribution of TCRE. These are then averaged and rounded to give the numbers presented in the main chapter (Table 2.2). The budgets are taken with respect to the 2006–2015 baseline for temperature and 1 January 2018 for cumulative emissions. In the main report (Section 2.2), as well as in Table 2.A.1, the estimates account for cumulative CO_2 emissions between the start of 2011 and the end of 2017 of about 290 $GtCO_2$.

Table 2.A.1: Remaining carbon dioxide only budget in $GtCO_2$ from 1.1.2018 for different levels of warming from 2006–2015 for normal and log-normal distributions of TCRE based on the AR5 likely range. 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017. The assessed warming from 1850–1900 to 2006–2015 is about 0.87°C with 1-σ uncertainty range of ±0.12°C.

CO_2 only Remaining budgets ($GtCO_2$) Additional warming from 2005-2015 °C	Normal distribution TCRE 0.35 °C per 1000$GtCO_2$ TCRE 33%	Normal distribution TCRE 0.45 °C per 1000$GtCO_2$ TCRE 50%	Normal distribution TCRE 0.55 °C per 1000$GtCO_2$ TCRE 67%	Log-normal distribution TCRE 0.30 °C per 1000$GtCO_2$ TCRE 33%	Log-normal distribution TCRE 0.38 °C per 1000$GtCO_2$ TCRE 50%	Log-normal distribution TCRE 0.50 °C per 1000$GtCO_2$ TCRE 67%
0.3	571	376	253	709	487	315
0.4	859	598	434	1042	746	517
0.5	1146	820	615	1374	1005	718
0.6	1433	1042	796	1707	1265	920
0.63	1519	1109	851	1807	1342	980
0.7	1720	1264	977	2040	1524	1122
0.8	2007	1486	1158	2373	1783	1323
0.9	2294	1709	1339	2706	2042	1525
1	2581	1931	1520	3039	2301	1726
1.1	2868	2153	1701	3372	2560	1928
1.13	2955	2219	1756	3472	2638	1989
1.2	3156	2375	1882	3705	2819	2130

Table 2.A.2: Remaining carbon dioxide budget from 1.1.2018 reduced by the effect of non-CO_2 forcers. Budgets are for different levels of warming from 2006–2015 for a normal distribution of TCRE based on the AR5 *likely* range of 0.2°C to 0.7°C per 1000 $GtCO_2$. 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017. This method employed the RNCTC estimates of non-CO_2 temperature change until the time of net zero CO_2 emissions.

Remaining carbon budgets ($GtCO_2$) Additional warming from 2006-2015 °C	**MAGICC RNCTC °C**	MAGICC TCRE 33%	MAGICC TCRE 50%	MAGICC TCRE 67%	**FAIR RNCTC °C**	FAIR TCRE 33%	FAIR TCRE 50%	FAIR TCRE 67%
0.3	0.14	184	77	9	0.06	402	245	146
0.4	0.15	434	270	166	0.08	629	421	289
0.5	0.16	681	461	322	0.10	856	596	433
0.6	0.18	930	654	480	0.12	1083	772	576
0.63	0.18	1005	712	527	0.13	1152	825	619
0.7	0.19	1177	845	635	0.14	1312	949	720
0.8	0.20	1427	1038	793	0.16	1539	1125	863
0.9	0.22	1674	1229	948	0.18	1766	1300	1006
1	0.23	1924	1422	1106	0.20	1993	1476	1149
1.1	0.24	2171	1613	1262	0.22	2223	1653	1294
1.13	0.25	2246	1671	1309	0.23	2291	1707	1338
1.2	0.26	2421	1806	1419	0.25	2449	1829	1437

2.A.1.2.2 Checks on approach

A simple approach to infer the carbon budget contribution from non-CO_2 forcers has been proposed based on global warming potential and is found to hold for a wide range of mitigation scenarios (Allen et al., 2018). This is based on an empirical relationship between peak temperature, TCRE, cumulative CO_2 emissions (G_{CO2}), non-CO_2 forcing ($\Delta F_{\text{non-CO2}}$) and the Absolute Global Warming Potential of CO_2 ($\text{AGWP}_H(\text{CO}_2)$) over time horizon H, taken to be 100 years:

$$\Delta T_{\text{peak}} \approx \text{TCRE} \times \left(G_{\text{CO2}} + \Delta F_{\text{non-CO2}} \times \left(H/\text{AGWP}_H(\text{CO}_2)\right)\right) \tag{1}$$

This method reduces the budget by an amount proportional to the change in non-CO_2 forcing. To determine this non-CO_2 forcing contribution, a Reference Non-CO_2 Forcing Contribution (RNCFC) is estimated from the MAGICC and FAIR runs. The RNCFC is defined as $\Delta F_{\text{non-CO2}}$ in eq. (1) which is a watts-per-metre-squared difference in the non-CO_2 effective radiative forcing between the 20 years before peak temperature is reached and 1996–2015. This provides an estimate of the non-CO_2 forcing contribution to the change in carbon budget. A similar calculation was performed for aerosol forcing in isolation (ΔF_{aer}) to show that the weakening aerosol forcing is the largest contributor to the smaller carbon budget, compared to the CO_2 only budget. AGWP_{100} values are taken from AR5 (Myhre et al., 2013) and the resultant remaining carbon budgets given in Table 2.A.3. This method reduces the remaining carbon budget by 1091 $GtCO_2$ per Wm^{-2} of non-CO_2 effective radiative forcing (with a 5% to 95% range of 886 to 1474 $GtCO_2$). These results show good agreement to those computed with the RNCTC method from Table 2.A.2, adding confidence to both methods. The RNCFC method is approximate and the choice of periods to use for averaging forcing is somewhat subjective, so the RNCTC is preferred over the RNCFC for this assessment.

Table 2.A.3: Remaining carbon dioxide budgets from 1.1.2018 reduced by the effect of non-CO_2 forcers calculated by using a simple empirical approach based on non-CO_2 forcing (RNCFC) computed by the FAIR model. Budgets are for different levels of warming from 2006–2015 and for a normal distribution of TCRE based on the AR5 likely range of 0.2°C to 0.7°C per 1000 $GtCO_2$. 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017.

Remaining budgets ($GtCO_2$) Additional warming from 2006-2015 °C	**FAIR RNCFC** (Wm^{-2})	**FAIR**		
		TCRE 33%	TCRE 50%	TCRE 67%
0.3	0.191	363	168	45
0.4	0.211	629	368	204
0.5	0.232	893	568	362
0.6	0.253	1157	767	521
0.63	0.259	1237	827	568
0.7	0.273	1423	967	680
0.8	0.294	1687	1166	838
0.9	0.314	1952	1366	997
1	0.335	2216	1566	1155
1.1	0.356	2481	1765	1314
1.13	0.362	2560	1825	1361
1.2	0.376	2746	1965	1473

2.A.1.2.3 Uncertainties

Uncertainties are explored across several lines of evidence and summarised in Table 2.2 of the main report. Expert judgement is both used to estimate an overall uncertainty estimate and the estimate to remove 100 $GtCO_2$ to account for possible missing permafrost and wetlands feedbacks (see Section 2.2). The uncertainty in the warming to the base period (1850–1900 to 2006–2015) estimated in Chapter 1 is 0.87°C with a ±0.12 °C *likely* (1-σ) range affects how close warming since preindustrial levels is to the 1.5°C and

2°C limits, so the remaining budgets for a range of future warming thresholds between 0.3 and 1.2 °C above present-day are analysed. The uncertainty in 2006–2015 warming compared to 1850–1900 relates to a ±250 $GtCO_2$ uncertainty in carbon budgets for a best estimate TCRE.

A measure of the uncertainty due to variations in the consistent level of non-CO_2 mitigation at the time net-zero CO_2 emissions are reached in pathways is analysed by a quantile regression of each pathway's median peak temperature against its corresponding median RNCTC (evaluated with the FAIR model), for the 5th, median and 95th percentiles of scenarios. A variation of approximately ±0.1°C around the median RNCTC is observed for median peak temperatures between 0.3 and 1.2°C above the 2006-2015 mean. This variation is equated to a ±250 $GtCO_2$ uncertainty in carbon budgets for a median TCRE estimate of about 0.45°C per 1000 $GtCO_2$. An uncertainty of -400 to +200 $GtCO_2$ is associated with the non-CO_2 forcing and response. This is analysed from a regression of 5th and 95th percentile RNCTC against 5th and 95th percentile peak temperature calculated with FAIR, compared to the median RNCTC response. These uncertainty contributions are shown in Table 2.2 in the main chapter

The effects of uncertainty in the TCRE distribution was gauged by repeating the remaining budget estimate for a log-normal distribution of the AR5 *likely* range. This reduces the median TCRE from 0.45 °C per 1000 $GtCO_2$ to 0.38°C per 1000 $GtCO_2$ (see Table 2A.1). Table 2.A.4 presents these remaining budgets and shows that around 200 $GtCO_2$ would be added to the budget by assuming a log-normal *likely* range. The assessment and evidence supporting either distribution is discussed in the main chapter.

Table 2.A.4: Remaining carbon dioxide budget from 1.1.2018 reduced by the effect of non-CO_2 forcers. Numbers are differences between estimates of the remaining budget made with the log-normal distribution compared to that estimated with a normal distribution of TCRE based on the AR5 *likely* range (see Table 2.A.1). 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017. This method employed the FAIR model RNCTC estimates of non-CO_2 temperature response.

Remaining budgets ($GtCO_2$) Additional warming from 2006-2015 °C	**Log-normal minus normal TCRE distribution** TCRE 33%	 TCRE 50%	 TCRE 67%
0.3	110	89	50
0.4	146	118	66
0.5	183	148	82
0.6	219	177	99
0.63	230	186	103
0.7	255	207	115
0.8	291	236	131
0.9	328	265	148
1	364	294	164
1.1	400	324	180
1.13	411	333	185
1.2	436	353	197

Uncertainties in past CO_2 emissions ultimately impact estimates of the remaining carbon budgets for 1.5°C or 2°C. Uncertainty in CO_2 emissions induced by past land-use and land-cover changes contributes most, representing about 240 $GtCO_2$ from 1870 to 2017. Yet, this uncertainty is substantially reduced when deriving cumulative CO_2 emissions from a recent period. The cumulative emissions from the 2006–2015 reference period to 2017 used employed in this report are approximately 290 $GtCO_2$ with an uncertainty of about 20 $GtCO_2$.

2.A.2 Integrated Assessment Models

The set of process-based integrated assessment models (IAMs) that provided input to this assessment is not fundamentally different from those underlying the IPCC AR5 assessment of transformation pathways (Clarke et al., 2014) and an overview of these integrated modelling tools can be found there. However, there have been a number of model developments since AR5, in particular improving the sectorial detail of IAMs (Edelenbosch et al., 2017b), the representation of solar and wind energy (Creutzig et al., 2017; Johnson et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017), the description of bioenergy and food production and associated sustainability trade-offs (Havlík et al., 2014; Weindl et al., 2017; Bauer et al., 2018; Frank et al., 2018), the representation of a larger portfolio of carbon dioxide removal (CDR) technologies (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b), the accounting of behavioural change (McCollum et al., 2016; van Sluisveld et al., 2016; van Vuuren et al., 2018) and energy demand developments (Edelenbosch et al., 2017a, c; Grubler et al., 2018), and the modelling of sustainable development implications (van Vuuren et al., 2015; Bertram et al., 2018), for example, relating to water use (Bonsch et al., 2014; Hejazi et al., 2014; Fricko et al., 2016; Mouratiadou et al., 2016, 2018), access to clean water and sanitation (Parkinson et al., 2017), materials use (Pauliuk et al., 2017), energy access (Cameron et al., 2016), air quality (Rao et al., 2017), and bioenergy use and food security (Frank et al., 2017; Humpenöder et al., 2018). Furthermore, since AR5, a harmonised model documentation of IAMs and underlying assumptions has been established within the framework of the EU ADVANCE project, and made available at http://www.fp7-advance.eu/content/model-documentation.

2.A.2.1 Short introduction to the scope, use and limitations of integrated assessment modelling

IAMs are characterised by a dynamic representation of coupled systems, including energy, land, agricultural, economic and climate systems (Weyant, 2017). They are global in scope, and typically cover sufficient sectors and sources of greenhouse gas emissions to project anthropogenic emissions and climate change and identify consistency of different pathways with long-term goals of limiting warming to specific levels (Clarke et al., 2014). IAMs can be applied in a forward-looking manner to explore internally consistent socio-economic-climate futures, often extrapolating current trends under a range of assumptions or using counterfactual “no policy” assumptions to generate baselines for subsequent climate policy analysis. They can also be used in a back-casting mode to explore the implications of climate policy goals and climate targets for systems transitions and near-to-medium term action. In most IAM-based studies, both applications of IAMs are used concurrently (Clarke et al., 2009; Edenhofer et al., 2010; Luderer et al., 2012; Kriegler et al., 2014, 2015b, 2016; Riahi et al., 2015; Tavoni et al., 2015). Sometimes the class of IAMs is defined more narrowly as the subset of integrated pathway models with an economic core and equilibrium assumptions on supply and demand, although non-equilibrium approaches to integrated assessment modelling exist (Guivarch et al., 2011; Mercure et al., 2018). IAMs with an economic core describe consistent price-quantity relationships, where the “shadow price” of a commodity generally reflects its scarcity in the given setting. To this end, the price of greenhouse gas emissions emerging in IAMs reflects the restriction of future emissions imposed by a warming limit (Cross-chapter Box 5 in Chapter 2, Section 2.A.2.2). Such price needs to be distinguished from suggested levels of emissions pricing in multi-dimensional policy contexts that are adapted to existing market environments and often include a portfolio of policy instruments (Section 2.5.2) (Stiglitz et al., 2017).

Detailed-process IAMs that describe energy-land transitions on a process level are critically different from stylized cost-benefit IAMs that aggregate such processes into stylized abatement cost and climate damage relationships to identify cost-optimal responses to climate change (Weyant, 2017). A key component of cost-benefit IAMs is the representation of climate damages which has been debated in the recent literature (Revesz et al., 2014; Cai et al., 2015; Lontzek et al., 2015; Burke et al., 2016; Stern, 2016). In the meantime, new approaches and estimates for improving the representation of climate damages are emerging (Dell et al., 2014; Burke et al., 2015, 2018; Hsiang et al., 2017) (Chapter 3 Box 3.6). A detailed discussion of the strengths and weaknesses of cost-benefit IAMs is provided in AR5 (Clarke et al., 2014; Kolstad et al., 2014; Kunreuther et al., 2014) (see also Cross-Chapter Box 5 in Chapter 2). The assessment of 1.5°C-consistent pathways in Chapter 2 relies entirely on detailed-process IAMs. These IAMs have so far rarely attempted a full representation of climate damages on socio-economic systems for mainly three reasons: a focus on the implications of mitigation goals for transition pathways (Clarke et al., 2014), the computational challenge to represent, estimate and integrate the complete range of climate impacts on a process level (Warszawski et al., 2014), and ongoing fundamental research on measuring the breadth and depth of how bio-physical climate impacts can affect societal welfare (Dennig et al., 2015; Adler et al., 2017; Hallegatte and Rozenberg, 2017). While some detailed-process IAMs account for climate impacts in selected sectors, e.g. agriculture (Stevanović et al., 2016), these IAMs do not take into account climate impacts as a whole in their pathway modelling. 1.5°C and 2°C-consistent pathways available to this report hence do not reflect climate impacts and adaptation challenges below 1.5°C and 2°C, respectively. Pathway modelling to date is also not able to identify socio-economic benefits of avoided climate damages between 1.5°C-consistent pathways and pathways leading to higher warming levels. These limitations are important knowledge gaps (Section 2.6) and subject of active research. Due to these limitations, the use of the integrated pathway literature in this report is concentrated on the assessment of mitigation action to limit warming to 1.5°C, while the assessment of impacts and adaptation challenges in 1.5°C warmer worlds relies on a different body of literature (see Chapters 3 to 5).

The use of IAMs for climate policy assessments has been framed in the context of solution-oriented assessments (Edenhofer and Kowarsch, 2015; Beck and Mahony, 2017). This approach emphasizes the exploratory nature of integrated assessment modelling to produce scenarios of internally consistent, goal-oriented futures. They describe a range of pathways that achieve long-term policy goals, and at the same time highlight trade-offs and opportunities associated with different courses of action. This literature has noted, however, that such exploratory knowledge generation about future pathways cannot be completely isolated from societal discourse, value formation and decision making and therefore needs to be reflective of its performative character (Edenhofer and Kowarsch, 2015; Beck and Mahony, 2017). This suggests an interactive approach which engages societal values and user perspectives in the pathway production process. It also requires transparent documentation of IAM frameworks and applications to enable users to contextualize pathway results in the assessment process. Integrated assessment modelling results assessed in AR5 were documented in Annex II of AR5 (Krey et al., 2014b), and this Annex aims to document the IAM frameworks that fed into the assessment of 1.5°C-consistent pathways in Chapter 2 of this report. It draws upon increased efforts to extend and harmonize IAM documentations[1] (Section 2.A.2.5). Another important aspect for the use of IAMs in solution-oriented assessments is trust building in their applicability and validity. The literature has discussed approaches to IAM evaluation (Schwanitz, 2013; Wilson et al., 2017), including model diagnostics (Kriegler et al., 2015a; Wilkerson et al., 2015; Craxton et al., 2017) and comparison with historical developments (Wilson et al., 2013; van Sluisveld et al., 2015).

2.A.2.2. Economics and Policy Assumptions in IAMs

Experiments with IAMs most often create scenarios under idealised policy conditions which assume that climate change mitigation measures are undertaken where and when they are the most effective (Clarke et al., 2014). Such 'idealised implementation' scenarios assume that a global price on GHG emissions is implemented across all countries, all economic sectors, and rises over time through 2100 in a way that will minimise discounted economic costs. The emissions price reflects marginal abatement costs and is often used as a proxy of climate policy costs (see Section 2.5.2). Scenarios developed under these assumptions are often referred to as 'least-cost' or 'cost-effective' scenarios because they result in the lowest aggregate global mitigation costs when assuming that global markets and economies operate in a frictionless, idealised way (Clarke et al., 2014; Krey et al., 2014b). However, in practice, the feasibility (see Cross-Chapter Box 3 in Chapter 1) of a global carbon pricing mechanism deserves careful consideration (see Chapter 4.4). Scenarios from idealised conditions provide benchmarks for policy makers, since deviations from the idealized approaches capture important challenges for socio-technical and economic systems and resulting climate outcomes.

Model experiments diverging from idealised policy assumptions aim to explore the influence of policy barriers to implementation of globally cost-effective climate change mitigation, particularly in the near term. Such scenarios are often referred to as 'second-best' scenarios. They include, for instance, (i) fragmented

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[1] FOOTNOTE: http://www.fp7-advance.eu/content/model-documentation

policy regimes in which some regions champion immediate climate mitigation action (e.g. 2020) while other regions join this effort with a delay of one or more decades (Clarke et al., 2009; Blanford et al., 2014; Kriegler et al., 2015b), (ii) prescribed near-term mitigation efforts (until 2020 or 2030) after which a global climate target is adopted (Luderer et al., 2013, 2016; Rogelj et al., 2013b; Riahi et al., 2015), or (iii) variations in technology preferences in mitigation portfolios (Edenhofer et al., 2010; Luderer et al., 2012; Tavoni et al., 2012; Krey et al., 2014a; Kriegler et al., 2014; Riahi et al., 2015; Bauer et al., 2017, 2018). Energy transition governance adds a further layer of potential deviations from cost-effective mitigation pathways and has been shown to lead to potentially different mitigation outcomes (Trutnevyte et al., 2015; Chilvers et al., 2017; Li and Strachan, 2017). Governance factors are usually not explicitly accounted for in IAMs.

Pricing mechanisms in IAMs are often augmented by assumptions about regulatory and behavioural climate policies in the near- to mid-term (Bertram et al., 2015; van Sluisveld et al., 2016; Kriegler et al., 2018). The choice of GHG price trajectory to achieve a pre-defined climate goal varies across IAMs and can affect the shape of mitigation pathways. For example, assuming exponentially increasing CO_2 pricing to stay within a limited CO_2 emissions budget is consistent with efficiency considerations in an idealized economic setting, but can lead to temporary overshoot of the carbon budget if carbon dioxide removal (CDR technologies) are available. The pricing of non-CO_2 greenhouse gases is often pegged to CO_2 pricing using their global warming potentials (mostly GWP_{100}) as exchange rates (see Cross-Chapter Box 2 in Chapter 1). This leads to stringent abatement of non-CO_2 gases in the medium- to long-term, but also incentivizes continued compensation of these gases by CDR even after their full abatement potential is exploited, thus contributing to the pattern of peaking and declining temperatures in many mitigation pathways.

The choice of economic discount rate is usually reflected in the increase of GHG pricing over time and thus also affects the timing of emissions reductions. For example, the deployment of capital-intensive abatement options like renewable energy can be pushed back by higher discount rates. IAMs make different assumptions about the discount rate, with many of them assuming a social discount rate of ca. 5% per year (Clarke et al., 2014). In a survey of modelling teams contributing scenarios to the database for this assessment, discount rate assumptions varied between 2%/year and 8%/year depending on whether social welfare considerations or the representation of market actor behaviour is given larger weight. Some IAMs assume fixed charge rates that can vary by sector taking into account that private actors require shorter time horizons to amortize their investment. The impact of the choice of discount rate on mitigation pathways is underexplored in the literature. In general, the choice of discount rate is expected to have smaller influence on low-carbon technology deployment schedules for tighter climate targets as they leave less flexibility in the timing of emissions reductions. However, the introduction of large-scale CDR options might increase sensitivity again. It was shown, for example, that if a long-term CDR option like direct air capture with CCS (DACCS) is introduced in the mitigation portfolio, lower discount rates lead to more early abatement and less CDR deployment (Chen and Tavoni, 2013). If discount rates vary across regions, with higher costs of capital in developing countries, industrialized countries mitigate more and developing countries less at higher overall mitigation costs compared to a case with globally uniform discounting (Iyer et al., 2015). More work is needed to study the sensitivity of the deployment schedule of low-carbon technologies to the choice of the discount rate. However, as overall emissions reductions need to remain consistent with the choice of climate goal, mitigation pathways from detailed process-based IAMs are still less sensitive to the choice of discount rate than cost-optimal pathways from cost-benefit IAMs (see Box 6.1 in Clarke et al., 2014) which have to balance near-term mitigation with long-term climate damages across time (Nordhaus, 2005; Dietz and Stern, 2008; Kolstad et al., 2014; Pizer et al., 2014) (see Cross-Chapter Box 5 in Chapter 2).

2.A.2.3. Technology assumptions and transformation modelling

Although model-based assessments project drastic near, medium and long-term transformations in 1.5°C scenarios, projections also often struggle to capture a number of hallmarks of transformative change, including disruption, innovation, and nonlinear change in human behaviour (Rockström et al., 2017). Regular revisions and adjustments are standard for expert and model projections, for example, to account for new information such as the adoption of the Paris Agreement. Costs and deployment of mitigation technologies will differ in reality from the values assumed in the full-century trajectories of the model results. CCS and nuclear provide examples of where real-world costs have been higher than anticipated (Grubler, 2010; Rubin et al., 2015) while solar PV is an example where real-world costs have been lower (Creutzig et al., 2017; Figueres et al., 2017; Haegel et al., 2017). Such developments will affect the low-carbon transition for achieving stringent mitigation targets. This shows the difficulty of adequately estimating social and technological transitions and illustrates the challenges of producing scenarios consistent with a quickly evolving market (Sussams and Leaton, 2017).

Behavioural and institutional frameworks affect the market uptake of mitigation technologies and socio-technical transitions (see Chapter 4.4). These aspects co-evolve with technology change and determine, among others, the adoption and use of low-carbon technologies (Clarke et al., 2014), which in turn can affect both the design and performance of policies (Kolstad et al., 2014; Wong-Parodi et al., 2016). Pre-determining technological change in models can preclude the examination of policies that aim to promote disruptive technologies (Stanton et al., 2009). In addition, knowledge creation, networks, business strategies, transaction costs, microeconomic decision-making processes and institutional capacities influence (no-regret) actions, policy portfolios and innovation processes (and vice versa) (Mundaca et al., 2013; Lucon et al., 2014; Patt, 2015; Wong-Parodi et al., 2016; Geels et al., 2017); however, they are difficult to capture in equilibrium or cost-minimisation model-based frameworks (Laitner et al., 2000; Wilson and Dowlatabadi, 2007; Ackerman et al., 2009; Ürge-Vorsatz et al., 2009; Mundaca et al., 2010; Patt et al., 2010; Brunner and Enting, 2014; Grubb et al., 2014; Patt, 2015; Turnheim et al., 2015; Geels et al., 2017; Rockström et al., 2017). It is argued that assessments that consider greater end-user heterogeneity, realistic market behaviour, and end-use technology details can address a more realistic and varied mix of policy instruments, innovation processes and transitional pathways (Ürge-Vorsatz et al., 2009; Mundaca et al., 2010; Wilson et al., 2012; Lucon et al., 2014; Li et al., 2015; Trutnevyte et al., 2015; McCollum et al., 2016; Geels et al., 2017). So-called 'rebound' effects in which behavioural changes partially offset policies, such as consumers putting less effort into demand reduction when efficiency is improved, are captured to a varying and in many cases only limited degree in IAMs.

There are also substantial variation in mitigation options represented in IAMs (see Section 2.A.2.6) which depend, on the one hand, on the constraints of individual modelling frameworks and on the other hand on model development decisions influenced by modellers' beliefs and preferences (Section 2.3.1.2). Further limitations can arise on the system level. For example, trade-offs between material use for energy versus other uses are not fully captured in many IAMs (e.g. petroleum for plastics, biomass for material substitution). An important consideration for the analysis of mitigation potential is the choice of baseline. For example, IAMs often assume, in line with historical experience, that economic growth leads to a reduction in local air pollution as populations become richer (i.e. an environmental Kuznets curve) (Rao et al., 2017). In such cases, the mitigation potential is small because reference emissions that take into account this economic development effect are already low in scenarios that see continued economic development over their modelling time horizon. Assumptions about reference emissions are important because high reference emissions lead to high perceived mitigation potentials and potential overestimates of the actual benefit, while low reference emissions lead to low perceived benefits of mitigation measures and thus less incentive to address these important climate and air pollutants (Gschrey et al., 2011; Shindell et al., 2012; Amann et al., 2013; Rogelj et al., 2014; Shah et al., 2015; Velders et al., 2015).

2.A.2.4. Land use and bioenergy modelling in IAMs

The IAMs used in the land use assessment in this chapter and that are based on the SSPs (Popp et al., 2017; Riahi et al., 2017) all include an explicit land model.[2] These land models calculate the supply of food, feed, fiber, forestry, and bioenergy products (see also Chapter 2 Box 2.1). The supply depends on the amount of land allocated to the particular good, as well as the yield for the good. Different IAMs have different means of calculating land allocation and different assumptions about yield, which is typically assumed to increase

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[2] FOOTNOTE: There are other IAMs that do not include an explicit land use representation. These models use supply curves to represent bioenergy; that is, they have an exogenously specified relationship between the quantity of bioenergy supplied and the price of bioenergy. These models include land use change emissions in a similar manner, with the amount of emissions depending on the amount of bioenergy supplied. For some of these models, LUC emissions are assumed to be zero, regardless of the amount of bioenergy.

over time reflecting technological progress in the agricultural sector (see (Popp et al., 2014) for examples). In these models, the supply of bioenergy (including BECCS) depends on the price and yield of bioenergy, the policy environment (e.g., any taxes or subsidizes affecting bioenergy profits), as well the demand for land for other purposes. Dominant bioenergy feedstocks assumed in IAMs are woody and grassy energy crops (2nd generation biomass) in addition to residues. Some models implement a "food first" approach, where food demands are met before any land is allocated to bioenergy. Other models use an economic land allocation approach, where bioenergy competes with other land uses depending on profitability. Competition between land uses depend strongly on socio-economic drivers such as population growth and food demand, and are typically varied across scenarios. When comparing global bioenergy yields from IAMs with the bottom-up literature, care must be taken that assumptions are comparable. An in-depth assessment of the land-use components of IAMs is outside the scope of this Special Report.

In all IAMs that include a land model, the land-use change emissions associated with these changes in land allocation are explicitly calculated. Most IAMs use an accounting approach to calculating land use change emissions, similar to Houghton (Houghton et al., 2012). These models calculate the difference in carbon content of land due to the conversion from one type to another, and then allocate that difference across time in some manner. For example, increases in forest cover will increase terrestrial carbon stock, but that increase may take decades to accumulate. If forestland is converted to bioenergy, however, those emissions will enter the atmosphere more quickly.

IAMs often account for carbon flows and trade flows related to bioenergy separately. That is, IAMs may treat bioenergy as "carbon neutral" in the energy system, in that the carbon price does not affect the cost of bioenergy. However, these models will account for any land-use change emissions associated with the land conversions needed to produce bioenergy. Additionally, some models will separately track the carbon uptake from growing bioenergy and the emissions from combusting bioenergy (assuming it is not combined with CCS).

Table 2.A.5: Land-use types descriptions as reported in pathways (adapted from the SSP database: https://tntcat.iiasa.ac.at/SspDb/)

Land use type	Description/examples
Energy crops	Land dedicated to second generation energy crops. (e.g., switchgrass, miscanthus, fast-growing wood species)
Other crops	Food and feed/fodder crops
Pasture	Pasture land. All categories of pasture land - not only high quality rangeland. Based on FAO definition of "permanent meadows and pastures"
Managed forest	Managed forests producing commercial wood supply for timber or energy but also afforestation (note: woody energy crops are reported under "energy crops")
Natural forest	Undisturbed natural forests, modified natural forests and regrown secondary forests
Other natural land	Unmanaged land (e.g., grassland, savannah, shrubland, rock ice, desert), excluding forests

2.A.2.5. Contributing modelling framework reference cards

For each of the contributing modelling frameworks a reference card has been created highlighting the key features of the model. These reference cards are either based on information received from contributing modelling teams upon submission of scenarios to the SR1.5 database, or alternatively drawn from the ADVANCE IAM wiki documentation, available at http://www.fp7-advance.eu/content/model-documentation, and updated. These reference cards are provided in part II of this annex.

2.A.2.6 Overview mitigation measures in contributed IAM scenarios

Table 2.A.6: Overview of representation of mitigation measures in the integrated pathway literature, as submitted to the database supporting this report. Levels of inclusion have been elicited directly from contributing modelling teams by means of a questionnaire. The table shows the reported data. Dimensions of inclusion are explicit versus implicit, and endogenous or exogenous. An implicit level of inclusion is assigned when a mitigation measure is represented by a proxy like a marginal abatement cost curve in the AFOLU sector without modelling individual technologies or activities. An exogenous level of inclusion is assigned when a mitigation measure is not part of the dynamics of the modelling framework but can be explored through alternative scenarios.

Levels of inclusion

	Explicit	Implicit
Endogenous	**A**	C
Exogenous	B	D

E Not represented by model

Model names	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Demand side measures																					
Energy efficiency improvements in energy end uses (e.g., appliances in buildings, engines in transport, industrial processes)	**A**	**A**	C	D	**A**	D	B	D	B	**A**	**A**	**A**	**A**	**A**	C	C	B	C	C	B	C
Electrification of transport demand (e.g., electric vehicles, electric rail)	**A**	**A**	**A**	D	**A**	**A**	B	**A**	**A**	**A**	**A**	**A**	**A**	**A**	C	**A**	**A**	**A**	**A**	B	**A**
Electrification of energy demand for buildings (e.g., heat pumps, electric/induction stoves)	**A**	**A**	**A**	D	**A**	**A**	B	**A**	D	**A**	**A**	C	C	**A**	C	**A**	**A**	**A**	C	B	C
Electrification of industrial energy demand (e.g., electric arc furnace, heat pumps, electric boilers, conveyor belts, extensive use of motor control, induction heating, industrial use of microwave heating)	**A**	**A**	C	D	**A**	C	D	**A**	D	**A**	**A**	C	C	**A**	C	**A**	**A**	C	C	B	E
CCS in industrial process applications (cement, pulp and paper, iron steel, oil and gas refining, chemicals)	**A**	E	**A**	D	D	**A**	E	E	C	**A**	**A**	E	E	**A**	E	**A**	**A**	E	**A**	B	C
Higher share of useful energy in final energy (e.g., insulation of buildings, lighter weight vehicles, combined heat and power generation, district heating, …)	C	E	C	D	**A**	C	D	D	C	B	B	D	D	**A**	C	**A**	**A**	**A**	C	D	E
Reduced energy and service demand in **industry** (e.g., process innovations, better control)	C	C	C	D	C	C	C	D	D	B	B	C	C	B	C	C	B	B	C	C	D
Reduced energy and service demand in **buildings** (e.g., via behavioural change, reduced material and floor space demand, infrastructure and buildings configuration)	C	C	C	D	C	C	C	D	D	C	C	D	D	C	C	C	B	B	C	C	E
Reduced energy and service demand in **transport** (e.g., via behavioural change, new mobility business models, modal shift in individual transportation, eco-driving, car/bike-sharing schemes)	C	C	C	D	C	**A**	B	D	B	B	C	C	C	C	C	C	B	B	C	C	E
Reduced energy and service demand in **international transport** (international shipping and aviation)	**A**	E	**A**	D	D	**A**	C	E	B	B	B	C	C	C	C	B	B	**A**	D	C	E
Reduced material demand via higher resource efficiency, structural change, behavioural change and material substitution (e.g., steel and cement substitution, use of locally available building materials)	**A**	E	E	D	D	D	C	E	D	B	B	E	E	B	E	D	B	E	C	C	E
Urban form (incl. integrated on-site energy, influence of avoided transport and building energy demand)	E	E	E	D	D	E	E	D	E	B	E	D	D	E	E	E	B	E	E	C	E

Levels of inclusion

	Explicit	Implicit
Endogenous	**A**	C
Exogenous	B	D

E Not represented by model

Levels of inclusion	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Switch from traditional biomass and solid fuel use in the residential sector to modern fuels, or enhanced combustion practices, avoiding wood fuel	D	**A**	**A**	D	D	B	E	**A**	**A**	**A**	**A**	E	E	**A**	E	**A**	**A**	B	D	C	**A**
Dietary changes, reducing meat consumption	**A**	E	E	D	D	**A**	E	E	B	E	E	E	E	B	E	B	B	B	B	E	E
Substitution of livestock-based products with plant-based products (cultured meat, algae-based fodder)	C	E	E	D	E	E	E	E	E	E		E	E	B	E	E	E	E	E	E	E
Food processing (e.g., use of renewable energies, efficiency improvements, storage or conservation)	C	E	E	D	E	E	E	E	E	C	C	E	E	E	E	B	B	E	D	E	E
Reduction of food waste (incl. reuse of food processing refuse for fodder)	B	E	E	D	E	D	E	E	E	E	E	E	E	B	E	B	B	E	B	E	E
Supply side measures																					
Decarbonisation of electricity:																					
Solar PV	**A**	**A**	**A**	D	**A**	**A**	B	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**
Solar CSP	E	E	**A**	D	E	**A**	E	**A**	E	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**
Wind (on-shore and off-shore)	**A**	**A**	**A**	D	**A**	**A**	B	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**
Hydropower	**A**	**A**	**A**	D	**A**	**A**	B	**A**	**A**	**A**	**A**	**A**	**A**	B	**A**	**A**	**A**	**A**	**A**	**A**	**A**
Bio-electricity, including biomass co-firing	**A**	**A**	**A**	D	**A**	**A**	B	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**
Nuclear energy	**A**	**A**	**A**	D	**A**	**A**	B	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**
Advanced, small modular nuclear reactor designs (SMR)	E	E	**A**	D	E	**A**	E	E	E	C	C	E	E	E	**A**	E	E	E	E	C	E
Fuel cells (hydrogen)	E	E	**A**	D	**A**	**A**	E	**A**	**A**	**A**	**A**	E	E	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**
CCS at coal and gas-fired power plants	**A**	**A**	**A**	D	**A**	**A**	B	E	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	E	**A**	**A**	B	**A**
Ocean energy (incl. tidal and current energy)	E	E	E	D	E	E	D	**A**	E	**A**	**A**	E	E	E	E	E	E	**A**	E	**A**	E
High-temperature geothermal heat	**A**	B	**A**	D	**A**	**A**	D	E	**A**	**A**	**A**	E	E	B	E	**A**	**A**	**A**	E	C	E
Decarbonisation of non-electric fuels:																					
Hydrogen from biomass or electrolysis	E	**A**	**A**	D	**A**	**A**	E	**A**	**A**	**A**	C	E	E	**A**	**A**	**A**	**A**	**A**	**A**	**A**	E
1st generation biofuels	**A**	E	**A**	D	**A**	**A**	B	E	**A**	**A**	**A**	C	**A**	**A**	**A**	B	B	**A**	B	**A**	**A**
2nd generation biofuels (grassy or woody biomass to liquids)	**A**	**A**	**A**	D	**A**	**A**	D	**A**	**A**	**A**	**A**	E	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**
Algae biofuels	E	E	**A**	D	E	E	E	C	E	E	C	E	E	E	E	E	E	E	E	**A**	E
Power-to-gas, methanisation, synthetic fuels	E	C	**A**	D	**A**	E	E	**A**	E	E	B	E	E	E	**A**	**A**	**A**	E	E	E	E
Solar and geothermal heating	E	E	**A**	D	E	E	B	**A**	E	**A**	**A**	E	E	E	E	**A**	**A**	**A**	**A**	**A**	E

Levels of inclusion

	Explicit	Implicit
Endogenous	**A**	C
Exogenous	B	D

E	Not represented by model

Levels of inclusion	**Model names**																				
	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Nuclear process heat	E	E	E	D	E	E	E	E	E	**A**	**A**	E	E	E	E	**A**	**A**	E	E	C	E
Other processes:																					
Fuel switching and replacing fossil fuels by electricity in end-use sectors (partially a demand-side measure)	**A**	**A**	C	D	**A**	**A**	B	**A**	**A**	**A**	**A**	C	C	**A**	C	**A**	**A**	**A**	**A**	**A**	B
Substitution of halocarbons for refrigerants and insulation	C	E	E	D	E	C	C	E	E	E	E	E	E	**A**	E	**A**	**A**	**A**	D	E	C
Reduced gas flaring and leakage in extractive industries	C	E	**A**	D	D	C	C	E	E	E	**A**	E	E	C	E	B	B	**A**	C	D	D
Electrical transmission efficiency improvements, including smartgrids	B	E	C	D	**A**	E	E	E	E	B	B	E	E	B	C	E	E	E	E	B	E
Grid integration of intermittent renewables	E	E	C	D	**A**	C	E	C	D	**A**	**A**	E	E	C	C	C	C	**A**	**A**	D	C
Electricity storage	E	E	**A**	D	**A**	C	E	**A**	E	**A**	C	E	E	C	C	**A**	**A**	**A**	**A**	E	C
AFOLU measures																					
Reduced deforestation, forest protection, avoided forest conversion	**A**	E	**A**	D	B	**A**	E	E	B	D	D	E	E	B	E	**A**	**A**	B	B	D	C
Forest management	C	E	E	D	E	C	E	E	C	D	D	E	E	B	E	**A**	**A**	B	E	D	C
Reduced land degradation, and forest restoration	C	E	D	D	E	E	E	E	C	D	D	E	E	B	E	E	E	B	C	D	E
Agroforestry and silviculture	E	E	D	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Urban and peri-urban agriculture and forestry	E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Fire management and (ecological) pest control	C	E	D	D	E	C	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Changing agricultural practices enhancing soil carbon	C	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	B	E	D	E
Conservation agriculture	E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	**A**	**A**	E	E	E	C
Increasing agricultural productivity	**A**	E	**A**	D	**A**	B	E	E	B	D	D	E	**A**	B	E	**A**	**A**	E	**A**	D	C
Methane reductions in rice paddies	C	E	C	D	C	C	C	E	C	D	D	E	C	C	E	**A**	**A**	B	C	D	C
Nitrogen pollution reductions, e.g., by fertilizer reduction, increasing nitrogen fertilizer efficiency, sustainable fertilizers	C	E	C	D	C	C	C	E	E	D	D	E	**A**	C	E	**A**	**A**	B	C	D	C
Livestock and grazing management, for example, methane and ammonia reductions in ruminants through feeding management or feed additives, or manure management for local biogas production to replace traditional biomass use	C	E	C	D	C	C	C	E	C	D	D	E	**A**	C	E	**A**	**A**	B	C	D	C
Manure management	C	E	C	D	C	C	C	E	C	D	D	E	C	C	E	**A**	**A**	E	C	E	C
Influence on land albedo of land use change	E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	D	D	E
Carbon dioxide (greenhouse gas) removal																					

	Explicit	Implicit
Endogenous	**A**	C
Exogenous	B	D

E Not represented by model

Levels of inclusion	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Biomass use for energy production with carbon capture and sequestration (BECCS) (through combustion, gasification, or fermentation)	**A**	**A**	**A**	D	**A**	**A**	E	E	**A**	**A**	**A**	**A**	**A**	**A**	**A**	**A**	E	**A**	**A**	B	**A**
Direct air capture and sequestration (DACS) of CO_2 using chemical solvents and solid absorbents, with subsequent storage	E	E	E	D	E	E	E	E	E	E	E	E	E	E	**A**	E	E	E	**A**	E	E
Mineralization of atmospheric CO_2 through enhanced weathering of rocks	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Afforestation / Reforestation	**A**	E	**A**	C	**A**	**A**	E	E	**A**	E	E	E	E	B	E	**A**	**A**	B	**A**	D	**A**
Restoration of wetlands (e.g., coastal and peat-land restoration, blue carbon)	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Biochar	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Soil carbon enhancement, enhancing carbon sequestration in biota and soils, e.g. with plants with high carbon sequestration potential (also AFOLU measure)	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	**A**	**A**	B	C	E	E
Carbon Capture and Usage – CCU; bioplastics (bio-based materials replacing fossil fuel uses as feedstock in the production of chemicals and polymers), carbon fibre	E	E	E	D	E	C	E	E	E	**A**	B	E	E	**A**	E	E	E	E	E	**A**	E
Material substitution of fossil CO_2 with bio-CO_2 in industrial application (e.g. the beverage industry)	E	E	E	D	E	C	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Ocean iron fertilization	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Ocean alkalinisation	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Removing CH_4, N_2O and halocarbons via photocatalysis from the atmosphere	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E

2.A.3 Overview of SR1.5 scenario database collected for the assessment in the Chapter

The scenario ensemble collected in the context of this report represents an ensemble of opportunity based on available published studies. The submitted scenarios cover a wide range of scenario types and thus allow exploration of a wide range of questions. For this to be possible, however, critical scenario selection based on scenario assumptions and setup is required. For example, as part of the SSP framework, a structured exploration of 1.5°C pathways was carried out under different future socioeconomic developments (Rogelj et al., 2018). This allows to determine the fraction of successful (feasible) scenarios per SSPs (Table 2.A.7), an assessment which cannot be carried out with a more arbitrary ensemble of opportunity.

Table 2.A.7: Summary of models (with scenarios in the database) attempting to create scenarios with an end-of-century forcing of 1.9W m^{-2}, consistent with limiting warming to below 1.5°C in 2100, and related SPAs. Notes: 1= successful scenario consistent with modelling protocol; 0= unsuccessful scenario; x= not modelled; 0*= not attempted because scenarios for a 2.6 W m^{-2} target were already found to be unachievable in an earlier study. SSP3-SPA3for a more stringent 1.9 W m^{-2} radiative forcing target has thus not been attempted anew by many modelling teams. Marker implementations for all forcing targets within each SSP are indicated in blue. Source: (Rogelj et al., 2018).

Model	Methodology	Reported scenario				
		SSP1-SPA1	SSP2-SPA2	SSP3-SPA3	SSP4-SPA4	SSP5-SPA5
AIM	General Equilibrium (GE)	1	1	0*	0	0
GCAM4	Partial Equilibrium (PE)	1	1	X	0	1
IMAGE	Hybrid (system dynamic models and GE for agriculture)	1	1	0*	X	X
MESSAGE-GLOBIOM	Hybrid (systems engineering PE model)	1	1	0*	X	X
REMIND-MAgPIE	General Equilibrium (GE)	1	1	X	X	1
WITCH-GLOBIOM	General Equilibrium (GE)	1	1	0	1	0

2.A.3.1 *Configuration of SR1.5 scenario database*

The Integrated Assessment Modelling Consortium (IAMC), as part of its ongoing cooperation with Working Group III of the IPCC, issued a call for submissions of scenarios of 1.5°C global warming and related scenarios to facilitate the assessment of mitigation pathways in this special report. This database is hosted by the International Institute for Applied Systems Analysis (IIASA) at http://data.ene.iiasa.ac.at/sr1p5/. Upon approval of this report, the database of scenarios underlying this assessment will also be published. Computer scripts and tools used to conduct the analysis and generate figures are also available for download from that website.

2.A.3.1.1 Criteria for submission to the scenario database

Scenarios submitted to the database were required to either aim at limiting warming to 1.5°C or 2°C in the long term, or to provide context for such scenarios, for example, corresponding NDC and baseline scenarios without climate policy. Model results should constitute an emissions trajectory over time with underlying socio-economic development until at least the year 2050 generated by a formal model such as a dynamic systems, energy-economy, partial or general equilibrium or integrated assessment model.

The end of the 21st century is referred to as “long term” in the context of this scenario compilation. For models with time horizons shorter than 2100, authors and/or submitting modelling teams were asked to explain how they evaluated their scenario as being consistent with 1.5°C in the long term. Ultimately, scenarios that only covered part of the 21st century could only to a very limited degree be integrated in the assessment, as the longer-term perspective was lacking. Submissions of emissions scenarios for individual regions and specific sectors were possible, but no such scenarios were received.

Each scenario submission required a supporting publication in a peer-reviewed journal that was accepted until 15 May 2018. Alternatively, the scenario must have been published by the same date in a report that has been determined by IPCC to be eligible grey literature (see Table 2.A.9). As part of the submission process, the authors of the underlying modelling team agreed to the publication of their model results in this scenario database.

2.A.3.1.2 Historical consistency analysis of submitted scenarios

Submissions to the scenario database were compared to the following data sources for historical periods to identify reporting issues.

Historical emissions database (CEDS)
Historical emissions imported from the *Community Emissions Data System (CEDS) for Historical Emissions* (http://www.globalchange.umd.edu/ceds/) have been used as a reference and for use in figures (van Marle et al., 2017; Hoesly et al., 2018). Historical N_2O emissions, which are not included in the CEDS database, are compared against the RCP database (http://tntcat.iiasa.ac.at/RcpDb/).

Historical IEA World Energy Balances and Statistics
Aggregated historical time series of the energy system from the IEA World Energy Balances and Statistics (revision 2017) were used as a reference for validation of submitted scenarios and for use in figures.

2.A.3.1.3 Verification of completeness and harmonization for climate impact assessment

Categorizing scenarios according to their long-term warming impact requires reported emissions time series until the end of the century of the following species: CO_2 from energy and industrial processes, methane, nitrous oxide and sulphur. The long-term climate impact could not be assessed for scenarios not reporting these species, and these scenarios were hence not included in any subsequent analysis.

For the diagnostic assessment of the climate impact of each submitted scenario, reported emissions were harmonized to historical values (base year 2010) as provided in the RCP database by applying an additive offset, which linearly decreased until 2050. For non-CO_2 emissions where this method resulted in negative values, a multiplicative offset was used instead. Emissions other than the required species that were not reported explicitly in the submitted scenario were filled from RCP2.6 (Meinshausen et al., 2011b; van Vuuren et al., 2011) to provide complete emissions profiles to MAGICC and FAIR (see section 2.A.1).

The harmonization and completion of non-reported emissions was only applied to the diagnostic assessment as input for the climate impact using MAGICC and FAIR. All figures and analysis used in the chapter analysis are based on emissions as reported by the modelling teams, except for column “cumulative CO_2 emissions, harmonized” in Table 2.A.12.

2.A.3.1.4 Validity assessment of historical emissions for aggregate Kyoto greenhouse gases

The AR5 WGIII report assessed Kyoto greenhouse gases (GHG) in 2010 to fall in the range of 44.5-53.5 $GtCO_2e$/yr using the GWP_{100}-metric from the IPCC Second Assessment Report. As part of the diagnostics, the Kyoto GHG aggregation was recomputed using GWP_{100} according to SAR, AR4 and AR5 for all scenarios that provided sufficient level of detail for their emissions. A total of 33 scenarios from three modelling frameworks showed recomputed Kyoto GHG outside the year-2010 range assessed by the AR5 WGIII report. These scenarios were excluded from all analysis of near-term emissions evolutions, in particular in Figures 2.6, 2.7 and 2.8, and Table 2.4.

2.A.3.1.5 Plausibility assessment of near-term development

Submitted scenarios were assessed for the plausibility of their near-term development across a number of dimensions. One issue identified were drastic reductions of CO_2 emissions from the land-use sector already in 2020. Given recent trends, this was considered implausible and all scenarios from the ADVANCE and EMF33 studies reporting negative CO_2 emissions from the land-use sector in 2020 were excluded from the analysis throughout this chapter.

2.A.3.1.6 Missing carbon price information

Out of the 132 scenarios limiting global warming to 2°C throughout the century (see Table 2.A.8), a total of twelve scenarios submitted by three modelling teams reported carbon prices of 0 or missing values in at least one year. These scenarios were excluded from the analysis.in Section 2.5 and Figure 2.26 in the chapter.

2.A.3.2. Contributions to the SR1.5 database by modelling framework

In total, 19 modelling frameworks submitted 529 individual scenarios based manuscripts that were published or accepted for publication by 15 May 2018 (Table 2.A.8).

Table 2.A.8: Overview of submitted scenarios by modelling framework, including the categorization according to the climate impact (cf. Section 2.A.4) and outcomes of validity and near-term plausibility assessment of pathways (cf. Section 2.A.3.1).

	Below-1.5°C	**1.5°C return with low OS**	**1.5°C return with high OS**	**Lower 2°C**	**Higher 2°C**	**Above 2°C**	**Scenarios assessed**	**Not full century**	**Missing emissions species for assessment**	**Negative CO^2 emissions (AFOLU) in 2020**	**Scenarios submitted**
AIM		6	1	24	10	49	**90**				**90**
BET									16		**16**
C-ROADS	2	1	2			1	**6**				**6**
DNE21+									21		**21**
FARM									13		**13**
GCAM		1	2	1	3	16	**23**			24	**47**
GEM-E3								4			**4**
GENeSYS-MOD								1			**1**
GRAPE									18		**18**
IEA ETP								1			**1**
IEA World Energy Model					1		**1**				**1**
IMACLIM								7	12		**19**
IMAGE		7	4	6	9	35	**61**				**61**
MERGE		1			1	1	**3**				**3**
MESSAGE		6	6	11	13	22	**58**				**58**
POLES	4	7	5	9	3	9	**37**				**37**
REMIND	2	11	17	16	16	31	**93**				**93**
Shell World Energy Model								1			**1**
WITCH	1	4		7	2	25	**39**				**39**
Total	**9**	**44**	**37**	**74**	**58**	**189**	**411**	**14**	**80**	**24**	**529**

2.A.3.3. Overview and scope of studies available in SR1.5 database

Table 2.A.9: Recent studies included in the scenario database that this chapter draws upon and their key foci indicating which questions can be explored by the scenarios of each study. The difference between “Scenarios submitted” and “Scenarios assessed” is due to criteria described in Section 2.A.3.1. The numbers between brackets indicate the modelling frameworks assessed.

Study/model name	**Key focus**	**Reference papers**	**Modelling frameworks**	**Scenarios submitted**	**Scenarios assessed**
Multi-model studies					
SSPx-1.9	Development of new community scenarios based on the full SSP framework limiting end-of-century radiative forcing to 1.9 W $m^{-2.}$	Riahi et al. (2017) Rogelj et al. (2018)	6	126	126
ADVANCE	Aggregate effect of the INDCs, comparison to optimal 2°C/1.5°C scenarios ratcheting up after 2020. Decarbonisation bottlenecks and the effects of following the INDCs until 2030 as opposed to ratcheting up to optimal ambition levels after 2020 in terms of additional emissions locked in. Constraint of 400 $GtCO_2$ emissions from energy and industry over 2011-2100.	Vrontisi et al. (2018) Luderer et al. (2018)	9 (6)	74	55
CD-LINKS	Exploring interactions between climate and sustainable development policies with the aim to identify robust integral policy packages to achieve all objectives. Evaluating implications of short-term policies on the mid-century transition in 1.5°C pathways linking the national to the global scale. Constraint of 400 $GtCO_2$ emissions over 2011-2100.	McCollum et al. (2018)	8 (6)	36	36
EMF-33	Study of the bioenergy contribution in deep mitigation scenarios. Constraint of 400 $GtCO_2$ emissions from energy and industry over 2011-2100.	Bauer et al. (2018)	11 (5)	183	86
Single-model studies					
IMAGE 1.5	Understanding the dependency of 1.5°C pathways on negative emissions.	van Vuuren et al. (2018)		8	8
IIASA LED (MESSAGEix)	A global scenario of Low Energy Demand (LED) for Sustainable Development below 1.5°C without Negative Emission Technologies.	Grubler et al. (2018)		1	1
GENeSYS-MOD	Application of the Open-Source Energy Modelling System to the question of 1.5°C and 2°C pathways.	Löffler et al. (2017)		1	0
IEA WEO	World Energy Outlook.	OECD/IEA and IRENA (2017)		1	1
OECD/IEA ETP	Energy Technology Perspectives.	IEA (2017)		1	0
PIK CEMICS (REMIND)	Study of CDR requirements and portfolios in 1.5°C pathways.	Strefler et al. (2018a)		7	7
PIK PEP (REMIND-MAgPIE)	Exploring short-term policies as entry points to global 1.5°C pathways.	Kriegler et al. (2018)		13	13
PIK SD (REMIND-MAgPIE)	Targeted policies to compensate risk to sustainable development in 1.5°C scenarios.	Bertram et al. (2018)		12	12
AIM SFCM	Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C.	Liu et al. (2017)		33	33
C-Roads	Interactions between emissions reductions and carbon dioxide removal.	Holz et al. (2018)		6	6
PIK EMC		Luderer et al. (2013)		8	8
MESSAGE GEA		Rogelj et al. (2013a, 2013b, 2015)		10	10
AIM TERL	The contribution of transport policies to the mitigation potential and cost of 2 °C and 1.5 °C goals	Zhang et al. (2018)		6	6
MERGE-ETL	The role of Direct Air Capture and Storage (DACS) in 1.5°C pathways.	Marcucci et al. (2017)		3	3
Shell SKY	A technically possible, but challenging pathway for society to achieve the goals of the Paris Agreement.	Shell International B.V. (2018)		1	0

2.A.3.4. Data collected

A reporting template was developed to facilitate the collection of standardized scenario results. The template was structured in nine categories, and each category was divided into four priority levels: “Mandatory”, “High priority (Tier 1)”, “Medium priority (Tier 2)”, and “Other”. In addition, one category was included to collect input assumptions on capital costs to facilitate the comparison across engineering-based models. An overview and definitions of all variables will be made available as part of the database publication.

Table 2.A.10: Number of variables (time series of scenario results) per category and priority level.

Category	Description	Mandatory (Tier 0)	High priority (Tier 1)	Medium priority (Tier 2)	Other	Total
Energy	Configuration of the energy system (for the full conversion chain of energy supply from primary energy extraction, electricity capacity, to final energy use)	19	91	83	0	193
Investment	Energy system investment expenditure	0	4	22	17	43
Emissions	Emissions by species and source	4	19	55	25	103
CCS	Carbon capture and sequestration	3	10	11	8	32
Climate	Radiative forcing and warming	0	11	2	8	21
Economy	GDP, prices, policy costs	2	15	25	7	49
SDG	Indicators on sustainable development goals achievement	1	9	11	1	22
Land	Agricultural production & demand	0	14	10	5	29
Water	Water consumption & withdrawal	0	0	16	1	17
Capital costs	Major electricity generation and other energy conversion technologies	0	0	0	31	31
Total		**29**	**173**	**235**	**103**	**540**

2.A.4 Scenario classification

A total of 529 scenarios were submitted to the scenario database. Of these, 14 scenarios did not report results until the end of the century and an additional 80 scenarios did not report the required emissions species. During the validation and diagnostics, 24 scenarios were excluded because of negative CO_2 emissions from the land-use sector by 2020 (see Section 2.A.3). Therefore, the analysis in this report is based on 411 scenarios, of which 90 scenarios are consistent with 1.5°C at the end of the century and 132 remain below 2°C throughout the century (not including the 90 scenarios that are deemed consistent with 1.5°C). Table 2.A.11 provides an overview of the number of scenarios per class. Table 2.A.12 provides an overview of geophysical characteristics per class.

Table 2.A.11: Overview of pathway class specifications

Pathway group	**Class name**	**Short name combined classes**	**MAGICC exceedance probability filter**	**Number of scenarios**
1.5°C	Below 1.5°C	-	**P(1.5°C) ≤ 0.34**	**0**
	Below 1.5°C	Below-1.5°C	**0.34 < P(1.5°C) ≤ 0.5**	**9**
	1.5°C Return with low OS	1.5°C-low-OS	**0.5 < P(1.5°C) ≤ 0.67** AND **P(1.5°C in 2100) ≤ 0.5**	**34**
			0.5 < P(1.5°C) ≤ 0.67 AND **0.34 < P(1.5°C in 2100) ≤ 0.5**	**10**
	1.5°C Return with high OS	1.5°C-high-OS	**0.67 < P(1.5°C)** AND **P(1.5°C in 2100) ≤ 0.34**	**19**
			0.67 < P(1.5°C) AND **0.34 < P(1.5°C in 2100) ≤ 0.5**	**18**
2°C	Lower 2°C	Lower-2°C	**P(2°C) ≤ 0.34** (excluding above)	**74**
	Higher 2°C	Higher-2°C	**0.34 < P(2°C) ≤ 0.5** (excluding above)	**58**
	Above 2°C	-	**0.5 < P(2°C)**	**189**

As noted in the chapter text, scenario classification was based on probabilistic temperature outcomes assessed using the AR5 assessment of composition, forcing and climate response. These were represented within the MAGICC model (Meinshausen et al., 2009, 2011a) which was used in the same setup as AR5 WGIII analyses. As discussed in Section 2.2, updates in geophysical understanding would alter such results were they incorporated within MAGICC, though central outcomes would remain well within the probability distribution of the setup used here (see Section 2.A.1).

Table 2.A.12: Geophysical characteristics of mitigation pathways derived at median peak temperature and at the end of the century (2100). Geophysical characteristics of overshoot for mitigation pathways exceeding 1.5°C is given in the last two columns. Overshoot severity is the sum of degree warming years exceeding 1.5°C over the 21st century. NA indicates that no mitigation pathways exhibits the given geophysical characteristics. Radiative forcing metrics are: total anthropogenic radiative forcing (RFall), CO_2 radiative forcing ($RFCO_2$), and non-CO_2 radiative forcing ($RFnonCO_2$). Cumulative CO2 emissions until peak warming or 2100 are given for submitted (Subm.) and harmonized (Harm.) IAM outputs and are rounded at the nearest 10 $GtCO_2$.

			Geophysical characteristics at peak warming											**Geophysical characteristics in 2100**									**Geophysical characteristics of the temperature overshoot**				
category	**# scenario with climate assessment**	**peak|median warming**	**peak|year**	**peak|CO_2 [ppm]**	**peak|RF all [Wm2]**	**peak|RF CO_2 [Wm2]**	**peak|RF non CO_2 [Wm2]**	**netzero CO_2 |year**	**cumulative CO_2 emissions (2016 to peak, as submitted)**	**cumulative CO_2 emissions (2016 to peak, harmonized)**	**peak|Prob Exceed 1.5°C [%]**	**peak|Prob Exceed 2.0°C [%**	**peak|Prob Exceed 2.5°C [%**	**2100| CO_2 [ppm]**	**2100|RF all [Wm2]**	**2100|RF CO_2 [Wm2]**	**2100|RF non CO_2 [Wm2]**	**cumulative CO_2 emissions (2016-2100), as submitted**	**cumulative CO_2 emissions (2016-2100), harmonized**	**2100|Prob Exceed 1.5°C [%**	**2100|Prob Exceed 2.0°C [%**	**2100|Prob Exceed 2.5°C [%**	**Overshoot|Duration [years]|2.0°C**	**Overshoot|Exceedance year|1.5°C**	**Overshoot|Exceedance year|2.0°C**	**Overshoot|Severity [temperature-years]|1.5°C**	**Overshoot|Duration [years]|1.5°C**
Below-1.5°C	5	1.5 (1.4, 1.5)	2041 (2040, 2048)	423 (419, 430)	2.9 (2.7, 2.9)	2.3 (2.2, 2.3)	0.6 (0.4, 0.7)	2044 (2037, 2054)	480 (470, 590)	470 (450, 600)	45 (39, 49)	5 (4, 7)	1 (1, 1)	376 (367, 386)	1.8 (1.8, 2.1)	1.6 (1.5, 1.8)	0.3 (0.2, 0.4)	180 (10, 270)	150 (5, 260)	16 (12, 24)	3 (2, 6)	1 (0, 1)	NaN	NaN	NaN	NaN	NaN
1.5°C-low-OS	37	1.6 (1.5, 1.6)	2048 (2039, 2062)	431 (424, 443)	3.0 (2.8, 3.2)	2.4 (2.3, 2.5)	0.6 (0.3, 0.8)	2050 (2038, 2082)	620 (530, 870)	630 (520, 880)	60 (51, 67)	10 (7, 14)	1 (1, 2)	380 (357, 418)	2.1 (1.8, 2.5)	1.7 (1.4, 2.2)	0.3 (0.1, 0.8)	250 (-120, 780)	260 (-130, 790)	28 (17, 45)	7 (4, 12)	1 (1, 3)	NaN	2035 (2031, 2049)	NaN	1 (0, 3)	27 (14, 54)
1.5°C-high-OS	38	1.7 (1.6, 1.9)	2051 (2043, 2058)	448 (433, 465)	3.2 (3.0, 3.5)	2.6 (2.4, 2.8)	0.6 (0.4, 0.8)	2052 (2044, 2066)	860 (610, 1050)	860 (620, 1070)	75 (67, 89)	18 (11, 34)	3 (1, 8)	385 (354, 419)	2.2 (1.8, 2.6)	1.8 (1.3, 2.2)	0.4 (0.2, 0.7)	330 (-100, 790)	340 (-90, 820)	34 (20, 50)	8 (4, 14)	2 (1, 4)	NaN	2033 (2030, 2035)	NaN	6 (2, 14)	52 (31, 68)
Lower-2°C	70	1.7 (1.5, 1.8)	2063 (2047, 2100)	453 (418, 475)	3.1 (2.7, 3.5)	2.6 (2.2, 2.9)	0.5 (0.2, 0.9)	2074 (2050, inf)	1000 (540, 1400)	990 (550, 1430)	78 (56, 86)	26 (12, 34)	7 (2, 10)	429 (379, 467)	2.8 (2.4, 3.2)	2.3 (1.7, 2.7)	0.4 (0.2, 0.9)	880 (180, 1400)	880 (190, 1420)	65 (51, 80)	20 (13, 34)	7 (3, 11)	NaN	2033 (2030, 2043)	NaN	NaN	NaN
Higher-2°C	59	1.9 (1.8, 2.0)	2075 (2051, 2100)	473 (444, 490)	3.4 (3.1, 3.6)	2.8 (2.5, 3.1)	0.5 (0.4, 1.0)	2082 (2051, inf)	1320 (880, 1690)	1340 (890, 1660)	87 (78, 93)	40 (31, 50)	13 (7, 19)	452 (401, 490)	3.1 (2.6, 3.5)	2.6 (1.0, 3.0)	0.5 (0.3, 1.0)	1270 (510, 1690)	1270 (520, 1660)	83 (59, 89)	38 (17, 50)	13 (6, 19)	NaN	2033 (2030, 2039)	NaN	NaN	NaN
Above-2°C	183	3.1 (2.0, 5.4)	2100 (2067, 2100)	651 (472, 1106)	5.4 (3.4, 9.0)	4.6 (2.8, 7.4)	0.8 (0.4, 1.9)	inf (2067, inf)	3510 (1360, 8010)	3520 (1380, 8010)	100 (89, 100)	96 (50, 100)	83 (17, 100)	651 (438, 1106)	5.4 (2.9, 9.0)	4.6 (2.4, 7.4)	0.8 (0.4, 1.9)	3510 (1090, 8010)	3520 (1090, 8010)	100 (76, 100)	96 (34, 100)	83 (12, 100)	35 (17, 39) [3]	2032 (2029, 2037)	2051 (2042, 2100)	NaN	NaN

2.A.5 Mitigation and SDG pathway synthesis

The Chapter 2 synthesis assessment (see Figure 2.28) of interactions between 1.5°C mitigation pathways and sustainable development or Sustainable Development Goals (SDGs) is based on the assessment of interactions of mitigation measures and SDGs carried out by Chapter 5 (Section 5.4). To derive a synthesis assessment of the interactions between 1.5°C mitigation pathways and SDGs, a set of clear and transparent steps are followed, as described below.

- Table 5.1 is at the basis of all interactions considered between mitigation measures and SDGs.
- A condensed set of mitigation measures, selecting and combining mitigation measures from Table 5.1, is defined (see Table 2.A.13).
- If a measure in the condensed Chapter 2 set is a combination of multiple mitigation measures from Table 5.1, the main interaction (synergies, synergy or trade-off, trade-off) is based on all interactions with 3* and 4* confidence in Table 5.1. If no 3* or 4* interactions are available, lower confidence interactions are considered if available.
- The resulting interaction is defined by the interaction of the majority of cells.
- If one cell shows a diverging interaction and this interaction has 3* or more confidence level, a “synergy or trade-off” interaction is considered.
- If all interactions for a given mitigation measure and SDG combination are the same, the resulting interaction is represented with a bold symbol.
- If all 3* and 4* interactions are of the same nature, but a lower confidence interaction is opposite, the interaction is represented with a regular symbol.
- Confidence is defined by the rounded average of all available confidence levels of the predominant direction (rounded down; 4* confidence in Table 5.1 is also reported as 3* in the Chapter 2 synthesis)
- If a measure in Table 5.1 is assessed to result in either a neutral effect or a synergy or trade-off, the synergy or trade-off is reported in the Chapter 2 synthesis, but the confidence level is reduced by one notch.

To derive relative synergy-risk profiles for the four scenario archetypes used in Chapter 2 (S1, S2, S5, LED, see Sections 2.1 and 2.3), the relative deployment of the selected mitigation measures is used. For each mitigation measure, a proxy indicator is used (see Table 2.A.14). The proxy indicator values are displayed on a relative scale from zero to one where the value of the lowest pathway is set to the origin and the values of the other pathways scaled so that the maximum is one. The pathways with proxy indicators values that are neither 0 nor 1, receive a 0.5 weighting. These 0, 0.5, or 1 values are used to determine the relative achievement of specific synergies or trade-offs per SDG in each scenario, by summation of each respective interaction type (synergy, trade-off, or synergy or trade-off) over all proxy indicators. Ultimately these sums are synthesized in one interaction based on the majority of sub-interactions (synergy, trade-off, or synergy or trade-off). In cases where both synergies and trade-offs are identified, the ‘synergy or trade-off’ interaction is attributed.

Table 2.A.13: Mapping of mitigation measures assessed in Table 5.1 of Chapter 5 to the condensed set of mitigation measured used for the mitigation-SDG synthesis of Chapter 2.

Table 5.1 MITIGATION MEASURES SET			Chapter 2 CONDENSED SET
Demand	Industry	Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Low-carbon fuel switch	DEMAND: Fuel switch and access to modern low-carbon energy
		Decarbonisation/CCS/CCU	Not included
	Buildings	Behavioural response	DEMAND: Behavioural response reducing Building and Transport demand
		Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Improved access & fuel switch to modern low-carbon energy	DEMAND: Fuel switch and access to modern low-carbon energy
	Transport	Behavioural response	DEMAND: Behavioural response reducing Building and Transport demand
		Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Improved access & fuel switch to modern low-carbon energy	DEMAND: Fuel switch and access to modern low-carbon energy
Supply	Replacing coal	Non-biomass renewables: solar, wind, hydro	SUPPLY: Non-biomass renewables: solar, wind, hydro
		Increased use of biomass	SUPPLY: Increased use of biomass
		Nuclear/Advanced Nuclear	SUPPLY: Nuclear/Advanced Nuclear
		CCS: Bio energy	SUPPLY: Bioenergy with carbon capture and storage (BECCS)
	Advanced coal	CCS: Fossil	SUPPLY: Fossil fuels with carbon capture and storage (fossil-CCS)
Land & Ocean	Agriculture & Livestock	Behavioural response: Sustainable healthy diets and reduced food waste	DEMAND: Behavioural response: Sustainable healthy diets and reduced food waste
		Land based greenhouse gas reduction and soil carbon sequestration	LAND: Land based greenhouse gas reduction and soil carbon sequestration
		Greenhouse gas reduction from improved livestock production and manure management systems	LAND: Greenhouse gas reduction from improved livestock production and manure management systems
	Forest	Reduced deforestation, REDD+	LAND: Reduced deforestation, REDD+, Afforestation and reforestation
		Afforestation and reforestation	LAND: Reduced deforestation, REDD+, Afforestation and reforestation
		Behavioural response (responsible sourcing)	Not included
	Oceans	Ocean iron fertilization	Not included
		Blue carbon	Not included
		Enhanced Weathering	Not included

Table 2.A.14: Mitigation measure and proxy indicators reflecting relative deployment of given measure across pathway archetypes. Values of Indicators 2, 3, and 4 are inverse related with the deployment of the respective measures.

Mitigation measure		**Pathway proxy**	
Group	*description*	*number*	*description*
Demand	Accelerating energy efficiency improvements in end use sectors	1	Compound annual growth rate of primary energy (PE) to final energy (FE) conversion from 2020 to 2050
	Behavioural response reducing Building and Transport demand	2	% change in FE between 2010 and 2050
	Fuel switch and access to modern low-carbon energy	3	Year-2050 carbon intensity of FE
	Behavioural response: Sustainable healthy diets and reduced food waste	4	Year-2050 share of non-livestock in food energy supply
Supply	Non-biomass renewables: solar, wind, hydro	5	Year-2050 PE from non-biomass renewables
	Increased use of biomass	6	Year-2050 PE from biomass
	Nuclear/Advanced Nuclear	7	ear-2050 PE from nuclear
	Bioenergy with carbon capture and storage (BECCS)	8	Year-2050 BECCS deployment in $GtCO_2$
	Fossil fuels with carbon capture and storage (fossil-CCS)	9	Year-2050 Fossil-CCS deployment in $GtCO_2$
Land	Land based greenhouse gas reduction and soil carbon sequestration	10	Cumulative AFOLU CO_2 emissions over the 2020-2100 period
	Greenhouse gas reduction from improved livestock production and manure management systems	11	CH_4 and N_2O AFOLU emissions per unit of total food energy supply
	Reduced deforestation, REDD+, Afforestation and reforestation	12	Change in global forest area between 2020 and 2050

References

Ackerman, F., S.J. DeCanio, R.B. Howarth, and K. Sheeran, 2009: Limitations of integrated assessment models of climate change. *Climatic Change*, **95(3-4)**, 297-315, doi:10.1007/s10584-009-9570-x.

Adler, M.D. et al., 2017: Priority for the worse-off and the social cost of carbon. *Nature Clim. Change*, **7(6)**, 443-449, doi:10.1038/nclimate3298.

Allen, M.R. et al., 2018: Quantifying the impact of climate change agreements covering cumulative and short-lived climate pollutants. *Nature* (in press).

Amann, M., Z. Klimont, and F. Wagner, 2013: Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios. *Annual Review of Environment and Resources*, **38(1)**, 31-55, doi:10.1146/annurev-environ-052912-173303.

Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives. *Global Environmental Change*, **42**, 316-330, doi:10.1016/j.gloenvcha.2016.07.006.

Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF 33 model comparison. *Climatic Change* (in press), doi:10.1007/s10584-018-2226-y.

Beck, S. and M. Mahony, 2017: The IPCC and the politics of anticipation. *Nature Climate Change*, **7(5)**, 311-313, doi:10.1038/nclimate3264.

Bertram, C., G. Luderer, A. Popp, J.C. Minx, and W. Lamb, 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environ. Res. Lett* (in press).

Bertram, C. et al., 2015: Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change*, **5(3)**, 235-239, doi:10.1038/nclimate2514.

Blanford, G.J., E. Kriegler, and M. Tavoni, 2014: Harmonization vs. fragmentation: Overview of climate policy scenarios in EMF27. *Climatic Change*, **123(3-4)**, 383-396, doi:10.1007/s10584-013-0951-9.

Bonsch, M. et al., 2014: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11-24, doi:10.1111/gcbb.12226.

Brunner, S. and K. Enting, 2014: Climate finance: A transaction cost perspective on the structure of state-to-state transfers. *Global Environmental Change*, **27**, 138-143.

Burke, M., S.M. Hsiang, and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527**, 235-239, doi:10.1038/nature15725.

Burke, M., W.M. Davis, and N.S. Diffenbaugh, 2018: Large potential reduction in economic damages under UN mitigation targets. *Nature*, **557(7706)**, 549-553, doi:10.1038/s41586-018-0071-9.

Burke, M. et al., 2016: Opportunities for advances in climate change economics. *Science*, **352(6283)**, 292-293, doi:10.1126/science.aad9634.

Cai, Y., K.L. Judd, T.M. Lenton, T.S. Lontzek, and D. Narita, 2015: Environmental tipping points significantly affect the cost-benefit assessment of climate policies. *Proceedings of the National Academy of Sciences*, **112(15)**, 4606-4611, doi:10.1073/pnas.1503890112.

Cameron, C. et al., 2016: Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nature Energy*, **1(1)**, 15010, doi:10.1038/nenergy.2015.10.

Chen, C. and M. Tavoni, 2013: Direct air capture of CO2 and climate stabilization: A model based assessment. *Climatic Change*, **118(1)**, 59-72, doi:10.1007/s10584-013-0714-7.

Chilvers, J. et al., 2017: Realising transition pathways for a more electric, low-carbon energy system in the United Kingdom: Challenges, insights and opportunities. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, **231(6)**, 440-477, doi:10.1177/0957650917695448.

Clarke, L. et al., 2009: International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics*, **31**, S64-S81, doi:10.1016/j.eneco.2009.10.013.

Clarke, L. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413-510.

Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029-1136.

Craxton, M., J. Merrick, C. Makridis, and J. Taggart, 2017: On the climate policy implications of substitutability and flexibility in the economy: An in-depth integrated assessment model diagnostic. *Technological Forecasting and Social Change*, **125**, 289-298, doi:https://doi.org/10.1016/j.techfore.2017.07.003.

Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, **2(9)**, 17140, doi:10.1038/nenergy.2017.140.

Dell, M., B.F. Jones, and B.A. Olken, 2014: What Do We Learn from the Weather ? The New Climate-Economy

Literature. *Journal of Economic Literature*, **52(3)**, 740-798.

Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112(52)**, 15827-15832, doi:10.1073/pnas.1513967112.

Dietz, S. and N. Stern, 2008: Why Economic Analysis Supports Strong Action on Climate Change: A Response to the Stern Review's Critics. *Review of Environmental Economics and Policy*, **2(1)**, 94-113, doi:10.1093/reep/ren001.

Edelenbosch, O.Y. et al., 2017a: Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy*, **122**, 701-710, doi:10.1016/J.ENERGY.2017.01.017.

Edelenbosch, O.Y. et al., 2017b: Decomposing passenger transport futures: Comparing results of global integrated assessment models. *Transportation Research Part D: Transport and Environment*, **55**, 281-293, doi:10.1016/j.trd.2016.07.003.

Edelenbosch, O.Y. et al., 2017c: Transport fuel demand responses to fuel price and income projections: Comparison of integrated assessment models. *Transportation Research Part D: Transport and Environment*, **55**, 310-321, doi:10.1016/J.TRD.2017.03.005.

Edenhofer, O. and M. Kowarsch, 2015: Cartography of pathways: A new model for environmental policy assessments. *Environmental Science & Policy*, **51**, 56-64, doi:10.1016/j.envsci.2015.03.017.

Edenhofer, O. et al., 2010: The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. *The Energy Journal*, **31(Special Issue 1)**, 11-48, doi:10.2307/41323490.

Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614-12,623, doi:10.1002/2016GL071930.

Figueres, C. et al., 2017: Three years to safeguard our climate. *Nature*, **546(7660)**, 593-595, doi:10.1038/546593a.

Forster, P. et al., 2007: Changes in Atmospheric Constituents and in Radiative Forcing. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 129-234.

Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, 105004, doi:10.1088/1748-9326/aa8c83.

Frank, S. et al., 2018: Structural change as a key component for agricultural non-CO2 mitigation efforts. *Nature Communications*, **9(1)**, 1060, doi:10.1038/s41467-018-03489-1.

Fricko, O. et al., 2016: Energy sector water use implications of a 2 °C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.

Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**.

Grubb, M., J.C. Hourcade, and K. Neuhoff, 2014: *Planetary economics: energy, climate change and the three domains of sustainable development*. Routledge Earthscan, Oxon, New York, 520 pp.

Grubler, A., 2010: The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, **38(9)**, 5174-5188, doi:10.1016/J.ENPOL.2010.05.003.

Grubler, A. et al., 2018: A Global Scenario of Low Energy Demand for Sustainable Development below 1.5°C without Negative Emission Technologies. *Nature Energy* (in press), doi:10.1038/s41560-018-0172-6.

Gschrey, B., W. Schwarz, C. Elsner, and R. Engelhardt, 2011: High increase of global F-gas emissions until 2050. *Greenhouse Gas Measurement and Management*, **1(2)**, 85-92, doi:10.1080/20430779.2011.579352.

Guivarch, C., R. Crassous, O. Sassi, and S. Hallegatte, 2011: The costs of climate policies in a second-best world with labour market imperfections. *Climate Policy*, **11(1)**, 768-788, doi:10.3763/cpol.2009.0012.

Haegel, N.M. et al., 2017: Terawatt-scale photovoltaics: Trajectories and challenges. *Science*, **356(6334)**, 141-143, doi:10.1126/science.aal1288.

Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7**, 250.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **111(10)**, 3709-14, doi:10.1073/pnas.1308044111.

Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, **81**, 205-226, doi:10.1016/j.techfore.2013.05.006.

Hoesly, R.M. et al., 2018: Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, **11(1)**, 369-408, doi:10.5194/gmd-11-369-2018.

Holz, C., L. Siegel, E. Johnston, A.P. Jones, and J. Sterman, 2018: Ratcheting ambition to limit warming to 1.5°C - trade-offs between emission reductions and carbon dioxide removal. *Environmental Research Letters* (in press), doi:10.1088/1748-9326/aac0c1.

Houghton, R. et al., 2012: Carbon emissions from land use and land-cover change. *Biogeosciences*, **9(12)**, 5125-5142, doi:10.5194/bg-9-5125-2012.

Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356(6345)**, 1362 LP - 1369.

Humpenöder, F. et al., 2018: Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environmental*

Research Letters, **13(2)**, 024011, doi:10.1088/1748-9326/aa9e3b.

IEA, 2017: *Energy Technology Perspectives 2017*. International Energy Agency (IEA), Paris, France, 443 pp.

Iyer, G.C. et al., 2015: Improved representation of investment decisions in assessments of CO2 mitigation. *Nature Climate Change*, **5(5)**, 436-440, doi:10.1038/nclimate2553.

Johnson, N. et al., 2017: A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system. *Energy Economics*, **64**, 651-664, doi:10.1016/J.ENECO.2016.07.010.

Knutti, R. and J. Rogelj, 2015: The legacy of our CO2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change*, **133(3)**, 361-373, doi:10.1007/s10584-015-1340-3.

Kolstad, C. et al., 2014: Social, Economic and Ethical Concepts and Methods. In: *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadne, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207-282.

Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014a: Getting from here to there - energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, **123**, 369-382, doi:10.1007/s10584-013-0947-5.

Krey, V. et al., 2014b: Annex II: Metrics & Methodology. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1281-1328.

Kriegler, E. et al., 2014: The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, **123(3-4)**, 353-367, doi:10.1007/s10584-013-0953-7.

Kriegler, E. et al., 2015a: Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change*, **90(PA)**, 45-61, doi:10.1016/j.techfore.2013.09.020.

Kriegler, E. et al., 2015b: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change*, **90(PA)**, 24-44, doi:10.1016/j.techfore.2013.09.021.

Kriegler, E. et al., 2016: Will economic growth and fossil fuel scarcity help or hinder climate stabilization?: Overview of the RoSE multi-model study. *Climatic Change*, **136(1)**, 7-22, doi:10.1007/s10584-016-1668-3.

Kriegler, E. et al., 2018: Short term policies to keep the door open for Paris climate goals. *Environ. Res. Lett* (in press), doi:10.1088/1748-9326/aac4f1.

Kunreuther, H. et al., 2014: Integrated Risk and Uncertainty Assessment of Climate Change Response Policies. In: *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Laitner, J., S. De Canio, and I. Peters, 2000: Incorporating Behavioural, Social, and Organizational Phenomena in the Assessment of Climate Change Mitigation Options. *Society, Behaviour, and Climate Change Mitigation*, 1-64, doi:10.1007/0-306-48160-X_1.

Le Quéré, C. et al., 2016: Global Carbon Budget 2016. *Earth System Science Data*, **8(2)**, 605-649, doi:10.5194/essd-8-605-2016.

Le Quéré, C. et al., 2018: Global Carbon Budget 2017. *Earth Syst. Sci. Data*, **1010333739(10)**, 405-448, doi:10.5194/essd-10-405-2018.

Leach, N.J. et al., 2018: Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nature Geoscience* (in press).

Li, F.G.N. and N. Strachan, 2017: Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions*, **24**, 106-129, doi:10.1016/j.eist.2016.08.002.

Li, F.G.N., E. Trutnevyte, and N. Strachan, 2015: A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change*, **100**, 290-305, doi:10.1016/j.techfore.2015.07.017.

Liu, J.–Y. et al., 2017: Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C. *Carbon Management* (in press).

Löffler, K. et al., 2017: Designing a Model for the Global Energy System-GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies*, **10(10)**, 1468, doi:10.3390/en10101468.

Lontzek, T.S., Y. Cai, K.L. Judd, and T.M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change*, **5(5)**, 441-444.

Lucon, O. et al., 2014: Buildings. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P.

Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 671-738.

Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016: Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change*, **136(1)**, 127-140, doi:10.1007/s10584-013-0899-9.

Luderer, G. et al., 2012: The economics of decarbonizing the energy system - results and insights from the RECIPE model intercomparison. *Climatic Change*, **114(1)**, 9-37, doi:10.1007/s10584-011-0105-x.

Luderer, G. et al., 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters*, **8(3)**, 034033, doi:10.1088/1748-9326/8/3/034033.

Luderer, G. et al., 2017: Assessment of wind and solar power in global low-carbon energy scenarios: An introduction. *Energy Economics*, **64**, 542-551, doi:10.1016/J.ENECO.2017.03.027.

Luderer, G. et al., 2018: Residual fossil CO2 emissions in 1.5-2°C pathways. *Nature Climate Change* (in press), doi:10.1038/s41558-018-0198-6.

Marcucci, A., S. Kypreos, and E. Panos, 2017: The road to achieving the long-term Paris targets: Energy transition and the role of direct air capture. *Climatic Change*, **144(2)**, 181-193, doi:10.1007/s10584-017-2051-8.

McCollum, D.L., W. Zhou, C. Bertram, H.–S. de Boer, and V. Bosetti, 2018: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* (in press), doi:10.1038/s41560-018-0179-z.

McCollum, D.L. et al., 2016: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, doi:10.1016/j.trd.2016.04.003.

Meinshausen, M., T.M.L. Wigley, and S.C.B. Raper, 2011a: Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 2: Applications. *Atmospheric Chemistry and Physics*, **11(4)**, 1457-1471, doi:10.5194/acp-11-1457-2011.

Meinshausen, M. et al., 2009: Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature*, **458(7242)**, 1158-1162, doi:10.1038/nature08017.

Meinshausen, M. et al., 2011b: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109(1-2)**, 213-241, doi:10.1007/s10584-011-0156-z.

Mercure, J.–F. et al., 2018: Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy Strategy Reviews*, **20**, 195-208, doi:https://doi.org/10.1016/j.esr.2018.03.003.

Mouratiadou, I., A. Biewald, and M. Pehl, 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy*, **64**, 48-58.

Mouratiadou, I. et al., 2018: Water demand for electricity in deep decarbonisation scenarios: a multi-model assessment. *Climatic Change*, **147(1)**, 91-106, doi:10.1007/s10584-017-2117-7.

Mundaca, L., L. Neij, E. Worrell, and M. McNeil, 2010: Evaluating Energy Efficiency Policies with Energy-Economy Models. *Annual Review of Environment and Resources*, **35(1)**, 305-344, doi:10.1146/annurev-environ-052810-164840.

Mundaca, L., M. Mansoz, L. Neij, and G. Timilsina, 2013: Transaction costs analysis of low-carbon technologies. *Climate Policy*, **13(4)**, 490-513, doi:10.1080/14693062.2013.781452.

Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-740.

Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990-2015. *Atmospheric Chemistry and Physics*, **17(4)**, doi:10.5194/acp-17-2709-2017.

Nordhaus, W.D., 2005: A Review of The Stern Review on the Economics of Climate Change. *Journal of Economic Literature*, **XLV**, 686-702.

OECD/IEA and IRENA, 2017: *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*. OECD/IEA and IRENA, 204 pp.

Parkinson, S.C., V. Krey, and D. Huppmann, 2017: Quantifying interactions between SDG6 and a 1.5°C climate policy. (in press).

Patt, A.G., 2015: *Transforming energy: Solving climate change with technology policy*. Cambridge University Press, New york, 349 pp.

Patt, A.G. et al., 2010: Adaptation in integrated assessment modeling: where do we stand? *Climatic Change*, **99**, 383-402, doi:10.1007/s10584-009-9687-y.

Pauliuk, S., A. Arvesen, K. Stadler, and E.G. Hertwich, 2017: Industrial ecology in integrated assessment models. *Nature Climate Change*, **7(1)**, 13-20, doi:10.1038/nclimate3148.

Pietzcker, R.C. et al., 2017: System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Economics*, **64**, 583-599, doi:10.1016/j.eneco.2016.11.018.

Pizer, W. et al., 2014: Using and improving the social cost of carbon. *Science*, **346(6214)**, 1189-1190, doi:10.1126/science.1259774.

Popp, A. et al., 2014: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change***, 123(3-4)**, 495-509, doi:10.1007/s10584-013-0926-x.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change***, 42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002.

Rao, S. et al., 2017: Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change***, 42**, 346-358, doi:10.1016/j.gloenvcha.2016.05.012.

Revesz, R. et al., 2014: Global warming: Improve economic models of climate change. *Nature***, 508(7495)**, 173-175, doi:10.1038/508173a.

Riahi, K. et al., 2015: Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change***, 90(PA)**, 8-23, doi:10.1016/j.techfore.2013.09.016.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change***, 42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009.

Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science***, 355(6331)**, 1269-1271, doi:10.1126/science.aah3443.

Rogelj, J., D.L. McCollum, B.C. O'Neill, and K. Riahi, 2013a: 2020 emissions levels required to limit warming to below 2 C. *Nature Climate Change***, 3(4)**, 405-412, doi:10.1038/nclimate1758.

Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013b: Probabilistic cost estimates for climate change mitigation. *Nature***, 493(7430)**, 79-83, doi:10.1038/nature11787.

Rogelj, J. et al., 2014: Disentangling the effects of CO2 and short-lived climate forcer mitigation. *Proceedings of the National Academy of Sciences***, 111(46)**, 16325-16330, doi:10.1073/pnas.1415631111.

Rogelj, J. et al., 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change***, 5(6)**, 519-527, doi:10.1038/nclimate2572.

Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change***, 8(4)**, 325-332, doi:10.1038/s41558-018-0091-3.

Rubin, E.S., J.E. Davison, and H.J. Herzog, 2015: The cost of CO2 capture and storage. *International Journal of Greenhouse Gas Control***, 40**, 378-400, doi:10.1016/J.IJGGC.2015.05.018.

Schneider von Deimling, T. et al., 2012: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences***, 9(2)**, 649-665, doi:10.5194/bg-9-649-2012.

Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences***, 12(11)**, 3469-3488, doi:10.5194/bg-12-3469-2015.

Schwanitz, V.J., 2013: Evaluating integrated assessment models of global climate change. *Environmental Modelling & Software***, 50**, 120-131, doi:10.1016/j.envsoft.2013.09.005.

Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. LBNL-1003671, 58 pp.

Shell International B.V., 2018: *Shell Scenarios: Sky - Meeting the Goals of the Paris Agreement*. Shell International B.V. 36 pp.

Shindell, D.T. et al., 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science***, 335(6065)**, 183-189, doi:10.1126/science.1210026.

Smith, C.J. et al., 2018: FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development* (in press), doi:10.5194/gmd-2017-266.

Stanton, E.A., F. Ackerman, and S. Kartha, 2009: Inside the integrated assessment models: Four issues in climate economics. *Climate and Development***, 1(2)**, 166, doi:10.3763/cdev.2009.0015.

Stern, N., 2016: Current climate models are grossly misleading. *Nature***, 530**, 407-409, doi:10.1038/530407a.

Stevanović, M. et al., 2016: The impact of high-end climate change on agricultural welfare. *Science Advances***, 2(8)**, e1501452, doi:10.1126/sciadv.1501452.

Stiglitz, J.E. et al., 2017: *Report of the High-Level Commission on Carbon Prices*. Carbon Pricing Leadership Coalition, 68 pp.

Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33-115.

Strefler, J., T. Amann, N. Bauer, E. Kriegler, and J. Hartmann, 2018a: Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters***, 13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.

Strefler, J., N. Bauer, E. Kriegler, A. Popp, and O. Giannousakis, Anastasis Edenhofer, 2018b: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett***, 13**, 044015.

Sussams, L. and J. Leaton, 2017: *Expect the Unexpected - The Disruptive Power of Low-carbon Technology*. 52 pp.

Tavoni, M., E. De Cian, G. Luderer, J.C. Steckel, and H. Waisman, 2012: The value of technology and of its evolution towards a low carbon economy. *Climatic Change*, **114(1)**, 39-57, doi:10.1007/s10584-011-0294-3.

Tavoni, M. et al., 2015: Post-2020 climate agreements in the major economies assessed in the light of global models. *Nature Climate Change*, **5(2)**, 119-126, doi:10.1038/nclimate2475.

Trutnevyte, E., N. Strachan, P.E. Dodds, D. Pudjianto, and G. Strbac, 2015: Synergies and trade-offs between governance and costs in electricity system transition. *Energy Policy*, **85**, 170-181, doi:10.1016/j.enpol.2015.06.003.

Turnheim, B. et al., 2015: Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change*, **35**, 239-253, doi:10.1016/j.gloenvcha.2015.08.010.

Ürge-Vorsatz, D., A. Novikova, S. Köppel, and B. Boza-Kiss, 2009: Bottom-up assessment of potentials and costs of CO2 emission mitigation in the buildings sector: insights into the missing elements. *Energy Efficiency*, **2(4)**, 293-316, doi:10.1007/s12053-009-9051-0.

van Marle, M.J.E. et al., 2017: Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750-2015). *Geoscientific Model Development*, **10(9)**, 3329-3357, doi:10.5194/gmd-10-3329-2017.

van Sluisveld, M.A.E., S.H. Martínez, V. Daioglou, and D.P. van Vuuren, 2016: Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **102**, 309-319, doi:10.1016/J.TECHFORE.2015.08.013.

van Sluisveld, M.A.E. et al., 2015: Comparing future patterns of energy system change in 2 °C scenarios with historically observed rates of change. *Global Environmental Change*, **35**, 436-449, doi:10.1016/j.gloenvcha.2015.09.019.

van Vuuren, D.P. et al., 2011: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5-31, doi:10.1007/s10584-011-0148-z.

van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303-323, doi:10.1016/J.TECHFORE.2015.03.005.

van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391-397, doi:10.1038/s41558-018-0119-8.

Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123**, 200-209, doi:10.1016/j.atmosenv.2015.10.071.

Vrontisi, Z. et al., 2018: A multi-model assessment of the short-term effectiveness of Paris pledges towards a 1.5-2°C stabilization. *Environ. Res. Lett*, **13**, 044039, doi:10.1088/1748-9326/aab53e.

Warszawski, L. et al., 2014: The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP): Project framework. *Proceedings of the National Academy of Sciences*, **111(9)**, 3228-3232, doi:10.1073/pnas.1312330110.

Weindl, I. et al., 2017: Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics. *Global and Planetary Change*, **159**, 1-10, doi:10.1016/j.gloplacha.2017.10.002.

Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, **11(1)**, 115-137, doi:10.1093/reep/rew018.

Wilkerson, J.T., B.D. Leibowicz, D.D. Turner, and J.P. Weyant, 2015: Comparison of integrated assessment models: Carbon price impacts on U.S. energy. *Energy Policy*, **76**, 18-31, doi:https://doi.org/10.1016/j.enpol.2014.10.011.

Wilson, C. and H. Dowlatabadi, 2007: Models of Decision Making and Residential Energy Use. *Annual Review of Environment and Resources*, **32(1)**, 169-203, doi:10.1146/annurev.energy.32.053006.141137.

Wilson, C., A. Grubler, K.S. Gallagher, and G.F. Nemet, 2012: Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change*, **2(11)**, 780-788, doi:10.1038/NCLIMATE1576.

Wilson, C., A. Grubler, N. Bauer, V. Krey, and K. Riahi, 2013: Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Climatic Change*, **118(2)**, 381-395, doi:10.1007/s10584-012-0618-y.

Wilson, C. et al., 2017: Evaluating Process-Based Integrated Assessment Models of Climate Change Mitigation. IIASA Working Paper WP-17-007.

Wong-Parodi, G., T. Krishnamurti, A. Davis, D. Schwartz, and B. Fischhoff, 2016: A decision science approach for integrating social science in climate and energy solutions. *Nature Climate Change*, **6(6)**, 563-569, doi:10.1038/nclimate2917.

Zhang, R., S. Fujimori, and T. Hanaoka, 2018: The contribution of transport policies to the mitigation potential and cost of 2°C and 1.5°C goals. *Environmental Research Letters*, **13(5)**, 054008.

Chapter 2 - Technical Annex – Part II - Mitigation pathways compatible with 1.5°C in the context of sustainable development

Contributing modelling framework reference cards

For each of the contributing modelling frameworks a reference card has been created highlighting the key features of the model. These reference cards are either based on information received from contributing modelling teams upon submission of scenarios to the SR1.5 database, or alternatively drawn from the ADVANCE IAM wiki documentation, available at http://www.fp7-advance.eu/content/model-documentation, and updated. These reference cards are provided in part II of this annex.

Reference card – AIM-CGE

About

⇨ ***Name and version***

AIM-CGE

⇨ ***Institution and users***

National Institute for Environmental Studies (NIES), Japan

Model scope and methods

⇨ ***Objective***

AIM/CGE is developed to analyse the climate mitigation and impact. The energy system is disaggregated to meet this objective in both of energy supply and demand sides. Agricultural sectors have also been disaggregated for the appropriate land use treatment. The model is designed to be flexible in its use for global analysis.

⇨ ***Concept***

General Equilibrium with technology explicit modules in power sectors

⇨ ***Solution method***

Solving a mixed complementarity problem

⇨ ***Anticipation***

Myopic

⇨ ***Temporal dimension***

Base year: 2005**, time steps:** Annual, **horizon:** 2100

⇨ ***Spatial dimension***

Number of regions: 17

1. Japan
2. China
3. India
4. Southeast Asia
5. Rest of Asia
6. Oceania
7. EU25
8. Rest of Europe
9. Former Soviet Union
10. Turkey
11. Canada
12. United States
13. Brazil
14. Rest of South America
15. Middle East
16. North Africa
17. Rest of Africa

⇨ ***Policy implementation***

Climate policy such as emissions target, Emission permits trading and so on. Energy taxes and subsidies

Socio economic drivers

⇨ ***Exogenous drivers***

- Total Factor Productivity

Note: GDP is endogenous, while TFP is exogenous; but TFP can be calibrated so as to reproduce a given GDP pathway

⇨ ***Endogenous drivers***

- GDP (Non-baseline scenarios that take into account either climate change mitigation or impacts.)

⇨ ***Development***

- GDP per capita

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Transport
- Services

⇨ ***Cost measures***

- GDP loss
- Welfare loss
- Consumption loss

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity
- Food crops
- Emissions permits
- Non-energy goods

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

- Coal
- Oil
- Gas
- Biomass

⇨ ***Electricity technologies***

- Coal
- Gas
- Oil
- Nuclear
- Biomass
- Wind
- Solar PV
- CCS

⇨ ***Conversion technologies***

- Oil to liquids
- Biomass to liquids

- ⇨ ***Grid and infrastructure***
- ⇨ ***Energy technology substitution***
- – Discrete technology choices
- ⇨ ***Energy service sectors***
- – Transportation
- – Industry
- – Residential and commercial

Land use

- ⇨ ***Land cover***
- – Abandoned land
- – Cropland
- – Forest
- – Grassland
- – Extensive Pastures

Note: 6 AEZs (Agro-Ecological Zones) by Crop, pasture, forestry, Other forest, natural grassland and others There is a land competition under multi-nominal logit selection.

Other resources

Emissions and climate

- ⇨ ***Greenhouse gases***
- – CO_2
- – CH_4
- – N_2O
- – HFCs
- – CFCs
- – SF_6
- ⇨ ***Pollutants***
- – NO_X
- – SO_X
- – BC
- – OC
- – VOC
- – CO
- ⇨ ***Climate indicators***
- – CO_2e concentration (ppm)
- – Radiative Forcing (W/m^2)
- – Temperature change (°C)

Reference card – BET

About

⇨ *Name and version*

BET EMF33

⇨ *Institution and users*

CRIEPI

University of Tokyo

Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model doi: 10.1007/s10584-013-0938-6

Model scope and methods

⇨ *Objective*

The model is used for climate change studies on long-term mitigation scenarios. Typical application is to examine the role of electrification and advanced end-use technologies in climate change mitigation in a more systematic fashion, ranging from changes in usage of end-use technologies to power generation mix.

⇨ *Concept*

General equilibrium (closed economy)

⇨ *Solution method*

Optimization

⇨ *Anticipation*

Inter-temporal (foresight)

⇨ *Temporal dimension*

Base year: 2010**, time steps:** 10, **horizon:** 2010-2230

⇨ *Spatial dimension*

Number of regions: 13

1.	BRA	Brazil
2.	CAZ	Canada, Australia, and New Zealand
3.	CHA	China incl. Hong Kong
4.	EUR	EU27+3 (Switzerland, Norway, and Iceland)
5.	IND	India
6.	JPN	Japan
7.	MNA	Middle East and North Africa
8.	OAS	Other Asia
9.	OLA	Other Latin America
10.	ORF	Other Reforming Economies
11.	RUS	Russia
12.	SSA	Sub-Saharan Africa
13.	USA	United States

⇨ *Policy implementation*

Emission Tax/Pricing, Cap and Trade, Pricing Carbon Stocks

Socio economic drivers

⇨ *Exogenous drivers*

- Population
- Total Factor Productivity
- Autonomous Energy Efficiency Improvements

⇨ *Endogenous drivers*

- GDP

Macro economy

⇨ ***Economic sectors***

⇨ ***Cost measures***

- GDP loss
- Consumption loss
- Energy system costs

⇨ ***Trade***

- Coal
- Oil
- Gas
- Food crops
- Emissions permits
- Non-energy goods

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

- Coal
- Conventional Oil
- Unconventional Oil
- Conventional Gas
- Unconventional Gas
- Uranium
- Bioenergy

⇨ ***Electricity technologies***

- Coal w/o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Bioenergy w/o CCS
- Bioenergy w/ CCS
- Geothermal Power
- Nuclear Power
- Solar Power|Central PV
- Wind Power|Onshore
- Wind Power|Offshore
- Hydroelectric Power

⇨ ***Conversion technologies***

- Coal to Hydrogen w/ CCS
- Electrolysis
- Coal to Liquids w/o CCS
- Bioliquids w/o CCS
- Oil Refining
- Biomass to Gas w/o CCS

⇨ ***Grid and infrastructure***

- Electricity
- Gas

⇨ ***Energy technology substitution***

- Linear choice (lowest cost)
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***

- Cropland Food Crops
- Cropland Feed Crops
- Cropland Energy Crops
- Managed Forest
- Natural Forest
- Pasture

Other resources

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2

⇨ ***Pollutants***

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)

Reference card – C-ROADS

About

⇨ ***Name and version***

C-ROADS v5 005

⇨ ***Institution and users***

Climate Interactive, US, https://www.climateinteractive.org/.

Model scope and methods

⇨ ***Objective***

The purpose of C-ROADS is to improve public and decision-maker understanding of the long-term implications of international emissions and sequestration futures with a rapid-iteration, interactive tool as a path to effective action that stabilizes the climate.

⇨ ***Concept***

C-ROADS takes future population, economic growth and GHG emissions as scenario inputs specified by the user and currently omits the costs of policy options and climate change damage.

⇨ ***Solution method***

Recursive dynamic solution method (myopic)

⇨ ***Anticipation***

Simulation modelling framework, without foresight.

⇨ ***Temporal dimension***

Base year: 1850**, time steps:** 0.25 year time step, **horizon:** 2100

⇨ ***Spatial dimension***

Number of regions: 20

1. USA
2. European Union (EU) 27 (EU27) (plus Iceland, Norway and Switzerland)
3. Russia (includes fraction of former USSR)
4. Other Eastern Europe
5. Canada
6. Japan
7. Australia
8. New Zealand
9. South Korea
10. Mexico
11. China
12. India
13. Indonesia
14. Philippines, Thailand, Taiwan, Hong Kong, Malaysia, Pakistan, Singapore
15. Brazil
16. Latin America excluding Mexico and Brazil
17. Middle East
18. South Africa
19. Africa excluding South Africa
20. Asia excluding China, India, Indonesia, and those included in Other Large Asia

⇨ ***Policy implementation***

The model does not include explicit representation of policies.

Socio economic drivers

⇨ ***Exogenous drivers***

- Exogenous population
- Exogenous GDP

⇨ ***Endogenous drivers***

- None

⇨ ***Development***

- None

Macro economy

⇨ ***Economic sectors***

- Not represented by the model

⇨ ***Cost measures***

- Not represented by the model

⇨ ***Trade***

- Not represented by the model

Energy

⇨ ***Behaviour***

- Not represented by the model

⇨ ***Resource use***

- Not represented by the model

⇨ ***Electricity technologies***

- Not represented by the model

⇨ ***Conversion technologies***

- Not represented by the model

⇨ ***Grid and infrastructure***

- Not represented by the model

⇨ ***Energy technology substitution***

- Not represented by the model

⇨ ***Energy service sectors***

- Not represented by the model

Land use

⇨ ***Land cover***

- Not represented by the model

Other resources

- None

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6
- PFCs

⇨ ***Pollutants***

- Not covered by the model

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)
- Sea level rise
- Ocean acidification

Reference card – DNE21

About

⇨ *Name and version*

DNE21+ V.14C

⇨ *Institution and users*

Research Institute of Innovative Technology for the Earth (RITE), 9-2 Kizugawadai, Kizugawa-shi, Kyoto 619-0292
http://www.rite.or.jp/Japanese/labo/sysken/about-global-warming/download-data/RITE_GHGMitigationAssessmentModel_20150130.pdf

Model scope and methods

⇨ *Objective*

⇨ *Concept*

Minimizing Energy Systems Cost

⇨ *Solution method*

Optimization

⇨ *Anticipation*

Inter-temporal (foresight)

⇨ *Temporal dimension*

Base year: 2000**, time steps:** 5 year steps (2000 - 2030); 10 year-steps (2030 - 2050), **horizon:** 2000-2050

⇨ *Spatial dimension*

Number of regions: 54

1.	ARG+	Argentina, Paraguay, Uruguay
2.	AUS	Australia
3.	BRA	Brazil
4.	CAN	Canada
5.	CHN	China
6.	EU15	EU-15
7.	EEU	Eastern Europe (Other EU-28)
8.	IND	India
9.	IDN	Indonesia
10.	JPN	Japan
11.	MEX	Mexico
12.	RUS	Russia
13.	SAU	Saudi Arabia
14.	SAF	South Africa
15.	ROK	South Korea
16.	TUR	Turkey
17.	USA	United States of America
18.	OAFR	Other Africa
19.	MEA	Middle East & North Africa
20.	NZL	New Zealand
21.	OAS	Other Asia
22.	OFUE	Other FUSSR (Eastern Europe)
23.	OFUA	Other FUSSR (Asia)
24.	OLA	Other Latin America
25.	OWE	Other Western Europe

⇨ *Policy implementation*

Emission Tax/Pricing, Cap and Trade; Fuel Taxes; Fuel Subsidies; Feed-in-Tariff; Portfolio Standard; Capacity Targets; Emission Standards; Energy Efficiency Standards; Land Protection; Pricing Carbon Stocks

Socio economic drivers

⇨ *Exogenous drivers*

- Population
- Population Age Structure
- Education Level
- Urbanization Rate
- GDP
- Income Distribution
- Labour Participation Rate
- Labour Productivity

Macro economy

⇨ *Economic sectors*

- Agriculture
- Industry
- Energy
- Services

⇨ *Cost measures*

- Energy system costs

⇨ *Trade*

- Coal
- Oil
- Gas
- Electricity
- Emissions permits

Energy

⇨ *Behaviour*

- Transportation
- Industry
- Residential & Commercial
- Technology Adoption

⇨ *Resource use*

- Coal
- Conventional Oil
- Unconventional Oil
- Conventional Gas
- Unconventional Gas

⇨ *Electricity technologies*

- Coal w/o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Oil w/ CCS
- Bioenergy w/o CCS
- Bioenergy w/ CCS
- Geothermal Power
- Nuclear Power
- Solar Power
- Wind Power
- Hydroelectric Power

⇨ ***Conversion technologies***

- Coal to Hydrogen w/o CCS
- Coal to Hydrogen w/ CCS
- Natural Gas to Hydrogen w/o CCS
- Natural Gas to Hydrogen w/ CCS
- Biomass to Hydrogen w/o CCS
- Biomass to Hydrogen w/ CCS
- Electrolysis
- Coal to Liquids w/o CCS
- Bioliquids w/o CCS
- Oil Refining
- Coal to Gas w/o CCS

⇨ ***Grid and infrastructure***

- Electricity
- Gas
- CO_2
- H_2

⇨ ***Energy technology substitution***

- Linear choice (lowest cost)
- System integration constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***

- Cropland Food Crops
- Cropland Feed Crops
- Cropland Energy Crops
- Managed Forest
- Natural Forest
- Pasture

Other resources

⇨ ***Other resources***

- Water

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF6

⇨ ***Pollutants***

- NO_X
- SO_X
- BC
- OC

⇨ ***Climate indicators***

- CO_2e concentration (ppm)

- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – FARM 3.2

About

⇨ ***Name and version***

Future Agricultural Resources Model 3.2

⇨ ***Institution and users***

United States Department of Agriculture, Economic Research Service; Öko-Institut Germany – https://www.ers.usda.gov/webdocs/publications/81903/err-223.pdf?v=42738

Model scope and methods

⇨ ***Objective***

The Future Agricultural Resources Model (FARM) was originally designed as a static CGE model to simulate land use and climate impacts at a global scale. It has since been extended to simulate energy and agricultural systems through 2100 to enable participation in EMF and AgMIP model comparison studies.

⇨ ***Concept***

FARM models land use shifts among crops, pasture, and forests in response to population growth, changes in agricultural productivity, and policies such as a renewable portfolio standard or greenhouse gas cap-and-trade.

⇨ ***Solution method***

General equilibrium recursive-dynamic simulation

⇨ ***Anticipation***

Myopic

⇨ ***Temporal dimension***

Base year: 2011**, time steps:** 5 years, **horizon:** 2101

⇨ ***Spatial dimension***

Number of regions: 15

1. United States
2. Japan
3. European Union west (EU-15)
4. European Union east
5. Other OECD90
6. Russian Federation
7. Other Reforming Economies
8. China region
9. India
10. Indonesia
11. Other Asia
12. Middle East and North Africa
13. Sub-Saharan Africa
14. Brazil
15. Other Latin America

⇨ ***Policy implementation***

Emissions Tax/Pricing, Cap and Trade, Fuel Taxes and Subsidies, Portfolio Standards, Agricultural Producer, Subsidies, Agricultural Consumer Subsidies, Land Protection

Socio economic drivers

⇨ ***Exogenous drivers***

- Population
- Labour Productivity
- Land Productivity
- Autonomous Energy Efficiency Improvements
- Other input-specific productivity

⇨ ***Endogenous drivers***

- none

⇨ ***Development***

- none

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Services

⇨ ***Cost measures***

- GDP loss
- Welfare loss
    - Equivalent Variation
- Consumption loss

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity
- Food crops
- Non-energy goods

Energy

⇨ ***Behaviour***

- Substitution between energy and non-energy inputs in response to changes in relative prices

⇨ ***Resource use***

- Coal (supply Curve)
- Conventional Oil (Supply Curve)
- Conventional Gas (Supply Curve)
- Biomass (Supply Curve)

⇨ ***Electricity technologies***

- Coal (w/o and w/ CCS)
- Gas (w/o and w/ CCS)
- Oil (w/o and w/ CCS)
- Nuclear
- Biomass (w/o and w/ CCS)
- Wind
- Solar PV

⇨ ***Conversion technologies***

- Fuel to liquid, Oil Refining

⇨ ***Grid and infrastructure***

- Electricity (aggregate)
- Gas (aggregate)
- CO_2 (aggregate)

⇨ ***Energy technology substitution***

- Discrete technology choices with mostly high substitutability through production functions

⇨ ***Energy service sectors***

- Transportation (land, water, air)
- Buildings

Land use

⇨ ***Land cover***

- Crop Land
    - Food Crops
    - Feed Crops
    - Energy Crops
- Managed Forest
- Pastures

Other resources

⇨ ***Other resources***

- none

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
    - Fossil Fuels
    - Cement
    - Land Use

⇨ ***Pollutants***

- none

⇨ ***Climate indicators***

- none

Reference card – GCAM 4.2

About

⇨ *Name and version*

Global Change Assessment Model 4.2

⇨ *Institution and users*

Joint Global Change Research Institute – http://jgcri.github.io/gcam-doc/v4.2/toc.html

Model scope and methods

⇨ *Objective*

GCAM is a global integrated assessment model that represents the behaviour of, and complex interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate.

⇨ *Concept*

The core operating principle for GCAM is that of market equilibrium. Representative agents in GCAM use information on prices, as well as other information that might be relevant, and make decisions about the allocation of resources. These representative agents exist throughout the model, representing, for example, regional electricity sectors, regional refining sectors, regional energy demand sectors, and land users who have to allocate land among competing crops within any given land region. Markets are the means by which these representative agents interact with one another. Agents pass goods and services along with prices into the markets. Markets exist for physical flows such as electricity or agricultural commodities, but they also can exist for other types of goods and services, for example tradable carbon permits.

⇨ *Solution method*

Partial equilibrium (price elastic demand) recursive-dynamic

⇨ *Anticipation*

Myopic

⇨ *Temporal dimension*

Base year: 2010**, time steps:** 5 years, **horizon:** 2100

⇨ *Spatial dimension*

Number of regions: 32 (For CD-Links scenarios, GCAM included 82 regions)

1. USA (For CD-Links scenarios, the USA was subdivided into 50 states plus the District of Columbia)
2. Eastern Africa
3. Northern Africa
4. Southern Africa
5. Western Africa
6. Australia and New Zealand
7. Brazil
8. Canada
9. Central America and Caribbean
10. Central Asia
11. China
12. EU-12
13. EU-15
14. Eastern Europe
15. Non-EU Europe
16. European Free Trade Association
17. India
18. Indonesia
19. Japan
20. Mexico
21. Middle East
22. Pakistan
23. Russia
24. South Africa

25. Northern South America
26. Southern South America
27. South Asia
28. South Korea
29. Southeast Asia
30. Taiwan
31. Argentina
32. Colombia

⇨ ***Policy implementation***

- Climate Policies
    - Emission Tax/Pricing
    - Cap and Trade
- Energy Policies
    - Fuel Taxes
    - Fuel Subsidies
    - Portfolio Standard
- Energy Technology Policies
    - Capacity Targets
    - Energy Efficiency Standards
- Land Use Policies
    - Land Protection
    - Afforestation

Socio economic drivers

⇨ ***Exogenous drivers***

- Population
- GDP
- Labour Participation Rate
- Labour Productivity

⇨ ***Endogenous drivers***

- none

⇨ ***Development***

- none

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Transport
- Services
- Residential and Commercial

⇨ ***Cost measures***

- Area under MAC

⇨ ***Trade***

- Coal
- Oil
- Gas
- Uranium
- Bioenergy crops
- Food crops
- Emissions permits

Energy

⇨ *Behaviour*

- none

⇨ *Resource use*

- Coal (Supply Curve)
- Conventional Oil (Supply Curve)
- Unconventional Oil (Supply Curve)
- Conventional Gas (Supply Curve)
- Unconventional Gas (Supply Curve)
- Uranium (Supply Curve)
- Biomass (Process Model)
- Land

⇨ *Electricity technologies*

- Coal (w/ o and w/ CCS)
- Gas (w/o and w/ CCS)
- Oil (w/o and w/ CCS)
- Nuclear
- Biomass (w/o and w/ CCS)
- Wind (Onshore)
- Solar PV (Central PV, Distributed PV, and Concentrating Solar Power)
- CCS

⇨ *Conversion technologies*

- CHP
- Hydrogen
  - from Coal, Oil, Gas, and biomass, w/o and w/ CCS
  - Nuclear and Solar Thermochemical
- Fuel to gas
  - Coal to Gas w/o CCS
  - Biomass (w/o and w/ CCS)
- Fuel to liquid
  - Coal to Liquids (w/o and w/ CCS)
  - Gas to Liquids (w/o and w/ CCS)
  - Biomass to Liquids (w/o and w/ CCS)

⇨ *Grid and infrastructure*

- none

⇨ *Energy technology substitution*

- Discrete technology choices with usually high substitutability through logit-choice model

⇨ *Energy service sectors*

- Transportation
- Residential and commercial
- Industry

Land use

⇨ *Land cover*

- Cropland
  - Food Crops
  - Feed Crops
  - Energy Crops
- Forest
  - Managed Forest
  - Natural Forest
- Pasture
- Shrubland

  - Tundra
  - Urban
  - Rock, Ice, Desert

Other resources

⇨ ***Other resources***

- Water
- Cement

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2 (Fossil Fuels, Cement, Land Use)
- CH_4 (Energy, Land Use, Other)
- N_2O (Energy, Land Use, Other)
- HFCs
- CFCs
- SF6

⇨ ***Pollutants***

- NO_X (Energy, Land Use)
- SO_X (Energy, Land Use)
- BC (Energy, Land Use)
- OC (Energy, Land Use)
- NH3 (Energy, Land Use)

⇨ ***Climate indicators***

- Kyoto-Gases Concentration
- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – GEM-E3

About

⇨ *Name and version*

GEM-E3

⇨ *Institution and users*

Institute of Communication and Computer Systems (ICCS), Greece

Model scope and methods

⇨ *Objective*

The model puts emphasis on: i) The analysis of market instruments for energy-related environmental policy, such as taxes, subsidies, regulations, emission permits etc., at a degree of detail that is sufficient for national, sectoral and World-wide policy evaluation. ii) The assessment of distributional consequences of programmes and policies, including social equity, employment and cohesion for less developed regions.

⇨ *Concept*

General equilibrium

⇨ *Solution method*

The model is formulated as a simultaneous system of equations with an equal number of variables. The system is solved for each year following a time-forward path. The model uses the GAMS software and is written as a mixed non-linear complementarity problem solved by using the PATH algorithm using the standard solver options.

⇨ *Anticipation*

Myopic

⇨ *Temporal dimension*

Base year: 2011, **time steps:** Five year time steps, **horizon:** 2050

⇨ *Spatial dimension*

Different spatial dimension depending on application. Main applications feature one of the two regional disaggregation below.

Number of regions: 38

1. Austria
2. Belgium
3. Bulgaria
4. Croatia
5. Cyprus
6. Czech Republic
7. Germany
8. Denmark
9. Spain
10. Estonia
11. Finland
12. France
13. United Kingdom
14. Greece
15. Hungary
16. Ireland
17. Italy
18. Lithuania
19. Luxembourg
20. Latvia
21. Malta
22. Netherlands
23. Poland

24. Portugal
25. Slovakia
26. Slovenia
27. Sweden
28. Romania
29. USA
30. Japan
31. Canada
32. Brazil
33. China
34. India
35. Oceania
36. Russian federation
37. Rest of Annex I
38. Rest of the World

Or

Number of regions: 19

1. EU28
2. USA
3. Japan
4. Canada
5. Brazil
6. China
7. India
8. South Korea
9. Indonesia
10. Mexico
11. Argentina
12. Turkey
13. Saudi Arabia
14. Oceania
15. Russian federation
16. Rest of energy producing countries
17. South Africa
18. Rest of Europe
19. Rest of the World

⇨ ***Policy implementation***

Taxes, Permits trading, Subsidies, Energy efficiency standards, CO2 standards, Emission reduction targets, Trade agreements, R&D, adaptation.

Socio economic drivers

⇨ ***Exogenous drivers***

- Total Factor Productivity
- Labour Productivity
- Capital Technical progress
- Energy Technical progress
- Materials Technical progress
- Active population growth

⇨ ***Endogenous drivers***

- Learning-by-doing

⇨ ***Development***

- GDP per capita
- Labour participation rate

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Transport
- Services
- Other

Note: GEM-E3 represents the sectors below: Agriculture, Coal, Crude Oil, Oil, Gas, Electricity supply, Ferrous metals, Non-ferrous metals, Chemical Products, Paper&Pulp, Non-metallic minerals, Electric Goods, Conventional Transport Equipment, Other Equipment Goods, Consumer Goods Industries, Construction, Air Transport, Land Transport - passenger, Land Transport – freight, Water Transport – passenger, Water Transport – freight, Biofuel feedstock, Biomass, Ethanol, Biodiesel, Advanced electric appliances, Electric vehicles, Equipment for Wind, Equipment for PV, Equipment for CCS, Market Services, Non-Market Services, Coal fired, Oil fired, Gas fired, Nuclear, Biomass, Hydroelectric, Wind, PV, CCS coal, CCS Gas

⇨ ***Cost measures***

- GDP loss
- Welfare loss
- Consumption loss

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity
- Emissions permits
- Non-energy goods
- Agriculture
- Ferrous and non-ferrous metals
- Chemical products
- Other energy intensive
- Electric goods
- Transport equipment
- Other equipment goods
- Consumer goods industries

Energy

⇨ ***Behaviour***

The GEM-E3 model endogenously computes energy consumption, depending on energy prices, realised energy efficiency expenditures and autonomous energy efficiency improvements. Each agent decides how much energy it will consume in order to optimise its behaviour (i.e. to maximise profits for firms and utility for households) subject to technological constraints (i.e. a production function). At a sectoral level, energy consumption is derived from profit maximization under a nested CES (Constant Elasticity of Substitution) specification. Energy enters the production function together with other production factors (capital, labour, materials). Substitution of energy and the rest of the production factors is imperfect (energy is considered an essential input to the production process) and it is induced by changes in the relative prices of each input. Residential energy consumption is derived from the utility maximization problem of households. Households allocate their income between different consumption categories and savings to maximize their utility subject to their budget constraint. Consumption is split between durable (i.e. vehicles, electric appliances) and non-durable goods. For durable goods, stock accumulation depends on new purchases and scrapping. Durable goods consume (non-durable) goods and services, including energy products. The latter are endogenously determined depending on the stock of durable goods and on relative energy prices.

⇨ ***Resource use***

- Coal
- Oil
- Gas
- Biomass

⇨ ***Electricity technologies***

- Coal
- Gas
- Oil
- Nuclear
- Biomass
- Wind
- Solar PV
- CCS

⇨ ***Conversion technologies***

⇨ ***Grid and infrastructure***

- Electricity

⇨ ***Energy technology substitution***

- Discrete technology choices

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***

No land-use is simulated in the current version of GEM-E3.

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6

⇨ ***Pollutants***

- NO_X
- SO_X

⇨ ***Climate indicators***

Reference card – GENeSYS-MOD 1.0

About

⇨ ***Name and version***

GENeSYS-MOD 1.0

⇨ ***Institution and users***

Technische Universität (TU) Berlin, Germany / German Institute for Economic Research (DIW Berlin), Germany

Model scope and methods

⇨ ***Objective***

The Global Energy System Model (GENeSYS-MOD) is an open-source energy system model, based on the Open-Source Energy Modelling System (OSeMOSYS). The aim is to analyse potential pathways and scenarios for the future energy system, e.g. for an assessment of climate targets. It incorporates the sectors power, heat, and transportation and specifically considers sector-coupling aspects between these traditionally segregated sectors.

⇨ ***Concept***

The model minimizes the total discounted system costs by choosing the cost-optimal mix of generation and sector-coupling technologies for the sectors power, heat, and transportation.

⇨ ***Solution method***

Linear program optimization (minimizing total discounted system costs)

⇨ ***Anticipation***

Perfect Foresight

⇨ ***Temporal dimension***

Base year: 2015, **time steps:** 2015, 2020, 2030, 2035, 2040, 2045, 2050, **horizon:** 2015-2050

⇨ ***Spatial dimension***

Number of regions: 10

1. Europe
2. Africa
3. North America
4. South America
5. Oceania
6. China and Mongolia
7. India
8. Middle East
9. Former Soviet Union
10. Remaining Asian countries (mostly South-East-Asia)

⇨ ***Policy implementation***

Emission Tax/Pricing, Emissions Budget, Fuel Taxes, Fuel Subsidies, Capacity Targets, Emission Standards, Energy Efficiency Standards

Socio economic drivers

⇨ ***Exogenous drivers***

- Technical progress (such as efficiency measures)
- GDP per capita
- Population

⇨ ***Endogenous drivers***
⇨ ***Development***

Macro economy

⇨ ***Economic sectors***
⇨ ***Cost measures***
⇨ ***Trade***

Energy

⇨ ***Behaviour***
⇨ ***Resource use***

- Coal
- Oil
- Gas
- Uranium
- Biomass

⇨ ***Electricity technologies***

- Coal
- Gas
- Oil
- Nuclear
- Biomass
- Wind (onshore & offshore)
- Solar PV (utility PV & rooftop PV)
- CSP
- Geothermal
- Hydropower
- Wave & Tidal power

⇨ ***Conversion technologies***

- CHP
- Hydrogen (Electrolysis & Fuel Cells)
- Electricity & Gas storages

⇨ ***Grid and infrastructure***

- Electricity

⇨ ***Energy technology substitution***

- Discrete technology choices
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation (split up in passenger & freight)
- Total Power Demand
- Heat (divided up in warm water / space heating & process heat)

Land use

⇨ ***Land cover***

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2

- ⇨ ***Pollutants***
- ⇨ ***Climate indicators***

Reference card – GRAPE-15 1.0

About

⇨ *Name and version*

GRAPE-15 1.0

⇨ *Institution and users*

The Institute of Applied Energy, Japan – https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-13

Model scope and methods

⇨ *Objective*

GRAPE is an integrated assessment model with inter-temporal optimization model, which consists of modules of energy, macro economy, climate, land use and environmental impacts.

⇨ *Concept*

⇨ *Solution method*

Partial equilibrium (fixed demand) inter-temporal optimisation

⇨ *Anticipation*

Perfect foresight

⇨ *Temporal dimension*

Base year: 2005**, time steps:** 5 years, **horizon:** 2110

⇨ *Spatial dimension*

Number of regions: 15

1. Canada
2. USA
3. Western Europe
4. Japan
5. Oceania
6. China
7. Southeast Asia
8. India
9. Middle East
10. Sub-Sahara Africa
11. Brazil
12. Other Latin America
13. Central Europe
14. Eastern Europe
15. Russia

⇨ *Policy implementation*

Emissions Taxes/Pricing, Cap and Trade, Land Protection

Socio economic drivers

⇨ *Exogenous drivers*

- Population
- Population age Structure
- Education Level
- Urbanisation Rate
- GDP
- Income Distribution
- Total Factor Productivity
- Autonomous Energy Efficiency Improvements

⇨ *Endogenous drivers*

- none

⇨ *Development*

- Income distribution in a region (exogenous)

- Urbanisation rate (exogenous)
- Education level (exogenous)

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- Transport
- Services

⇨ ***Cost measures***

- GDP loss
- Welfare loss
- Consumption loss
- Energy system costs

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity
- Bioenergy crops
- Food crops
- Non-energy goods

Energy

⇨ ***Behaviour***

- none

⇨ ***Resource use***

- Coal (Supply Curve)
- Conventional Oil (Supply Curve)
- Unconventional Oil (Supply Curve)
- Conventional Gas (Supply Curve)
- Unconventional Gas (Supply Curve)
- Uranium (Supply Curve)
- Biomass (Supply Curve)
- Water (Process Model)
- Land

⇨ ***Electricity technologies***

- Coal (w/o and w/ CCS)
- Gas (w/o and w/ CCS)
- Oil (w/o and w/ CCS)
- Nuclear
- Biomass (w/o and w/ CCS)
- Wind (Onshore and Offshore)
- Solar PV (Central and Distributed)
- Geothermal
- Hydroelectric

⇨ ***Conversion technologies***

- CHP
- Coal/Oil/Gas/Biomass-to-Heat
- Hydrogen
    - Coal-to-H2 (w/o and w/ CCS)
    - Oil-to-H2 (w/o and w/ CCS)

  - Gas-to-H2 (w/o and w/ CCS)
  - Biomass-to-H2 (w/o CCS)
  - Nuclear and Solar Thermochemical
  - Electrolysis
- Fuel to gas
  - Coal-to-Gas (w/o and w/ CCS)
- Fuel to liquid
  - Coal-to-liquids (w/o and w/ CCS)
  - Gas-to-liquids (w/o and w/ CCS)
  - Biomass-to-liquids (w/o and w/ CCS)
  - Oil Refining

⇨ ***Grid and infrastructure***

- Electricity
- Gas
- Heat
- CO_2
- H_2

⇨ ***Energy technology substitution***

- Discrete technology choices with mostly high substitutability through linear choice (lowest cost)
- Expansion and decline constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***

- Energy Cropland
- Forest
- Pastures
- Built-up Area

Other resources

⇨ ***Other resources***

- Water

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
  - Fossil Fuels
  - Land Use
- CH_4
  - Energy
  - Land Use
- N_2O
  - Energy
- HFCs
- CFCs
- SF6
- CO
  - Energy Use

⇨ ***Pollutants***

Only for energy

- NO_X
- SO_X
- BC
- OC
- Ozone

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – ETP Model

About

⇨ ***Name and version***

ETP Model, version 3

⇨ ***Institution and users***

International Energy Agency – http://www.iea.org/etp/etpmodel/

Model scope and methods

⇨ ***Objective***

The analysis and modelling aim to identify an economical way for society to reach the desired outcomes of reliable, affordable and clean energy. For a variety of reasons the scenario results do not necessarily reflect the least-cost ideal. The ETP analysis takes into account those policies that have already been implemented or decided. In the short term, this means that deployment pathways may differ from what would be most cost-effective. In the longer term, the analysis emphasises a normative approach, and fewer constraints governed by current political objectives apply in the modelling. The objective of this methodology is to provide a model for a cost-effective transition to a sustainable energy system.

⇨ ***Concept***

Partial equilibrium (fixed energy service and material demands), with the exception for the transport sector where avoid and shift policies are being considered.

⇨ ***Solution method***

Optimization for power, other transformation and industry sectors; simulation for agriculture, residential, services and transport sectors

⇨ ***Anticipation***

Inter-temporal (foresight)

⇨ ***Temporal dimension***

Base year: 2014**, time steps:** 5 years, **horizon:** 2060

⇨ ***Spatial dimension***

Number of regions: differs between energy sectors (28-39 model regions)

1. Asian countries except Japan
2. Countries of the Middle East and Africa
3. Latin American countries
4. OECD90 and EU (and EU candidate) countries
5. Countries from the Reforming Economies of the Former Soviet Union
6. World
7. OECD countries
8. Non-OECD countries
9. Brazil
10. China
11. South Africa
12. Russia
13. India
14. ASEAN region countries
15. USA
16. European Union (28 member countries)
17. Mexico

⇨ ***Policy implementation***

Emission Tax/Pricing, Cap and Trade, Fuel Taxes, Fuel Subsidies, Feed-in-Tariff, Portfolio Standards, Capacity Targets, Emission Standards, Energy Efficiency Standards

Socio economic drivers

⇨ ***Exogenous drivers***

– Population

- Urbanisation rate
- GDP
- Autonomous Energy Efficiency Improvements

⇨ ***Endogenous drivers***

- none

⇨ ***Development***

- none

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Residential
- Services
- Transport
- Power
- Other transformation

⇨ ***Cost measures***

- None

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity - Yes

Energy

⇨ ***Behaviour***

- none

⇨ ***Resource use***

- Coal - Supply Curve
- Conventional Oil - Process Model
- Unconventional Oil - Supply Curve
- Conventional Gas - Process Model
- Unconventional Gas - Supply Curve
- Bioenergy - Supply Curve

⇨ ***Electricity technologies***

- Coal (w/o and w/ CCS)
- Gas (w/o and w/ CCS)
- Oil (w/o and w/ CCS)
- Nuclear
- Biomass (w/o and w/ CCS)
- Solar Power (Central PV, Distributed PV, and CSP)
- Wind Power (Onshore and Offshore)
- Hydroelectric Power
- Ocean Power

⇨ ***Conversion technologies***

- Coal to Hydrogen (w/o CCS and w/ CCS)
- Natural Gas to Hydrogen (w/o CCS and w/ CCS)
- Oil to Hydrogen (w/o CCS)
- Biomass to Hydrogen (w/o CCS and w/ CCS)
- Coal to Liquids (w/o CCS and w/ CCS)
- Gas to Liquids(w/o CCS and w/ CCS)
- Bioliquids (w/o CCS and w/ CCS)

- Oil Refining
- Coal to Gas (w/o CCS and w/ CCS)
- Oil to Gas (w/o CCS and w/ CCS)
- Biomass to Gas (w/o CCS and w/ CCS)
- Coal Heat
- Natural Gas Heat
- Oil Heat
- Biomass Heat
- Geothermal Heat
- Solarthermal Heat
- CHP (coupled heat and power)

⇨ ***Grid and infrastructure***

- Electricity (spatially explicit)
- Gas (aggregate)
- Heat (aggregate)
- Hydrogen (aggregate)
- CO_2 (spatially explicit)
- Gas spatially explicit for gas pipelines and LNG infrastructure between model regions

⇨ ***Energy technology substitution***

- Lowest cost with adjustment penalties. Discrete technology choices with mostly high substitutability in some sectors and mostly low substitutability in other sectors
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential & Commercial

Land use

⇨ ***Land cover***

  - Not represented by the model

Other resources

⇨ ***Other resources***

- none

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2 Fossil Fuels (endogenous & controlled)
- CO_2 Cement (endogenous & controlled)

⇨ ***Pollutants***

- none

⇨ ***Climate indicators***

- none

Reference card – IEA World Energy Model

About

- ⇨ ***Name and version***

IEA World Energy Model (version 2016)

- ⇨ ***Institution and users***

International Energy Agency - https://www.iea.org/weo/
http://www.iea.org/media/weowebsite/2017/WEM_Documentation_WEO2017.pdf

Model scope and methods

- ⇨ ***Objective***

The model is a large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the World Energy Outlook (WEO) scenarios.

- ⇨ ***Concept***

Partial equilibrium (price elastic demand)

- ⇨ ***Solution method***

Simulation

- ⇨ ***Anticipation***

Mix of "Inter-temporal (foresight)" and "Recursive-dynamic (myopic)"

- ⇨ ***Temporal dimension***

Base year: 2014, time steps: 1 year steps, horizon: 2050

- ⇨ ***Spatial dimension***

Number of regions:

11. United States
12. Canada
13. Mexico
14. Chile
15. Japan
16. Korea
17. OECD Oceania
18. Other OECD Europe
19. France, Germany, Italy, United Kingdom
20. Europe 21 excluding EUG4
21. Europe 7
22. Eurasia
23. Russia
24. Caspian
25. China
26. India
27. Indonesia
28. South East Asia (excluding Indonesia)
29. Rest of Other Developing Asia
30. Brazil
31. Other Latin America
32. North Africa
33. Other Africa
34. South Africa
35. Middle East

- ⇨ ***Policy implementation***

Emission Tax/Pricing, Cap and Trade (global and regional), Fuel Taxes, Fuel Subsidies, Feed-in-Tariff, Portfolio Standard, Capacity Targets, Emission Standards, Energy Efficiency Standards

Socio economic drivers

⇨ ***Exogenous drivers***

- Population (exogenous)
- Urbanization Rate (exogenous)
- GDP (exogenous)

⇨ ***Endogenous drivers***

- Autonomous Energy Efficiency Improvements (endogenous)

⇨ ***Development***

Macro economy

⇨ ***Economic sectors***

- Agriculture (economic)
- Industry (physical & economic)
- Services (economic)
- Energy (physical & economic)

⇨ ***Cost measures***

- Energy System Cost Mark-Up

⇨ ***Trade***

- Coal
- Oil
- Gas
- Bioenergy crops
- Emissions permits

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

- Coal (Process Model)
- Conventional Oil (Process Model)
- Unconventional Oil (Process Model)
- Conventional Gas (Process Model)
- Unconventional Gas (Process Model)
- Bioenergy (Process Model)

⇨ ***Electricity technologies***

- Coal
- Gas
- Oil
- Nuclear
- Geothermal
- Biomass
- Wind (Onshore and Offshore)
- Solar PV (Central and distributed)
- CCS
- CSP
- Hydropower
- Ocean power

Note: CCS can be combined with coal, gas and biomass power generation technologies

⇨ ***Conversion technologies***

- Natural Gas to Hydrogen w/o CCS
- Coal to Liquids w/o CCS
- Coal to Gas w/o CCS
- Coal Heat

- Natural Gas Heat
- Oil Heat
- Biomass Heat
- Geothermal Heat
- Solarthermal Heat
- CHP (coupled heat and power)

⇨ ***Grid and infrastructure***

- Electricity (aggregate)
- Gas (aggregate)

⇨ ***Energy technology substitution***

- Logit choice model
- Weibull function
- Discrete technology choices with mostly high substitutability in some sectors and mostly low substitutability in other sectors
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***

- Not covered by the model

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases****

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6

⇨ ***Pollutants****

- NOx
- SOx
- BC
- OC
- CO
- NH_3
- VOC

*NOTE: Non-energy CO_2, non-energy CH_4, non-energy N_2O, CFC, HFC, SF_6, CO, NOx, VOC, SO_2, are assumptions-based and not disaggregated (only total emissions are available).

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – IMACLIM

About

⇨ *Name and version*

IMACLIM 1.1 (Advance), IMACLIM-NLU 1.0 (EMF33)

⇨ *Institution and users*

Centre international de recherche sur l'environnement et le développement (CIRED), France, http://www.centre-cired.fr.

Societe de Mathematiques Appliquees et de Sciences Humaines (SMASH), France, http://www.smash.fr.

Model scope and methods

⇨ *Objective*

Imaclim-R is intended to study the interactions between energy systems and the economy, to assess the feasibility of low carbon development strategies and the transition pathway towards low carbon future.

⇨ *Concept*

Hybrid: general equilibrium with technology explicit modules. Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between two years parameters to the equilibrium evolve according to specified functions.

⇨ *Solution method*

Imaclim-R is implemented in Scilab, and uses the function fsolve from a shared C++ library to solve the static equilibrium system of non-linear equations.

⇨ *Anticipation*

Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between two years parameters to the equilibrium evolve according to specified functions.

⇨ *Temporal dimension*

Base year: 2001**, time steps:** Annual, **horizon:** 2050 or 2100

⇨ *Spatial dimension*

Number of regions: 12

1. USA
2. Canada
3. Europe
4. China
5. India
6. Brazil
7. Middle East
8. Africa
9. Commonwealth of Independent States
10. OECD Pacific
11. Rest of Asia
12. Rest of Latin America

⇨ *Policy implementation*

Baseline do not include explicit climate policies. Climate/energy policies can be implemented in a number of ways, depending on the policy. A number of general or specific policy choices can be modelled including: Emissions or energy taxes, permit trading, specific technology subsidies, regulations, technology and/or resource constraints

Socio economic drivers

⇨ *Exogenous drivers*

- Labour Productivity
- Energy Technical progress
- Population
- Active population

Note: Our model growth engine is composed of exogenous trends of active population growth and exogenous trends of labour productivity growth. The two sets of assumptions on demography and labour productivity, although exogenous, only prescribe natural growth. Effective growth results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) rigidities, such as fixed technologies, immobility of the installed capital across sectors or rigidities in real wages, which may lead to partial utilization of production factors (labour and capital).

⇨ ***Endogenous drivers***

⇨ ***Development***

- GDP per capita

Macro economy

⇨ ***Economic sectors***

- Agriculture
- Industry
- Energy
- *Transport*
- *Services*
- *Construction*

Note: The energy sector is divided into five sub-sectors: oil extraction, gas extraction, coal extraction, refinery, power generation. The transport sector is divided into three sub-sectors: terrestrial transport, air transport, water transport. The industry sector has one sub-sector: Energy intensive industry.

⇨ ***Cost measures***

- GDP loss
- Welfare loss
- Consumption loss
- Energy system costs

⇨ ***Trade***

- Coal
- Oil
- Gas
- Electricity
- Bioenergy crops
- Capital
- Emissions permits
- Non-energy goods
- Refined Liquid Fuels

Energy

⇨ ***Behaviour***

Price response (via elasticities), and non-price drivers (infrastructure and urban forms conditioning location choices, different asymptotes on industrial goods consumption saturation levels with income rise, speed of personal vehicle ownership rate increase, speed of residential area increase).

⇨ ***Resource use***

- Coal
- Oil
- Gas
- Biomass

⇨ ***Electricity technologies***

- Coal
- Gas
- Oil
- Nuclear
- Biomass

- Wind
- Solar PV
- CCS

⇨ ***Conversion technologies***

- Fuel to liquid

⇨ ***Grid and infrastructure***

- Electricity

⇨ ***Energy technology substitution***

- Discrete technology choices
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial
- Agriculture

Land use

⇨ ***Land cover***

- Cropland
- Forest
- Extensive Pastures
- Intensive Pastures
- Inaccessible Pastures
- Urban Areas
- Unproductive Land

Note:
IMACLIM 1.1 (Advance) : Bioenergy production is determined by the fuel and electricity modules of Imaclim-R using supply curves from Hoogwijk et al. (2009) (bioelectricity) and IEA (biofuel).
IMACLIM-NLU 1.0 (EMF33) : In this version the Imaclim-R model in linked to the land use mode Nexus Land use. Bioenergy demand level is determined by the fuel and electricity modules of Imaclim-R. The Nexus Land use gives the corresponding price of biomass feedstock, taking into account the land constaints and food production The production of biomass for electricity and ligno-cellulosic fuels is located on marginal lands (i.e., less fertile or accessible lands). By increasing the demand for land, and spurring agricultural intensification, Bioenergy propels land and food prices.

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2

⇨ ***Pollutants***

⇨ ***Climate indicators***

Reference card – IMAGE

About

⇨ *Name and version*

IMAGE framework 3.0

⇨ *Institution and users*

Utrecht University (UU), Netherlands, http://www.uu.nl.
PBL Netherlands Environmental Assessment Agency (PBL), Netherlands, http://www.pbl.nl.

Model scope and methods

⇨ *Objective*

IMAGE is an ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. The objective of the IMAGE model is to explore the long- term dynamics and impacts of global changes that result. More specifically, the model aims

1. to analyse interactions between human development and the natural environment to gain better insight into the processes of global environmental change;
2. to identify response strategies to global environmental change based on assessment of options and
3. to indicate key inter-linkages and associated levels of uncertainty in processes of global environmental change.

⇨ *Concept*

The IMAGE framework can best be described as a geographically explicit assessment, integrated assessment simulation model, focusing a detailed representation of relevant processes with respect to human use of energy, land and water in relation to relevant environmental processes.

⇨ *Solution method*

Recursive dynamic solution method

⇨ *Anticipation*

Simulation modelling framework, without foresight. However, a simplified version of the energy/climate part of the model (called FAIR) can be run prior to running the framework to obtain data for climate policy simulations.

⇨ *Temporal dimension*

Base year: 1970**, time steps:** 1-5 year time step, **horizon:** 2100

⇨ *Spatial dimension*

Number of regions: 26

21. Canada
22. USA
23. Mexico
24. Rest of Central America
25. Brazil
26. Rest of South America
27. Northern Africa
28. Western Africa
29. Eastern Africa
30. South Africa
31. Western Europe
32. Central Europe
33. Turkey
34. Ukraine +
35. Asian-Stan
36. Russia +
37. Middle East
38. India +
39. Korea
40. China +

41. Southeastern Asia
42. Indonesia +
43. Japan
44. Oceania
45. Rest of South Asia
46. Rest of Southern Africa

⇨ ***Policy implementation***

Key areas where policy responses can be introduced in the model are:

- Climate policy
- Energy policies (air pollution, access and energy security)
- Land use policies (food)
- Specific policies to project biodiversity
- Measures to reduce the imbalance of the nitrogen cycle

Socio economic drivers

⇨ ***Exogenous drivers***

- Exogenous GDP
- GDP per capita
- Population

⇨ ***Endogenous drivers***

- Energy demand
- Renewable price
- Fossil fuel prices
- Carbon prices
- Technology progress
- Energy intensity
- Preferences
- Learning by doing
- Agricultural demand
- Value added

⇨ ***Development***

- GDP per capita
- Income distribution in a region
- Urbanisation rate

Note: GDP per capita and income distribution are exogenous

Macro economy

⇨ ***Economic sectors***

Note: No explicit economy representation in monetary units. Explicit economy representation in terms of energy is modelled (for the agriculture, industry, energy, transport and built environment sectors)

⇨ ***Cost measures***

- Area under MAC
- Energy system costs

⇨ ***Trade***

- Coal
- Oil
- Gas
- Uranium
- Bioenergy crops
- Food crops
- Emissions permits
- Non-energy goods
- Bioenergy products

- Livestock products

Energy

⇨ *Behaviour*

In the energy model, substitution among technologies is described in the model using the multinomial logit formulation. The multinomial logit model implies that the market share of a certain technology or fuel type depends on costs relative to competing technologies. The option with the lowest costs gets the largest market share, but in most cases not the full market. We interpret the latter as a representation of heterogeneity in the form of specific market niches for every technology or fuel.

⇨ *Resource use*

- Coal
- Oil
- Gas
- Uranium
- Biomass

Note: Distinction between traditional and modern biomass

⇨ *Electricity technologies*

- Coal w/ CCS
- Coal w/o CCS
- Gas w/ CCS
- Gas w/o CCS
- Oil w/ CCS
- Oil w/o CCS
- Nuclear
- Biomass w/ CCS
- Biomass w/o CCS
- Wind
- Solar PV
- CSP
- Hydropower
- Geothermal

Note: wind: onshore and offshore; coal: conventional, IGCC, IGCC + CCS, IGCC + CHP, IGCC + CHP + CCS; oil: conventional, OGCC, OGCC + CCS, OGCC + CHP, OGCC + CHP + CCS); natural gas: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS; biomass: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS
hydropower and geothermal: exogenous

⇨ *Conversion technologies*

- CHP
- Hydrogen

⇨ *Grid and infrastructure*

- Electricity

⇨ *Energy technology substitution*

- Discrete technology choices
- Expansion and decline constraints
- System integration constraints

⇨ *Energy service sectors*

- Transportation
- Industry
- Residential and commercial

Land use

⇨ *Land cover*

- Forest
- Cropland

- Grassland
- Abandoned land
- Protected land

Other resources

⇨ ***Other resources***

- Water
- Metals
- Cement

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6
- PFCs

⇨ ***Pollutants***

- NO_X
- SO_X
- BC
- OC
- Ozone
- VOC
- NH3
- CO

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – MERGE-ETL 6.0

About

⇨ *Name and version*

MERGE-ETL 6.0

⇨ *Institution and users*

Paul Scherrer Institut
https://www.psi.ch/eem/ModelsEN/2012MergeDescription.pdf
https://www.psi.ch/eem/ModelsEN/2014MergeCalibration.pdf

Model scope and methods

⇨ *Objective*

MERGE (Model for Evaluating Regional and Global Effects of GHG reductions policies) is an integrated assessment model originally developed by Manne et al. (1995). It divides the world in geopolitical regions, each one represented by two coupled submodels describing the energy and economic sectors, respectively. MERGE acts as a global social planner with perfect foresight and determines the economic equilibrium in each region that maximizes global welfare, defined as a linear combination of the current and future regional welfares. Besides these regional energy-economic submodels, and linked to them, MERGE includes global submodels of greenhouse gas emissions and the climate to allow the analysis of the effectiveness and impacts of climate policies and the role of technologies to realize climate targets. The model is sufficiently flexible to explore views on a wide range of contentious issues: costs of abatement, damages of climate change, valuation and discounting.

⇨ *Concept*

The MERGE-ETL model is a hard-linked hybrid model as the energy sectors are fully integrated with the rest of the economy. The model combines a bottom-up description of the energy system disaggregated into electric and non-electric sectors, a top-down economic model based on macroeconomic production functions, and a simplified climate cycle model. The energy sectors endogenously accounts for technological change with explicit representation of two-factor learning curves.

⇨ *Solution method*

General equilibrium (closed economy). Two different solutions can be produced: a cooperative globally optimal solution and a non-cooperative solution equivalent to Nash equilibrium. It is programmed in GAMS and uses the CONOPT solver.

⇨ *Anticipation*

Inter-temporal (foresight) or myopic.

⇨ *Temporal dimension*

Base year: 2015**, time steps:** 10 years, **horizon:** 2015-2100

⇨ *Spatial dimension*

Number of regions: 10

1.	EUP	European Union
2.	RUS	Russia
3.	MEA	Middle East
4.	IND	India
5.	CHI	China
6.	JPN	Japan
7.	CANZ	Canada, Australia and New Zealand
8.	USA	United States of America
9.	ROW	Rest of the World
10.	SWI	Switzerland

⇨ *Policy implementation*

Emission Tax/Pricing, Cap and Trade, Fuel Taxes, Fuel Subsidies, Feed-in-Tariff, Portfolio Standard, Capacity Targets

Socio economic drivers

⇨ *Exogenous drivers*

Population, Population Age Structure, Autonomous Energy Efficiency Improvements

⇨ *Development*

GDP

Macro economy

⇨ *Economic sectors*

- One final good
- Electric and non-electric demand sectors

⇨ *Cost measures*

- GDP loss
- Welfare loss
- Consumption loss
- Area under MAC
- Energy system costs

⇨ *Trade*

- Non-Energy goods
- Coal
- Oil
- Gas
- Uranium
- Bioenergy crops
- Emissions permits

Energy

⇨ *Behaviour*

- Considered in side-constraints controlling technology deployment rates

⇨ *Resource use*

- Coal
- Conventional Oil
- Unconventional Oil
- Conventional Gas
- Unconventional Gas
- Uranium
- Bioenergy

Note: Cost-supply curves for the different resources are considered

⇨ *Electricity technologies*

- Coal
- Gas
- Oil
- Nuclear
- Biomass
- Wind
- Solar PV
- Hydrogen

Note: CCS can be combined with coal, gas and biomass power generation technologies

⇨ *Conversion technologies*

- Hydrogen
- Fuel to liquids

Note: CCS can be combined with coal, gas and biomass technologies

⇨ *Grid and infrastructure*

- Electricity

- Gas
- CO_2
- H_2

⇨ ***Energy technology substitution***

- Expansion and decline constraints
- System integration constraints
- Early technology retirement

⇨ ***Energy service sectors***

- Electric and non-electric demand that is further disaggregated to seven energy sectors/fuels, namely coal, oil, gas, biofuels, hydrogen, solar and heat

Land use

⇨ ***Land cover***

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- SF6

⇨ ***Pollutants***

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)
- Climate damages $ or equivalent

Reference card – MESSAGE(ix)-GLOBIOM

About

⇨ ***Name and version***

MESSAGE-GLOBIOM 1.0 and MESSAGE*ix*-GLOBIOM 1.0

⇨ ***Institution and users***

International Institute for Applied Systems Analysis (IIASA), Austria, global model description: http://data.ene.iiasa.ac.at/message-globiom/. Model documentation and code (MESSAGE*ix*) http://messageix.iiasa.ac.at

main users: IIASA, the MESSAGE model is distributed via the International Atomic Energy Agency (IAEA) to member countries, the new MESSAGE*ix* model is available as an open source tool via GitHub (https://github.com/iiasa/message_ix)

Model scope and methods

⇨ ***Objective***

MESSAGE-GLOBIOM is an integrated assessment framework designed to assess the transformation of the energy and land systems vis-a-vis the challenges of climate change and other sustainability issues. It consists of the energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregated macro-economic model MACRO and the simple climate model MAGICC.

⇨ ***Concept***

Hybrid model (energy engineering and land use partial equilibrium models soft-linked to macro-economic general equilibrium model)

⇨ ***Solution method***

Hybrid model (linear program optimization for the energy systems and land use modules, non-linear program optimization for the macro-economic module)

⇨ ***Anticipation***

Myopic/Perfect Foresight (MESSAGE can be run both with perfect foresight and myopically, while GLOBIOM runs myopically)

⇨ ***Temporal dimension***

Base year: 2010, **time steps:** 1990, 1995, 2000, 2005, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110, **horizon:** 1990-2110

⇨ ***Spatial dimension***

Number of regions: 11+1

36. AFR (Sub-Saharan Africa)
37. CPA (Centrally Planned Asia & China)
38. EEU (Eastern Europe)
39. FSU (Former Soviet Union)
40. LAM (Latin America and the Caribbean)
41. MEA (Middle East and North Africa)
42. NAM (North America)
43. PAO (Pacific OECD)
44. PAS (Other Pacific Asia)
45. SAS (South Asia)
46. WEU (Western Europe)
47. GLB (international shipping)

⇨ ***Policy implementation***

GHG and energy taxes; GHG emission cap and permits trading; energy taxes and subsidies; micro-financing (for energy access analysis); regulation: generation capacity, production and share targets

Socio economic drivers

⇨ ***Exogenous drivers***

- Labour Productivity
- Energy Technical progress

- GDP per capita
- Population

⇨ ***Endogenous drivers***

⇨ ***Development***

- GDP per capita
- Income distribution in a region
- Number of people relying on solid cooking fuels

Macro economy

⇨ ***Economic sectors***

Note: MACRO represents the economy in a single sector with the production function including capital, labour and energy nests

⇨ ***Cost measures***

- GDP loss
- Consumption loss
- Area under MAC
- Energy system costs

⇨ ***Trade***

- Coal
- Oil
- Gas
- Uranium
- Electricity
- Food crops
- Emissions permits

Note: bioenergy is only traded after processing to a secondary fuel (e.g., liquid biofuel)

Energy

⇨ ***Behaviour***

Non-monetary factors of decision making (e.g., behavioural impacts) are represented in MESSAGE via so-called inconvenience costs. These are generally included in the consumer-dominated energy end-use sectors (transportation sector, residential and commercial sector) and are particularly relevant in the modelling of energy access in developing countries.

⇨ ***Resource use***

- Coal
- Oil
- Gas
- Uranium
- Biomass

Note: modern and traditional applications of biomass are distinguished

⇨ ***Electricity technologies***

- Coal w /o CCS
- Coal w/ CCS
- Gas w/o CCS
- Gas w/ CCS
- Oil w/o CCS
- Biomass w/o CCS
- Biomass w/ CCS
- Nuclear
- Wind Onshore
- Wind Offshore
- Solar PV
- *CSP*

- *Geothermal*
- *Hydropower*

Note: CCS can be combined with coal, gas and biomass power generation technologies

⇨ ***Conversion technologies***

- CHP
- Hydrogen
- Fuel to gas
- Fuel to liquid

Note: CHP can be combined with all thermal power plant types, Hydrogen can be produced from coal, gas and biomass feedstocks and electricity, Fuel to liquids is represented for coal, gas and biomass feedstocks, Fuel to gas is represented for coal and biomass feedstocks

⇨ ***Grid and infrastructure***

- Electricity
- Gas
- Heat
- CO_2
- Hydrogen

⇨ ***Energy technology substitution***

- Discrete technology choices
- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Note: non-energy use (feedstock) of energy carriers is separately represented, but generally reported under industry

Land use

⇨ ***Land cover***

- Forest (natural/managed)
- Short-rotation plantations
- Cropland
- Grassland
- Other natural land

Other resources

⇨ ***Other resources***

- Water
- Cement

Note: cement is not modelled as a separate commodity, but process emissions from cement production are represented

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6

⇨ ***Pollutants***

- NOx

- SOx
- BC
- OC
- *CO*
- *NH3*
- *VOC*

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)

Reference card – POLES

About

⇨ *Name and version*

POLES ADVANCE (other versions are in use in other applications)

⇨ *Institution and users*

JRC - Joint Research Centre - European Commission (EC-JRC), Belgium, http://ec.europa.eu/jrc/en/poles. main users: - European Commission, JRC - Université de Grenoble UPMF, France - Enerdata

Model scope and methods

⇨ *Objective*

POLES was originally developed to assess energy markets, combining a detailed description of energy demand, transformation and primary supply for all energy vectors. It provides full energy balances on a yearly basis using frequent data updates to as to deliver robust forecasts for both short and long-term horizons. It has quickly been used, in the late 90s, to assess energy-related CO2 mitigation policies. Over time other GHG emissions have been included (energy and industry non-CO2 from the early 2000s), and linkages with agricultural and land use models have been progressively implemented.

⇨ *Concept*

Partial equilibrium

⇨ *Solution method*

Recursive simulation

⇨ *Anticipation*

Myopic

⇨ *Temporal dimension*

Base year: 1990-2015 (data up to current time -1/-2)**, time steps:** yearly, **horizon:** 2050-2100

⇨ *Spatial dimension*

Number of regions: 66

⇨ *Policy implementation*

- Energy taxes per sector and fuel, carbon pricing - Feed-in tariffs, green certificates, low interest rates, investment subsidies - Fuel efficiency standards in vehicles and buildings, white certificates

Socio economic drivers

⇨ *Exogenous drivers*

- Exogenous GDP
- Population

⇨ *Endogenous drivers*

- Value added
- Mobility needs
- Fossil fuel prices
- Buildings surfaces

⇨ *Development*

- GDP per capita
- Urbanisation rate

Macro economy

⇨ *Economic sectors*

- Agriculture
- Industry
- Services

⇨ *Cost measures*

- Area under MAC
- Energy system costs

Note: Investments: supply-side only

⇨ ***Trade***
- Coal
- Oil
- Gas
- Bioenergy crops
- Emissions permits
- Liquid biofuels

Energy

⇨ ***Behaviour***

Activity drivers depend on income per capita and energy prices via elasticities. Energy demand depends on activity drivers, energy prices and technology costs. Primary energy supply depends on remaining resources, production cost and price effects.

⇨ ***Resource use***
- Coal
- Oil
- Gas
- Uranium
- Biomass

⇨ ***Electricity technologies***
- Coal
- Gas
- Oil
- Nuclear
- Biomass
- Wind
- Solar PV
- CCS
- Hydropower
- Geothermal
- Solar CSP
- Ocean

⇨ ***Conversion technologies***
- CHP
- Hydrogen
- Fuel to liquid

⇨ ***Grid and infrastructure***
- Gas
- H_2

⇨ ***Energy technology substitution***

⇨ ***Energy service sectors***
- Transportation
- Industry
- Residential and commercial

Land use

⇨ ***Land cover***
- Cropland
- Forest
- Grassland
- Urban Areas
- Desert

Other resources

- ⇨ ***Other resources***

– Metals

Note: Steel tons

Emissions and climate

- ⇨ ***Greenhouse gases***

– CO_2

– CH_4

– N_2O

– HFCs

– SF_6

– PFCs

- ⇨ ***Pollutants***
- ⇨ ***Climate indicators***

Reference card – REMIND - MAgPIE

About

⇨ *Name and version*

REMIND 1.7 – MAgPIE 3.0

⇨ *Institution and users*

Potsdam Institut für Klimafolgenforschung (PIK), Germany,
https://www.pik-potsdam.de/research/sustainable-solutions/models/remind
https://redmine.pik-potsdam.de/projects/magpie/wiki/Overview

Model scope and methods

⇨ *Objective*

REMIND (Regionalized model of investment and development) is a global multi-regional model incorporating the economy, the climate system and a detailed representation of the energy sector. It allows analysing technology options and policy proposals for climate mitigation, and models regional energy investments and interregional trade in goods, energy carriers and emissions allowances.

MAgPIE (Model of Agricultural Production and its Impact on the Environment) is a global land use allocation model. MAgPIE derives future projections of spatial land use patterns, yields and regional costs of agricultural production.

⇨ *Concept*

- REMIND: Hybrid model that couples an economic growth model with a detailed energy system model and a simple climate model.
- MAgPIE: Gridded land use model with economic regions. Coupled to the grid-based dynamic vegetation model LPJmL providing gridded input on potential crop yields, water availabiility and terrestrial carbon content under various climate conditions.

⇨ *Solution method*

- REMIND: Inter-temporal optimization that maximizes cumulated discounted global welfare: Ramsey-type growth model with Negishi approach to regional welfare aggregation.
- MAgPIE: Partial equilibrium model with recursive-dynamic optimization. Optimal spatial patterns of land allocation and use are based on regional production cost minimization to meet a given amount of regional bioenergy and price-inelastic food and other agricultural demand.

⇨ *Anticipation*

- REMIND: Perfect Foresight
- MAgPIE: Myopic

⇨ *Temporal dimension*

- REMIND: Base year:2005**, time steps:** flexible time steps, default is 5-year time steps until 2050 and 10-year time steps until 2100; period from 2100-2150 is calculated to avoid distortions due to end effects, but typically only the time span 2005-2100 is used for model applications.
- MAgPIE: Base year: 1995, time steps: 5 and/or 10 years, horizon: 1995-2100

⇨ *Spatial dimension*

Number of regions: 11

1. AFR - Sub-Saharan Africa (excluding South Africa)
2. CHN - China
3. EUR - European Union
4. JPN - Japan
5. IND - India
6. LAM - Latin America
7. MEA - Middle East, North Africa, and Central Asia
8. OAS - other Asian countries (mainly South-East Asia)
9. RUS - Russia
10. ROW - rest of the World (Australia, Canada, New Zealand, Non-EU Europe, South Africa)
11. USA - United States of America

Note: MAgPIE operates on 10 socio-economic world regions which are mapped into REMIND-defined regions.

⇨ ***Policy implementation***

- REMIND: Pareto-optimal achievement of policy targets on temperature, radiative forcing, GHG concentration, or cumulative carbon budgets. Alternatively, calculation of Nash equilibrium without internalized technology spillovers. Possibility to analyse changes in expectations about climate policy goals as well as pre-specified policy packages until 2030/2050, including e.g. energy capacity and efficiency targets, renewable energy quotas, carbon and other taxes, and energy subsidies
- MAgPIE: Pricing of land carbon and agricultural emissions, land use regulation, REDD+ policies, afforestation, agricultural trade policies

Socio economic drivers

⇨ ***Exogenous drivers***

- REMIND: Labour productivity, energy efficiency parameters of the production function, population
- MAgPIE: Demand for bioenergy, food, feed, and material demand from the agricultural sector

⇨ ***Endogenous drivers***

  - REMIND: Investments in industrial capital stock. Endogenous learning-by-doing for wind and solar power as well as electric and fuel cell vehicle technologies (global learning curve, internalized spillovers).
  - MAgPIE: Investments in agricultural productivity, land conversion and (re)allocation of agricultural production.

⇨ ***Development***

- REMIND: GDP per capita

Macro economy (REMIND)

⇨ ***Economic sectors***

Note: The macro-economic part contains a single sector representation of the entire economy. A generic final good is produced from capital, labour, and different final energy types

⇨ ***Cost measures***

- GDP loss
- Welfare loss
- Consumption loss

⇨ ***Trade***

- Coal
- Oil
- Gas
- Uranium
- Bioenergy crops
- Capital
- Emissions permits
- Non-energy goods

Energy (REMIND)

⇨ ***Behaviour***

Price response through CES production function. No explicit modelling of behavioural change. Baseline energy demands are calibrated in such a way that the energy demand patterns in different regions slowly converge when displayed as per capita energy demand over per capita GDP"

⇨ ***Resource use***

- Coal
- Oil
- Gas
- Uranium
- Biomass

⇨ ***Electricity technologies***

- Coal (with and w/o CCS)
- Gas (with and w/o CCS)
- Oil (with and w/o CCS)
- Nuclear
- Biomass (with and w/o CCS)
- Wind
- Solar PV
- CCS
- *Solar CSP*
- *Hydropower*
- *Geothermal*

⇨ ***Conversion technologies***

- CHP
- Heat pumps
- Hydrogen (from fossil fuels and biomass with and w/o CCS; electrolytic hydrogen)
- Fuel to gas
- Fuel to liquid (from fossil fuels and biomass with and w/o CCS)
- *Heat plants*

⇨ ***Grid and infrastructure***

- Electricity
- Gas
- Heat
- CO_2
- H_2

Note: Generalized transmission and distribution costs are included, but not modelled on an explicit spatial level. Regionalized additional grid and storage costs for renewable integration are included.

⇨ ***Energy technology substitution***

- Discrete technology choices
- Expansion and decline constraints
- System integration constraints

Note: Expansion and decline, and system integration are influenced though cost markups rather than constraints.

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Note: In older versions of REMIND (REMIND 1.6 and earlier), the industry and residential and commercial sectors are not treated separately but represented jointly by one Stationary sector (referred to as 'Other Sector').

Land use (MAgPIE)

MAgPIE allocates land use to fulfil competing demands for commodities, feed, carbon storage, land conservation and environmental protection. Land use is broadly categorized in cropland, forest land, pasture land, and other natural land. Regional food energy demand is defined for an exogenously given population in 16 food energy categories, based on regional diets. Future trends in food demand are derived from a cross-country regression analysis, based on future scenarios on GDP and population growth. MAgPIE takes technological development and production costs as well as spatially explicit data on potential crop yields, land and water constraints (from LPJmL) into account. It includes agricultural trade with different levels of regional self-sufficiency constraints. Changes in soil and plant carbon from land conversion are accounted for. MAgPIE models the full suite of AFOLU emissions.

REMIND and MAgPIE are coupled by exchanging greenhouse gas prices and bioenergy demand from REMIND to MAgPIE, and bioenergy prices and AFOLU greenhouse gas emissions from MAgPIE to REMIND, and iterating until an equilibrium of prices and quantities is established.

Other resources

⇨ *Other resources*

- Cement

Note: Cement production is not explicitly modelled, but emissions from cement production are accounted for.

Emissions and climate

⇨ *Greenhouse gases*

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6

⇨ *Pollutants*

- NO_X
- SO_X
- BC
- OC
- Ozone
- *CO*
- *VOC*

Note: Ozone is not modelled as emission, but is an endogenous result of atmospheric chemistry.

⇨ *Climate indicators*

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)

Note: Different emissions are accounted for with different levels of detail depending on the types and sources of emissions (directly by source, via MAC curves, by econometric estimates, exogenous).

Reference card – Shell - World Energy Model

About

⇨ ***Name and version***

Shell World Energy Model 2018
2018 Edition (Version 2.10 series)

⇨ ***Institution and users***

Shell Corporation B.V., www.shell.com/scenariosenergymodels

Model scope and methods

⇨ ***Objective***

Exploratory simulations of plausible scenarios, covering both short-term drivers and momentum, together with the capability for long-term transformation of the energy system.

⇨ ***Concept***

Partial equilibrium (price elastic demand)

⇨ ***Solution method***

Simulation

⇨ ***Anticipation***

Recursive-dynamic (myopic)

⇨ ***Temporal dimension***

Base year: 2017, time steps: 1 year steps, horizon: 2100

⇨ ***Spatial dimension***

Number of regions: 100 (= 82 top countries + 18 rest of the world regions)

⇨ ***Policy implementation***

Emission Tax/Pricing, Cap and Trade, Fuel Taxes, Fuel Subsidies, Energy Efficiency Standards

Socio economic drivers

⇨ ***Exogenous drivers***

- Population
- Autonomous Energy Efficiency Improvements

⇨ ***Endogenous drivers***

⇨ ***Development***

Macro economy

⇨ ***Economic sectors***

Number of sectors: 14

  - Industry
  - Services
  - Energy
  - Energy service (sector-specific) and energy demand (in EJ) for each sector

⇨ ***Cost measures***

⇨ ***Trade***

- Coal
- Oil
- Gas
- Bioenergy crops

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

- Coal
- Conventional Oil (Process Model)
- Unconventional Oil (Process Model)

- Conventional Gas (Process Model)
- Unconventional Gas (Process Model)
- Bioenergy (Fixed)

⇨ ***Electricity technologies***

- Coal (w/o CCS and w/ CCS)
- Gas (w/o CCS and w/ CCS)
- Oil (w/o CCS and w/ CCS)
- Bioenergy (w/o CCS and w/ CCS)
- Geothermal Power
- Nuclear Power
- Solar Power (Central PV, Distributed PV, CSP)
- Wind Power
- Hydroelectric Power
- Ocean Power

⇨ ***Conversion technologies***

- Coal to Hydrogen (w/o CCS and w/ CCS)
- Natural Gas to Hydrogen (w/o CCS and w/ CCS)
- Oil to Hydrogen (w/o CCS and w/ CCS)
- Biomass to Hydrogen (w/o CCS and w/ CCS)
- Nuclear Thermochemical Hydrogen
- Electrolysis
- Coal to Liquids (w/o CCS and w/ CCS)
- Gas to Liquids (w/o CCS and w/ CCS)
- Bioliquids (w/o CCS and w/ CCS)
- Oil Refining
- Coal to Gas (w/o CCS and w/ CCS)
- Oil to Gas (w/o CCS and w/ CCS)
- Biomass to Gas (w/o CCS and w/ CCS)
- Coal Heat
- Natural Gas Heat
- Oil Heat
- Biomass Heat
- Geothermal Heat
- Solarthermal Heat

⇨ ***Grid and infrastructure***

⇨ ***Energy technology substitution***

- Logit choice model
- Discrete technology choices with mostly high substitutability
- Mostly a constrained logit model; some derivative choices (e.g. refinery outputs) have pathway dependent choices
- Constraints are imposed both endogenously and after off-model analysis

⇨ ***Energy service sectors***

- Transportation
- Industry
- Residential and commercial

Land use

- ⇨ ***Land cover***

Other resources

- ⇨ ***Other resources***

Emissions and climate

- ⇨ ***Greenhouse gases***
- – CO_2 Fossil Fuels (endogenous & uncontrolled)
- ⇨ ***Pollutants***
- ⇨ ***Climate indicators***

Reference card – WITCH

About

⇨ *Name and version*

WITCH

⇨ *Institution and users*

Fondazione Eni Enrico Mattei (FEEM), Italy, http://www.feem.it.
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy, http://www.cmcc.it.

Model scope and methods

⇨ *Objective*

WITCH evaluates the impacts of climate policies on global and regional economic systems and provides information on the optimal responses of these economies to climate change. The model considers the positive externalities from leaning-by-doing and learning-by-researching in the technological change.

⇨ *Concept*

Hybrid: Economic optimal growth model, including a bottom-up energy sector and a simple climate model, embedded in a `game theory` framework.

⇨ *Solution method*

Regional growth models solved by non-linear optimization and game theoretic setup solved by tatonnement algorithm (cooperative solution: Negishi welfare aggregation, non-cooperative solution: Nash equilibrium)

⇨ *Anticipation*

Perfect foresight

⇨ *Temporal dimension*

Base year: 2005**, time steps:5**, **horizon:** 2150

⇨ *Spatial dimension*

Number of regions: 14

1. cajaz: Canada, Japan, New Zealand
2. china: China, including Taiwan
3. easia: South East Asia
4. india: India
5. kosau: South Korea, South Africa, Australia
6. laca: Latin America, Mexico and Caribbean
7. indo: Indonesia
8. mena: Middle East and North Africa
9. neweuro: EU new countries + Switzerland + Norway
10. oldeuro: EU old countries (EU-15)
11. sasia: South Asia
12. ssa: Sub Saharan Africa
13. te: Non-EU Eastern European countries, including Russia
14. usa: United States of America

⇨ *Policy implementation*

Quantitative climate targets (temperature, radiative forcing, concentration), carbon budgets, emissions profiles as optimization constraints. Carbon taxes. Allocation and trading of emission permits, banking and borrowing. Subsidies, taxes and penalty on energies sources.

Socio economic drivers

⇨ *Exogenous drivers*

- Total Factor Productivity
- Labour Productivity
- Capital Technical progress

⇨ ***Development***

Macro economy

⇨ ***Economic sectors***

- Energy
- Other

Note: A single economy sector is represented. Production inputs are capital, labour and energy services, accounting for the Energy sector split into 8 energy technologies sectors (coal, oil, gas, wind & solar, nuclear, electricity and biofuels).

⇨ ***Cost measures***

- GDP loss
- Welfare loss
- Consumption loss
- Energy system costs

⇨ ***Trade***

- Coal
- Oil
- Gas
- Emissions permits

Energy

⇨ ***Resource use***

- Coal
- Oil
- Gas
- Uranium
- Biomass

⇨ ***Electricity technologies***

- Coal
- Gas
- Oil
- Nuclear
- Biomass
- Wind
- Solar PV
- CCS

⇨ ***Conversion technologies***

⇨ ***Grid and infrastructure***

- Electricity
- CO_2

⇨ ***Energy technology substitution***

- Expansion and decline constraints
- System integration constraints

⇨ ***Energy service sectors***

- Transportation

Land use

⇨ ***Land cover***

- Cropland
- Forest

Note: Bioenergy related cost and emissions are obtained by soft linking with the GLOBIOM model.

Other resources

⇨ ***Other resources***

- Water

Emissions and climate

⇨ ***Greenhouse gases***

- CO_2
- CH_4
- N_2O
- HFCs
- CFCs
- SF_6

⇨ ***Pollutants***

- NO_X
- SO_X
- BC
- OC

⇨ ***Climate indicators***

- CO_2e concentration (ppm)
- Radiative Forcing (W/m^2)
- Temperature change (°C)
- Climate damages $ or equivalent

Chapter 3: Impacts of 1.5ºC global warming on natural and human systems

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Executive Summary

This chapter builds on findings of the AR5 and assesses new scientific evidence of changes in the climate system and the associated impacts on natural and human systems, with a specific focus on the magnitude and pattern of risks for global warming of 1.5°C above the pre-industrial period. Chapter 3 explores observed impacts and projected risks for a range of natural and human systems with a focus on how risk levels change at 1.5ºC and 2ºC. The chapter also revisits major categories of risk (Reasons for Concern) based on the assessment of the new knowledge available since the AR5.

1.5°C and 2°C warmer worlds

The global climate has changed relative to the preindustrial period with multiple lines of evidence that these changes have had impacts on organisms and ecosystems, as well as human systems and well-being (*high confidence*). The increase in global mean surface temperature (GMST), which reached 0.87°C in 2006-2015 relative to 1850-1900, has increased the frequency and magnitude of impacts (*high confidence*), strengthening evidence of how increasing GMST to 1.5°C or higher could impact natural and human systems (1.5°C versus 2°C) {3.3.1, 3.3, 3.4, 3.5, 3.6, Cross-Chapter Boxes 6, 7 and 8 in this Chapter}.

Human-induced global warming has already caused multiple observed changes in the climate system (*high confidence*). In particular this includes increases in both land and ocean temperatures, as well as more frequent heatwaves in most land regions (*high confidence*). There is also *high confidence* that it has caused an increase in the frequency and duration of marine heatwaves. Further, there is evidence that global warming has led to an increase in the frequency, intensity and/or amount of heavy precipitation events at global scale (*medium confidence*), as well as having increased the risk of drought in the Mediterranean region (*medium confidence*) {3.3.1, 3.3.2, 3.3.3, 3.3.4}.

Changes in temperature extremes and heavy precipitation indices are detectable in observations for the 1991-2010 period compared with 1960-1979, when a global warming of approximately 0.5°C occurred (*high confidence*). The observed tendencies over that time frame are consistent with attributed changes since the mid-20th century (*high confidence*) {3.3.1, 3.3.2, 3.3.3}.

There is no single '1.5°C warmer world' (*high confidence*). Important aspects to consider (beside that of global temperature) are the possible occurrence of an overshoot and its associated peak warming and duration, how stabilization of global surface temperature at 1.5°C is achieved, how policies might be able to influence the resilience of human and natural systems, and the nature of the regional and sub-regional risks (*high confidence*). Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (*high confidence*). The rate of change for several types of risks may also have relevance with potentially large risks in case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later (*medium confidence*). If overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions is very small, which implies that large, immediate, and unprecedented global efforts to mitigate greenhouse gases are required (*high confidence*) {Cross-Chapter Box 8 in this Chapter; Sections 3.2 and 3.6.2}.

Substantial global differences in temperature and extreme events are expected if GMST reaches 1.5°C versus 2°C above the preindustrial period (*high confidence*). Regional surface temperature means and extremes are higher at 2°C as compared to 1.5°C for oceans in near all locations *(high confidence)*. Temperature means and extremes are higher at 2°C as compared to 1.5°C global warming in near all inhabited land regions, and display in some regions 2-3 times greater warming when compared to the GMST (*high confidence*). There are also substantial increases in temperature means and extremes at 1.5°C versus present (*high confidence*) {3.3.1, 3.3.2}. There are decreases in the occurrence of cold extremes, but substantial increases in their temperature {3.3.1}.

Substantial changes in regional climate occur between 1.5°C and 2°C global warming (*high confidence*), depending on the variable and region in question *(high confidence)*. Particularly large differences are found for temperature extremes *(high confidence)*. Hot extremes display the strongest warming in mid-latitudes in the warm season (with increases of up to 3°C at 1.5°C of warming, i.e. a factor of two) and cold extremes at high-latitudes in the cold season (with increases of up to 4.5°C at 1.5°C of warming, i.e. a factor of three) (*high confidence*). The strongest warming of hot extremes is found in Central and Eastern North America, Central and Southern Europe, the Mediterranean region (including Southern Europe, Northern Africa and the near-East), Western and Central Asia, and Southern Africa (*medium confidence*). The number of highly unusual hot days increase the most in the tropics, where inter-annual temperature variability is lowest; the emergence of extreme heatwaves is thus earliest in these regions, where they become already widespread at 1.5°C global warming (*high confidence*). Limiting global warming to 1.5°C instead of 2°C could result in around 420 million fewer people being frequently exposed to extreme heatwaves, and about 65 million fewer people being exposed to exceptional heatwaves, assuming constant vulnerability (*medium confidence*) {3.3.1, 3.3.2, Cross-Chapter Box 8 in this Chapter}.

Limiting global warming to 1.5°C limits risks of increases in heavy precipitation events in several regions (*high confidence*). The regions with the largest increases in heavy precipitation events for 1.5°C to 2°C global warming include several high-latitude regions such as Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, northern Asia; mountainous regions (e.g. Tibetan Plateau); as well as Eastern Asia (including China and Japan) and in Eastern North America (*medium confidence*). {3.3.3}. Tropical cyclones are projected to increase in intensity (with associated increases in heavy precipitation) although not in frequency (*low confidence*, *limited evidence*) {3.3.3, 3.3.6}.

Limiting global warming to 1.5°C is expected to substantially reduce the probability of drought and risks associated with water availability (i.e. water stress) in some regions (*medium confidence*). In particular, risks associated with increases in drought frequency and magnitude are substantially larger at 2°C than at 1.5°C in the Mediterranean region (including Southern Europe, Northern Africa, and the Near-East) and Southern Africa (*medium confidence*) {3.3.4, Box 3.1, Box 3.2}.

Risks to natural and human systems are lower at 1.5ºC than 2ºC *(high confidence)*. This is owing to the smaller rates and magnitudes of climate change, including reduced frequencies and intensities of temperature-related extremes. Reduced rates of change enhance the ability of natural and human systems to adapt, with substantial benefits for a range of terrestrial, wetland, coastal and ocean ecosystems (including coral reefs and wetlands), freshwater systems, as well as food production systems, human health, tourism, energy systems, and transportation {3.3.1, 3.4}.

Some regions are projected to experience multiple compound climate-related risks at 1.5°C that will increase with warming of 2°C and higher (*high confidence*). Some regions are projected to be affected by collocated and/or concomitant changes in several types of hazards. Multi-sector risks are projected to overlap spatially and temporally, creating new (and exacerbating current) hazards, exposures, and vulnerabilities that will affect increasing numbers of people and regions with additional warming. Small island states and economically disadvantaged populations are particularly at risk. {Box 3.5, 3.3.1, 3.4.5.3, 3.4.5.6, 3.4.11, 3.5.4.9}.

There is *medium confidence* that a global warming of 2°C would lead to an expansion of areas with significant increases in runoff as well as those affected by flood hazard, as compared to conditions at 1.5°C global warming. A global warming of 1.5°C would also lead to an expansion of the global land area with significant increases in runoff (*medium confidence*) as well as an increase in flood hazard in some regions (*medium confidence*) when compared to present-day conditions {3.3.5}.

There is *high confidence* that the probability of a sea-ice-free Arctic Ocean during summer is substantially higher at 2°C when compared to 1.5°C. It is *very likely* that there will be at least one sea-ice-free Arctic summer out of 10 years for warming at 2°C, with the frequency decreasing to one sea-ice-free Arctic summer every 100 years at 1.5°C. There is also *high confidence* that an intermediate temperature overshoot will have no long-term consequences for Arctic sea-ice coverage and that hysteresis behaviour is not expected {3.3.8, 3.4.4.7}.

Global mean sea level rise will be around 0.1 m less by the end of the century in a 1.5°C world as compared to a 2°C warmer world (*medium confidence*). Reduced sea level rise could mean that up to 10.4 million fewer people (based on the 2010 global population and assuming no adaptation) are exposed to the impacts of sea level globally in 2100 at 1.5°C as compared to 2°C {3.4.5.1}. A slower rate of sea level rise enables greater opportunities for adaptation (*medium confidence*) {3.4.5.7}. There is *high confidence* that sea level rise will continue beyond 2100. Instabilities exist for both the Greenland and Antarctic ice sheets that could result in multi-meter rises in sea level on centennial to millennial timescales. There is medium confidence that these instabilities could be triggered under 1.5° to 2°C of global warming {3.3.9, 3.6.3}.

The ocean has absorbed about 30% of the anthropogenic carbon dioxide, resulting in ocean acidification and changes to carbonate chemistry that are unprecedented in 65 million years at least (*high confidence*). Risks have been identified for the survival, calcification, growth, development, and abundance of a broad range of taxonomic groups (i.e. from algae to fish) with substantial evidence of predictable trait-based sensitivities. Multiple lines of evidence reveal that ocean warming and acidification (corresponding to global warming of 1.5°C of global warming) is expected to impact a wide range of marine organisms, ecosystems, as well as sectors such as aquaculture and fisheries (*high confidence*) {3.3.10, 3.4.4}.

There are larger risks at 1.5°C than today for many regions and systems, with adaptation being required now and up to 1.5°C. There are, however, greater risks and effort needed for adaptation to 2°C *(high confidence)* {3.4, Box 3.4, Box 3.5, Cross-Chapter Box 6 in this Chapter}.

Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (*high confidence*). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, *medium confidence*). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.

Climate change risks for natural and human systems

Terrestrial and Wetland Ecosystems

Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (*medium confidence*). The number of species projected to lose over half of their climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (*high confidence*). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (*high confidence*), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.

Constraining global warming to 1.5°C rather than 2°C and higher has strong benefits for terrestrial and wetland ecosystems and for the preservation of their services to humans (*high confidence*). Risks for natural and managed ecosystems are higher on drylands compared to humid lands. The terrestrial area affected by ecosystem transformation (13%) at 2°C, which is approximately halved at 1.5°C global warming (*high confidence*). Above 1.5°C, an expansion of desert and arid vegetation would occur in the Mediterranean biome (*medium confidence*), causing changes unparalleled in the last 10,000 years (*medium confidence*) {3.3.2.2, 3.4.3.5, 3.4.6.1., 3.5.5.10, Box 4.2}.

Many impacts are projected to be larger at higher latitudes due to mean and cold-season warming rates above the global average (*medium confidence*). High-latitude tundra and boreal forest are particularly at risk, and woody shrubs are already encroaching into tundra (*high confidence*). Further warming is projected to cause greater effects in a 2°C world than a 1.5°C world, for example, constraining warming to 1.5°C would prevent the melting of an estimated permafrost area of 2 million km^2 over centuries compared to 2°C (*high confidence*) {3.3.2, 3.4.3, 3.4.4}.

Ocean ecosystems

Ocean ecosystems are experiencing large-scale changes, with critical thresholds expected to be reached at 1.5ºC and above (*high confidence*). In the transition to 1.5°C, changes to water temperatures will drive some species (e.g. plankton, fish) to relocate to higher latitudes and for novel ecosystems to appear *(high confidence)*. Other ecosystems (e.g. kelp forests, coral reefs) are relatively less able to move, however, and will experience high rates of mortality and loss (*very high confidence*). For example, multiple lines of evidence indicate that the majority of warmer water coral reefs that exist today (70-90%) will largely disappear when global warming exceeds 1.5°C (*very high confidence*) {3.4.4, Box 3.4}.

Current ecosystem services from the ocean will be reduced at 1.5ºC, with losses being greater at 2ºC (*high confidence*). The risks of declining ocean productivity, shifts of species to higher latitudes, damage to ecosystems (e.g. coral reefs, as well as from mangroves, seagrass and other wetland ecosystems), loss of fisheries productivity (at low latitudes), and changing ocean chemistry (e.g., acidification, hypoxia, dead zones), however, are projected to be substantially lower when global warming is limited to 1.5°C (*high confidence*) {3.4.4, Box 3.4}.

Water Resources

The projected frequency and magnitude of floods and droughts in some regions are smaller under a 1.5°C versus 2°C of warming (*medium confidence*). Human exposure to increased flooding is projected to be substantially lower at 1.5°C as compared to 2°C of global warming, although projected changes create regionally differentiated risks (*medium confidence*). The differences in the risks among regions are strongly influenced by local socio-economic conditions (*medium confidence*) {3.3.4, 3.3.5, 3.4.2}.

Risks to water scarcity are greater at 2°C than at 1.5°C of global warming in some regions (*medium confidence*). Limiting global warming to 1.5°C would approximately halve the fraction of world population expected to suffer water scarcity as compared to 2°C, although there is considerable variability between regions (*medium confidence*). Socioeconomic drivers, however, are expected to have a greater influence on these risks than the changes in climate (*medium confiden*ce) {3.3.5, 3.4.2, Box 3.5}.

Land Use, Food Security and Food Production Systems

Global warming of 1.5°C (as opposed to 2ºC) is projected to reduce climate induced impacts on crop yield and nutritional content in some regions (*high confidence*). Affected areas include Sub-Saharan Africa (West Africa, Southern Africa), South-East Asia, and Central and South America. A loss of 7-10% of rangeland livestock globally is projected for approximately 2°C of warming with considerable economic consequences for many communities and regions {3.6, 3.4.6, Box 3.1, Cross-Chapter Box 6 in this Chapter}.

Risks of food shortages are lower in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon at 1.5ºC of global warming when compared to 2°C (*medium confidence*). This suggests a transition from medium to high risk of regionally differentiated impacts between 1.5 and 2°C for food security (*medium confidence*). International food trade is *likely* to be a potential adaptation response for alleviating hunger in low- and middle-income countries {Cross-Chapter Box 6 in this Chapter}.

Fisheries and aquaculture are important to global food security but are already facing increasing risks from ocean warming and acidification (*medium confidence*), which will increase at 1.5°C global warming. Risks are increasing for marine aquaculture and many fisheries at warming and acidification at 1.5°C (e.g., many bivalves such as oysters, and fin fish; *medium confidence*), especially at low latitudes (*medium confidence*). Small-scale fisheries in tropical regions, which are very dependent on habitat provided by coastal ecosystems such as coral reefs, mangroves, seagrass and kelp forests, are at a high risk at 1.5°C due to loss of habitat (*medium confidence*). Risks of impacts and decreasing food security become greater as warming and acidification increase, with substantial losses likely for coastal livelihoods and industries (e.g. fisheries, aquaculture) as temperatures increase beyond 1.5°C (*medium to high confidence*). {3.4.4, 3.4.5, 3.4.6, Box 3.1, Box 3.4, Box 3.5, Cross-Chapter Box 6 in this Chapter}

Land use and land-use change emerge as a critical feature of virtually all mitigation pathways that seek to limit global warming to 1.5ºC (*robust evidence, high agreement*). Most least-cost mitigation pathways to limit peak or end-of-century warming to 1.5°C make use of Carbon Dioxide Removal (CDR), predominantly employing significant levels of Bioenergy with Carbon Capture and Storage (BECCS) and/or Afforestation and Reforestation (AR) in their portfolio of mitigation measures (*robust evidence, high agreement*) {Cross-Chapter Box 7 in this Chapter}.

Large-scale, deployment of BECCS and/or AR would have a far-reaching land and water footprint (*medium evidence, high agreement*). Whether this footprint results in adverse impacts, for example on biodiversity or food production, depends on the existence and effectiveness of measures to conserve land carbon stocks, measures to limit agricultural expansion so as to protect natural ecosystems, and the potential to increase agricultural productivity (*high agreement, medium evidence*). In addition, BECCS and/or AR would also have substantial direct effects on regional climate through biophysical feedbacks, which are generally not included in Integrated Assessments Models (*high confidence*). {Cross-Chapter Boxes 7 and 8 in this Chapter, Section 3.6.2}

The impacts of large-scale CDR deployment can be greatly reduced if a wider portfolio of CDR options is deployed, a holistic policy for sustainable land management is adopted and if increased mitigation effort strongly limits demand for land, energy and material resources, including through lifestyle and dietary change (*medium agreement, medium evidence*). In particular, reforestation may be associated with significant co-benefits if implemented so as to restore natural ecosystems *(high confidence)* {Cross-Chapter Box 7 in this Chapter}

Human Systems: Human Health, Well-Being, Cities, and Poverty

Any increase in global warming (e.g., +0.5ºC) will affect human health (*high confidence*). Risks will be lower at 1.5°C than at 2°C for heat-related morbidity and mortality (*very high confidence*), particularly in urban areas because of urban heat islands (*high confidence*). Risks also will be greater for ozone-related mortality if the emissions needed for the formation of ozone remain the same (*high confidence*), and for undernutrition (*medium confidence*). Risks are projected to change for some vector-borne diseases such as malaria and dengue fever (*high confidence*), with positive or negative trends depending on the disease, region, and extent of change (*high confidence*). Incorporating estimates of adaptation into projections reduces the magnitude of risks (*high confidence*) {3.4.7, 3.4.7.1}.

Global warming of 2°C is expected to pose greater risks to urban areas than global warming of 1.5°C (*medium confidence*). The extent of risk depends on human vulnerability and the effectiveness of adaptation for regions (coastal and non-coastal), informal settlements, and infrastructure sectors (energy, water, and transport) (*high confidence*) {3.4.5, 3.4.8}.

Poverty and disadvantage have increased with recent warming (about 1ºC) and are expected to increase in many populations as average global temperatures increase from 1ºC to 1.5°C and beyond (*medium confidence*). Outmigration in agricultural-dependent communities is positively and statistically significantly associated with global temperature (*medium confidence*). Our understanding of the linkages of 1.5ºC and 2ºC on human migration are limited and represent an important knowledge gap {3.4.10, 3.4.11, 5.2.2, Table 3.5}.

Key Economic Sectors and Services

Globally, the projected impacts on economic growth in a 1.5°C warmer world are larger than those of the present-day (about 1°C), with the largest impacts expected in the tropics and the Southern Hemisphere subtropics (*limited evidence, low confidence*). At 2°C substantially lower economic growth is projected for many developed and developing countries *(limited evidence, medium confidence)*, with the potential to also limit economic damages at 1.5°C of global warming. {3.5.2, 3.5.3}.

The largest reductions in growth at 2°C compared to 1.5 °C of warming are projected for low- and middle-income countries and regions (the African continent, southeast Asia, India, Brazil and Mexico) (*limited evidence, medium confidence*) {3.5}.

Global warming has affected tourism and increased risks are projected for specific geographic regions and the seasonality of sun, beach, and snow sports tourism under warming of 1.5ºC (*very high confidence*). Risks will be lower for tourism markets that are less climate sensitive, such as non-environmental (e.g., gaming) or large hotel-based activities (*high confidence*) {3.4.9.1}. Risks for coastal tourism, particularly in sub-tropical and tropical regions, will increase with temperature-related degradation (e.g. heat extremes, storms) or loss of beach and coral reef assets (*high confidence*) {3.4.9.1, 3.4.4.12; 3.3.6, Box 3.4}.

Small islands, and coastal and low-lying areas

Small islands are projected to experience multiple inter-related risks at 1.5°C that will increase with warming of 2ºC and higher (*high confidence*). Climate hazards at 1.5°C are lower compared to 2°C (*high confidence*). Long term risks of coastal flooding and impacts on population, infrastructure and assets (*high confidence*), freshwater stress (*medium confidence*), and risks across marine ecosystems (*high confidence*), and critical sectors (*medium confidence)* increase at 1.5°C as compared to present and further increase at 2°C, limiting adaptation opportunities and increasing loss and damage (*medium confidence*). Migration in small islands (internally and internationally) occurs due to multiple causes and for multiple purposes, mostly for better livelihood opportunities (*high confidence*) and increasingly due to sea level rise (*medium confidence).* {3.3.2.2, 3.3.6-9, 3.4.3.2, 3.4.4.2, 3.4.4.5, 3.4.4.12, 3.4.5.3, 3.4.7.1, 3.4.9.1, 3.5.4.9, Box 3.4, Box 3.5}.

Impacts associated with sea level rise and changes to the salinity of coastal groundwater, increased flooding and damage to infrastructure, are critically important in sensitive environments such as small islands, low lying coasts and deltas at global warming of 1.5ºC and 2ºC (*high confidence*). Localised subsidence and changes to river discharge can potentially exacerbate these effects {3.4.5.4}. Adaptation is happening today (*high confidence*) and remains important over multi-centennial timescales {3.4.5.3, 3.4.5.7, Box 3.5, 5.4.5.4}.

Existing and restored natural coastal ecosystems may be effective in reducing the adverse impacts of rising sea levels and intensifying storms by protecting coastal and deltaic regions. Natural sedimentation rates are expected to be able to offset the effect of rising sea levels given the slower rates of sea-level rise associated with 1.5°C of warming (*medium confidence*). Other feedbacks, such as landward migration of wetlands and the adaptation of infrastructure, remain important (*medium confidence*) {3.4.4.12, 3.4.5.4, 3.4.5.7}

Increased reasons for concern

There are multiple lines of evidence that there has been a substantial increase since AR5 in the levels of risk associated with four of the five Reasons for Concern (RFCs) for global warming levels of up to 2°C (*high confidence*). Constraining warming to 1.5ºC rather than 2ºC avoids risk reaching a 'very high' level in RFC1 (Unique and Threatened Systems) (*high confidence*), and avoids risk reaching a 'high' level in RFC3 (Distribution of Impacts) (*high confidence*) and RFC4 (Global Aggregate Impacts) (*medium confidence*). It also reduces risks associated with RFC2 (Extreme Weather Events) and RFC5 (Large scale singular events) (*high confidence*) {3.5.2}.

In "Unique and Threatened Systems" (RFC1) the transition from high to very high risk is located between 1.5ºC and 2ºC global warming as opposed to at 2.6ºC global warming in AR5, owing to new and multiple lines of evidence for changing risks for coral reefs, the Arctic, and biodiversity in general (*high confidence*) {3.5}.

1. **In "Extreme Weather Events" (RFC2) the transition from moderate to high risk is located between 1.0ºC and 1.5ºC global warming,** which is very similar to the AR5 assessment but there is greater confidence in the assessment (*medium confidence*). The impact literature contains little

information about the potential for human society to adapt to extreme weather events and hence it has not been possible to locate the transition from 'high' (red) to 'very high' risk within the context of assessing impacts at 1.5°C versus 2°C global warming. There is thus *low confidence* in the level at which global warming could lead to very high risks associated with extreme weather events in the context of this report {3.5}.

2. **In "Distribution of impacts" (RFC3) a transition from moderate to high risk is now located between 1.5ºC and 2ºC global warming as compared with between 1.6**ºC **and 2.6**ºC **global warming in AR5**, due to new evidence about regionally differentiated risks to food security, water resources, drought, heat exposure, and coastal submergence *(high confidence)* {3.5}.

3. **In "Global aggregate impacts" (RFC4) a transition from moderate to high levels of risk now occurs between 1.5ºC and 2.5ºC global warming** as opposed to at 3ºC warming in AR5, owing to new evidence about global aggregate economic impacts and risks to the earth's biodiversity *(medium confidence)* {3.5}.
4. **In "Large scale singular events" (RFC5), moderate risk is located at 1ºC global warming and high risks are located at 2.5ºC global warming**, as opposed to 1.9ºC (moderate) and 4ºC global warming (high) risk in AR5 because of new observations and models of the West Antarctic ice sheet (*medium confidence*) {3.3.9, 3.5.2, 3.6.3}

3.1 About the chapter

Chapter 3 uses relevant definitions of a potential 1.5°C warmer world from Chapters 1 and 2 and builds directly on their assessment of gradual versus overshoot scenarios. It interacts with information presented in Chapter 2 via the provision of specific details relating to the mitigation pathways (e.g., land use changes) and their implications for impacts. Information for the assessment and implementation of adaptation options in Chapter 4, and the context for considering the interactions of climate change with sustainable development in Chapter 5 for the assessment of impacts on sustainability, poverty and inequalities at the level of sub-regions to households, are provided by Chapter 3.

This chapter is necessarily transdisciplinary in its coverage of the climate system, natural and managed ecosystems, and human systems and responses, due to the integrated nature of the natural and human experience. While climate change is acknowledged as a centrally important driver, it is not the only driver of risks to human and natural systems, and in many cases, it is the interaction between these two broad categories of risk that is important (Chapter 1).

The flow of the chapter, linkages between sections, a list of chapter and cross chapter boxes, and a content guide for reading according to focus or interest are given in Figure 3.1. Key definitions used in the chapter are collected in the Glossary. Confidence language is used throughout this chapter and likelihood statements (e.g. *likely*, *very likely*) are provided when there is *high* confidence in the assessment.

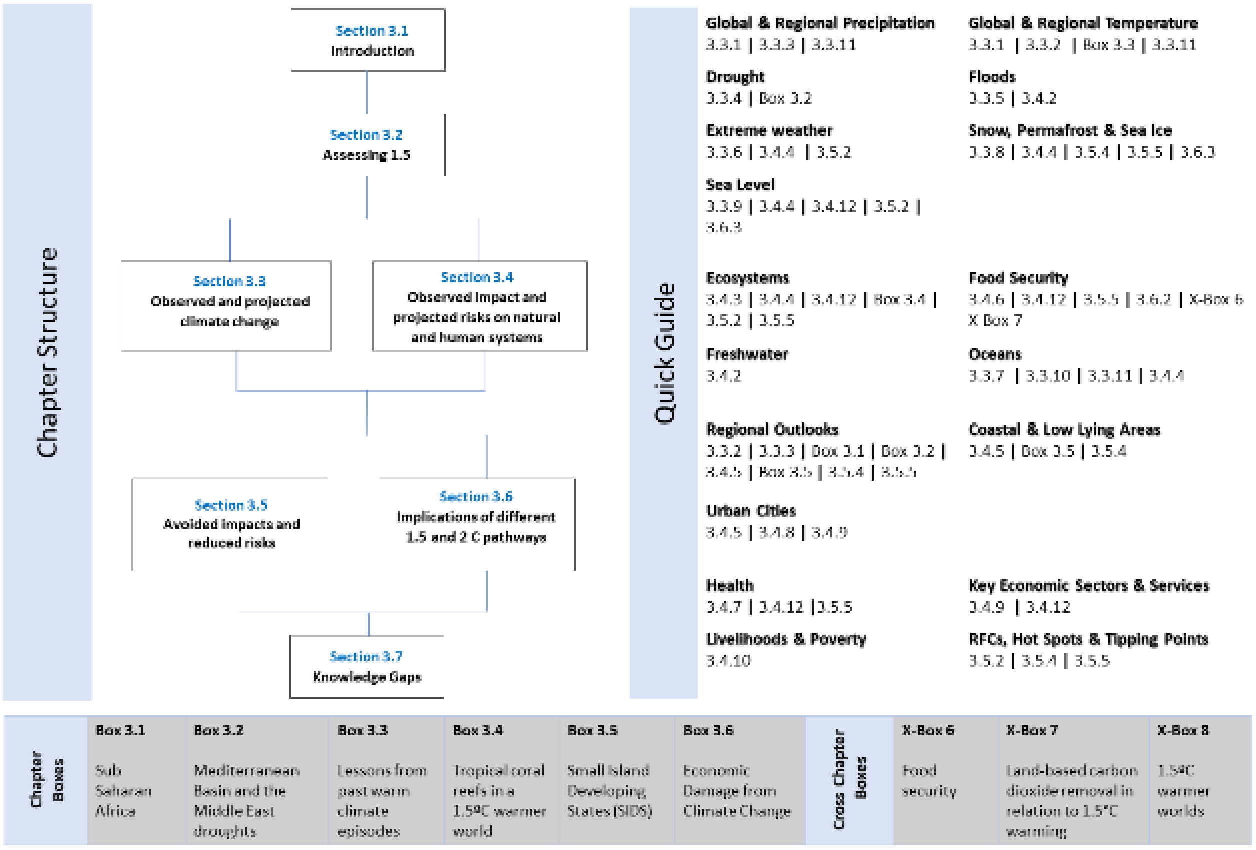

Figure 3.1: Chapter 3 structure and quick guide

The underlying literature assessed in Chapter 3 is broad, including a large number of recent publications specific to assessments for 1.5°C warming. The chapter also utilizes information covered in prior IPCC special reports, for example Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, IPCC, 2012), and many chapters which assess impacts on natural and managed ecosystems and humans and adaptation options from the IPCC WGII Fifth Assessment Report (AR5) (IPCC, 2014b). For this reason, the chapter provides information based on a broad range of assessment methods. Details about the approaches used are presented in Section 3.2.

Section 3.3 gives a general overview of recent literature on observed climate change impacts as the context for projected future risks. With a few exceptions, the focus is on analyses of *transient responses* at 1.5°C and 2°C, with simulations of *short-term stabilization scenarios* (Section 3.2) also assessed in some cases. In general, *long-term equilibrium stabilization responses* could not be assessed due to lack of data availability. A detailed analysis of detection and attribution is not provided. Furthermore, possible interventions in the climate system through radiation modification measures which are not tied to reductions of greenhouse gas emissions or concentrations are not assessed in this chapter.

Understanding the observed impacts and projected risks of climate change forms a crucial element in understanding how the world is likely to change under global warming of 1.5°C above the preindustrial period (with reference to 2ºC). Section 3.4 explores the new literature and updates the assessment of impacts and projected risks into the future for a large number of natural and human systems. By also exploring adaptation opportunities (where the literature allows), the section prepares the ground for later discussions in subsequent chapters about opportunities to tackle both mitigation and adaptation. The section is mostly globally focussed because of limited research on regional risks and adaptation options at 1.5ºC and 2ºC. For example, on the risks of warming of 1.5°C and 2°C in urban areas, and climate-sensitive health outcomes, such as climate related disease, medical impacts of poor air quality, or mental health, were not considered because of the lack of projections of how risks might change in 1.5ºC and 2°C worlds. In addition, the complex interactions of climate change with drivers of poverty and livelihoods meant it was not possible to detect and attribute recent changes to climate change, even with increasing documentation of climate-related impacts on places where indigenous peoples live and where subsistence-oriented communities are to be found, because of limited projections of the risks associated with warming of 1.5ºC and 2ºC.

To explore avoided impacts and reduced risks at 1.5ºC compared with 2ºC, the chapter adopts the AR5 'Reasons for Concern' aggregated projected risk framework (Section 3.5). Updates in terms of the aggregation of risk are informed by the most recent literature and the assessments offered in Sections 3.3 and 3.4 with focus on the avoided impacts at 1.5°C as compared to 2°C. Economic benefits to be obtained (Section 3.5.3), climate change 'hot spots' that can be avoided or reduced (Section 3.5.4 as guided by the assessments of Sections 3.3, 3.4 and 3.5), and tipping points that can be avoided (Section 3.5.5) at 1.5ºC compared to higher degrees of global warming, are all examined. These latter assessments are, however, constrained to regional analysis, and the section does not include an assessment of loss and damages.

Section 3.6 provides an overview on specific aspects of the mitigation pathways considered compatible with 1.5°C global warming including some overshoot above 1.5°C global warming during the 21st century. Non-CO_2 implications and projected risks of mitigation pathways, such as changes to land use and atmospheric compounds are presented and explored. Finally, implications for sea ice, sea level and permafrost beyond the end of the century are assessed.

The exhaustive assessment of 1.5°C specific literature presented across all the sections in Chapter 3 highlighted knowledge gaps resulting from the heterogeneous information across systems, regions and sectors. Some of these gaps are listed in Section 3.7.

3.2 How are risks at 1.5°C and higher levels of global warming assessed in this chapter?

The methods that are applied for assessing observed and projected changes in climate and weather are presented in Section 3.2.1 while those used for assessing the observed impacts and projected risks to natural and managed systems, and human settlements, are described in Section 3.2.2. Given that changes in climate associated with 1.5°C of global warming were not the focus of past IPCC reports, dedicated approaches based on recent literature and which are specific to the present report, are also described. Background on specific methodological aspects (climate model simulations available for assessments at 1.5°C global warming, attribution of observed changes in climate and their relevance for assessing projected changes at 1.5°C and 2°C global warming, and the propagation of uncertainties from climate forcing to impacts on the ecosystems) are provided in the Annex 3-1.

3.2.1 How are changes in climate and weather at 1.5°C versus higher levels of warming assessed?

Evidence for the assessment of changes to climate at 1.5°C versus 2°C can draw both from observations and model projections. Global Mean Surface Temperature (GMST) anomalies were about +0.87°C (±0.10°C *likely* range) above pre-industrial industrial (1850-1900) values in the 2006-2015 decade, with a recent warming of about 0.2°C (±0.10°C) per decade (Chapter 1). Human-induced global warming reached approximately 1ºC (±0.2°C *likely* range) in 2017 (Chapter 1). While some of the observed trends may be due to internal climate variability, methods of detection and attribution can be applied to assess which part of the observed changes may be attributed to anthropogenic forcing (Bindoff et al., 2013b). Hence, evidence from attribution studies can be used to assess changes in the climate system that are already detectable at lower levels of global warming and would thus continue to change for a further increase of 0.5°C or 1°C in global warming (see Annex 3.1 S3-2 and Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.3.11). A recent study also investigated significant changes in extremes for a 0.5°C difference in global warming based on the historical record (Schleussner et al., 2017).

Climate model simulations are necessary for the investigation of the response of the climate system to various forcings, in particular for forcings associated with higher levels of greenhouse gas concentrations. Model simulations include experiments with global and regional climate models, as well as impact models (driven with output from climate models) to evaluate the risk related to climate change for natural and human systems (Annex 3.1, S3.2). Climate model simulations were generally used in the context of particular 'climate scenarios' in previous IPCC reports (e.g., IPCC, 2007, 2013). This means that emission scenarios (IPCC, 2000) were used to drive climate models, providing different projections for given emissions pathways. The results were consequently used in a 'storyline' framework, which presents the development of climate in the course of the 21st century and beyond, if a given emission pathway was to be followed. Results were assessed for different time slices within the model projections, for example for 2016-2035 ('near term', which is slightly below a 1.5°C global warming in most scenarios, Kirtman et al., 2013), 2046-65 (mid 21st century, Collins et al., 2013), and 2081-2100 (end of 21st century, Collins et al., 2013). Given that this report focuses on climate change for a given mean global temperature response (1.5°C or 2°C), methods of analysis had to be developed and/or adapted from previous studies in order to provide assessments for the specific purposes here.

A major challenge in assessing climate change under 1.5°C (or 2°C and higher-level) global warming pertains to the **definition of a '1.5°C or 2°C climate projection'** (see also Cross-Chapter Box 8 in this Chapter). Resolving this challenge includes the following considerations:

A. The need for distinguishing between (a) **transient climate responses** (i.e. those that 'pass through' 1.5°C or 2°C global warming), (b) **short-term stabilization responses** (i.e. late 21st-century scenarios that result in stabilization at a mean global warming of 1.5°C or 2°C by 2100), and (c) **long-term equilibrium stabilization responses** (i.e. once climate equilibrium at 1.5°C or 2°C is reached, after several millennia). These responses can be very different in terms of climate variables and the inertia associated with a given climate forcing. A striking example is Sea Level Rise (SLR). In this case, projected increases within the 21st century are minimally dependent on the considered scenario yet stabilize at very different levels for a long-term warming of 1.5°C versus 2°C (Section 3.3.9).

B. That '1.5°C or 2°C emissions scenarios' presented in Chapter 2 are targeted to hold warming below 1.5°C or 2°C with a certain probability (generally 2/3) over the course, or end, of the 21st century.

These scenarios should be seen as operationalisations of 1.5°C or 2°C worlds. However, when these emission scenarios are used to drive climate models, some of the resulting simulations lead to warming above these respective thresholds (typically with a probability of 1/3, see Chapter 2 and Cross-Chapter Box 8 in this Chapter). This is due both to discrepancies between models and internal climate variability. For this reason, the climate outcome for any of these scenarios, even those excluding an overshoot (see next point, C.), include some probability of reaching a global climate warming higher than 1.5°C or 2°C. Hence, a comprehensive assessment of climate risks associated with '1.5°C or 2°C climate scenarios' needs to include consideration of higher levels of warming (e.g. up to 2.5°C -3°C, see Chapter 2 and Cross-Chapter Box 8 in this Chapter).

C. Most of the '1.5°C scenarios', and some of the '2°C emissions scenarios' of Chapter 2, include a temperature overshoot during the course of the 21st century. This means that median temperature projections under these scenarios exceed the target warming levels over the course of the century (typically up to 0.5°C-1°C higher than the respective target levels at most), before warming returns to below 1.5°C or 2°C achieved by 2100. During the overshoot phase, impacts would therefore correspond to higher transient temperature levels than 1.5°C or 2°C. For this reason, impacts for transient responses at these higher levels are also partly addressed in Cross-Chapter Box 8 in this Chapter on 1.5°C warmer worlds, and some analyses for changes in extremes are also displayed for higher levels of warming in Section 3.3 (Figures 3.5, 3.6, 3.9, 3.10, 3.12, 3.13). Most importantly, different overshoot scenarios may have very distinct impacts depending on (a) the peak temperature of the overshoot, (b) the length of the overshoot period, and (c) the associated rate of change in global temperature over the time period of the overshoot. While some of these issues are briefly addressed in Sections 3.3 and 3.6, and the Cross-Chapter Box 8 (in this Chapter), the definition and questions surrounding overshoot will need to be addressed more comprehensively in the IPCC AR6 report.

D. The meaning of '1.5°C or 2°C' global warming climate was not defined prior to this report, although it is defined as relative to the climate associated with the Pre-Industrial Period. This requires an agreement on the exact reference time period (for 0°C warming) and the time frame over which the global warming is assessed (e.g. typically a climatic time period, such as one that is 20 or 30 years in length). As discussed in Chapter 1, a 1.5°C climate is one in which temperature differences averaged over a multi-decade timescale are 1.5°C above the pre-industrial reference period. Greater detail is provided in the Cross-Chapter Box 8. Inherent to this is the observation that the mean temperature of a '1.5°C warmer world' can be regionally and temporally much higher (e.g. regional annual temperature extremes can display a warming of up to 4.5°C on average, see Section 3.3 and Cross-Chapter Box 8 in this Chapter).

E. Non-greenhouse gas related interference with mitigation pathways can strongly affect regional climate. For example, biophysical feedbacks from changes in land use and irrigation (e.g. Hirsch et al., 2017; Thiery et al., 2017), or projected changes in short-lived pollutants (e.g. Z. Wang et al., 2017), can have large influences on local temperatures and climate conditions. While these effects are not explicitly integrated into the scenarios developed in Chapter 2, they may affect projected changes in climate for 1.5°C of global warming. These issues are addressed in more detail in Section 3.6.2.2.

The assessment done in the current chapter largely focusses on the analysis of **transient responses in climate at 1.5°C versus 2°C** and higher levels of warming (see point A. above, Section 3.3). It generally uses the Empirical Scaling Relationship approach (ESR, Seneviratne et al., 2018c), also termed 'time sampling' approach (James et al., 2017), which consists of sampling the response at 1.5°C and other levels of global warming from all available global climate model scenarios for the 21st century (e.g., Schleussner et al., 2016b; Seneviratne et al., 2016; Wartenburger et al., 2017). The ESR approach focuses more on the derivation of a continuous relationship, while the term time sampling is more commonly used when comparing a limited number of warming levels (e.g. 1.5°C versus 2°C). A similar approach in the case of Regional Climate Model (RCM) simulations consists of sampling the RCM model output corresponding to the time frame at which the driving General Circulation Model (GCM) reaches the considered temperature level (e.g., as done within the IMPACT2C project (Jacob and Solman, 2017), see description in Vautard et al. (2014)). As an alternative to the ESR or time sampling approach, pattern scaling may be used. Pattern scaling is a statistical approach that describes relationships of specific climate responses as a function of global temperature change. Some assessments of this chapter are also based on this method. The disadvantage of pattern scaling, however, is that the relationship may not perfectly emulate the models' responses at each location and for each global temperature level (James et al., 2017). Expert judgement is a third methodology that can be used to assess probable changes at 1.5°C or 2°C by combining changes that have been attributed for the observed time period (corresponding already to a warming of 1°C or smaller if assessed over a shorter time period) and known projected changes at 3°C or 4°C above the pre-industrial (Annex 3.1 S3-2). In order to compare effects induced by a 0.5°C difference in global warming, it is also possible to use, in a first approximation, the historical record as a proxy in which two periods are compared in cases where they approximate this difference in warming (e.g. such as 1991-2010 and 1960-1979, e.g. Schleussner et al., 2017). Using observations, however, does not allow an accounting for possible non-linear changes that would occur above 1°C or as 1.5°C of global warming is achieved.

In some cases, assessments for **short-term stabilization responses** could also be provided, derived from using a subset of model simulations that reach a given temperature limit by 2100, or were driven with Sea Surface Temperature (SST) consistent with such scenarios. This includes new results from the 'Half a degree additional warming, prognosis and projected impacts' (HAPPI) project (Chapter 1, Section 1.5.2, Mitchell et al., 2017). It should be noted that there is evidence that for some variables (e.g. temperature and precipitation extremes), responses after short-term stabilization (i.e. approximately equivalent to the RCP2.6 scenario) are very similar to the transient response of higher-emission scenarios (Seneviratne et al., 2016, 2018a; Wartenburger et al., 2017; Tebaldi and Knutti, 2018). This is, however, less the case for mean precipitation (e.g., Pendergrass et al., 2015)) for which other aspects of the emissions scenarios appear relevant.

For the assessment of **long-term equilibrium stabilization responses**, this chapter uses results from existing simulations where available (e.g. for sea level rise), although the available data for this type of projections is limited for many variables and scenarios and will need to be addressed in more depth in the IPCC AR6 report.

Annex 3.1 (S3-2) of this chapter includes greater detail of the climate models and associated simulations that were used to support the present assessment, as well as a background on detection and attribution approaches of relevance to assessing changes in climate at 1.5°C global warming.

3.2.2 How are potential impacts on ecosystems assessed at 1.5°C versus higher levels of warming?

Considering that the observed impacts so far are for a lower global warming than 1.5°C (generally up to the 2006-2015 decade, i.e. for a global warming of 0.87°C or less; see above), direct information on the impacts of a global warming of 1.5°C is not yet available. The global distribution of observed impacts shown in the AR5 (Cramer et al., 2014), however, demonstrates that methodologies now exist which are capable of detecting impacts in systems strongly influenced by confounding factors (e.g. urbanization or more generally human pressure) or where climate may play only a secondary role in driving impacts. Attribution of observed impacts to greenhouse gas forcing is more rarely performed, but a recent study (Hansen and Stone, 2016) shows that most of the detected temperature-related impacts that were reported in the AR5 (Cramer et al., 2014) can be attributed to anthropogenic climate change, while the signals for precipitation-induced responses are more ambiguous.

One simple approach for assessing possible impacts on natural and managed systems at 1.5ºC versus 2°C consists of identifying impacts of a global 0.5°C warming in the observational record (e.g., Schleussner et al., 2016b), assuming that the impacts would scale linearly for higher levels of warming (although this may not be appropriate). Another approach is to use conclusions from past climates combined with the modeling of the relationships between climate drivers and natural systems (Box 3.3). A more complex approach relies on laboratory or field experiments (Dove et al., 2013; Bonal et al., 2016) which provide useful information on the causal effect of a few factors (which can be as diverse as climate, greenhouse gases (GHG), management practices, biological and ecological factors) on specific natural systems that may have unusual physical and chemical characteristics (e.g., Fabricius et al., 2011; Allen et al., 2017). The latter can be important in helping to develop and calibrate impact mechanisms and models through empirical experimentation and observation.

Risks for natural and human systems are often assessed with impact models where climate inputs are provided by Representative Concentration Pathway (RCP)-based climate projections. Studies projecting impacts at 1.5°C or 2°C global warming have increased in recent times (see Section 3.4) even if the four RCP scenarios used in the AR5 are not strictly associated to these levels of global warming levels. Several approaches have been used to extract the required climate scenarios, as described in Section 3.2.1. As an example, Schleussner et al. (2016b) applied time sampling (or ESR) approach (described in Section 3.2.1) to estimate the differential effect of 1.5°C and 2°C global warming on water availability and impacts on agriculture using an ensemble of simulations under the RCP8.5 scenario. As a further example using a different approach, Iizumi et al. (2017) derived a 1.5°C scenario from simulations with an crop model using interpolation between the no-change (approximately 2010) conditions and the RCP2.6 scenario (with a global warming of +1.8°C in 2100), and derived the corresponding 2°C scenario from RCP2.6 and RCP4.5 simulations in 2100. The Inter-Sectoral Impact Model Integration and Intercomparison Project Phase 2 (ISIMIP2) (Frieler et al., 2017) extended this approach to a number of sectoral impacts on the terrestrial and marine ecosystems. In most cases, the risks are assessed by impact models coupled offline to climate models after bias correction, which may modify long-term trends (Grillakis et al., 2017).

Assessment of local impacts of climate change necessarily involves a change in scale (i.e from the global scale to that of natural or human systems) (Frieler et al., 2017; Reyer et al., 2017d; Jacob et al., 2018). An appropriate method of downscaling (Annex 3.1 S3-2) is crucially important in translating perspectives on 1.5°C and 2°C to scales and impacts relevant to humans and ecosystems. A major challenge that is associated with this requirement is to reproduce correctly the variance of local to regional changes, as well as the frequency and amplitude of the extreme events (Vautard et al., 2014). In addition, maintaining physical consistency between downscaled variables is also important, but challenging (Frost et al., 2011).

Another major challenge relates to the propagation of the uncertainties at each step of the methodology, from the global forcings to the global climate, and regional climate to the impacts at the ecosystem level, taking into account local disturbances and local policy effects. The risks for natural and human systems are the result of intricate global and local drivers, which makes quantitative uncertainty analysis difficult. Such analyses are partly done using multi-model approaches, such as multi-climate and multi-impact models (Warszawski et al., 2013, 2014; Frieler et al., 2017). In some cases, the greater proportion of the uncertainty (e.g., crop projections) is due to variation among crop models rather than that of the downscaled climate models being used (Asseng et al., 2013). The study of the error propagation is an important issue for coupled models. Dealing correctly with the uncertainties in a robust probabilistic model is particularly important when considering the potential for relatively small changes to affect the already small signal associated with 0.5°C (Annex 3.1 S3-2). The computation of the impact per unit of climatic change either based on models or data is a simple way to present the probabilistic ecosystem response taking into account the various sources of uncertainties (Fronzek et al., 2011).

In summary, in order to assess risks at 1.5°C and higher levels of global warming, several considerations need to be taken into account. Projected climates under 1.5°C of global warming can be different depending on the temporal aspects and pathways of emissions. Considerations include whether global temperature is a) temporarily at this level (i.e. is a transient phase on its way to higher levels of warming), b) arrives at 1.5°C after stabilization of greenhouse gas concentrations with or without overshoot, or c) is at this level as part of long-term climate equilibrium (after several millennia). Assessments of impacts of 1.5°C warming are generally based on climate simulations for these different possible pathways. More data and analyses are available for transient impacts (a). There are fewer data for dedicated climate model simulations that are able to assess pathways consistent with (b). There are very limited data available for the assessment of changes at climate equilibrium (c). In some cases, inferences regarding the impacts of further warming of 0.5°C above today (i.e. 1.5ºC global warming) can also be drawn from observations of similar sized changes (0.5ºC) that have occurred in the past (e.g. last 50 years). However, impacts can only be partly inferred from these types of observations given the strong possibility of non-linear changes, as well as lag effects for some climate variables (e.g. sea level rise, snow and ice melt). For the impact models, three problems are noted about the coupling procedure: (i) the bias correction of the climate model which may modify the simulated response of the ecosystem, (ii) the necessity to downscale the climate model outputs to reach a pertinent scale for the ecosystem without losing the physical consistency of the downscaled climate fields, and (iii) the necessity to develop an integrated study of the uncertainties.

3.3 Global and regional climate changes and associated hazards

This section provides the assessment of changes in climate at 1.5°C global warming relative to higher global mean temperatures. Section 3.3.1 provides a brief overview of changes to global climate. Sections 3.3.2-3.3.11 provide assessments for specific aspects of the climate system, including regional assessments for temperature (Section 3.3.2) and precipitation (Section 3.3.3) means and extremes. Analyses of regional changes are based on the set of regions displayed in Figure 3.2. A synthesis of the main conclusions of this section is provided in Section 3.3.11. The section builds upon assessments from the IPCC AR5 WG1 report (Bindoff et al., 2013a; Christensen et al., 2013; Collins et al., 2013; Hartmann et al., 2013; IPCC, 2013) and Chapter 3 of the IPCC Special Report on Managing the Risks of Extreme Events and disasters to Advance Climate Change Adaptation (SREX)(Seneviratne et al., 2012), as well as a substantial body of new literature related to projections of climate at 1.5°C and 2°C of warming above the pre-industrial period (e.g., Vautard et al., 2014; Fischer and Knutti, 2015; Schleussner et al., 2016b; Seneviratne et al., 2016, 2018c; Déqué et al., 2017; Maule et al., 2017; Mitchell et al., 2017; Wartenburger et al., 2017; Zaman et al., 2017; Betts et al., 2018; Jacob et al., 2018; Kharin et al., 2018; Mitchell et al., 2018; Wehner et al., 2018). The main assessment methods are as already detailed in Section 3.2.

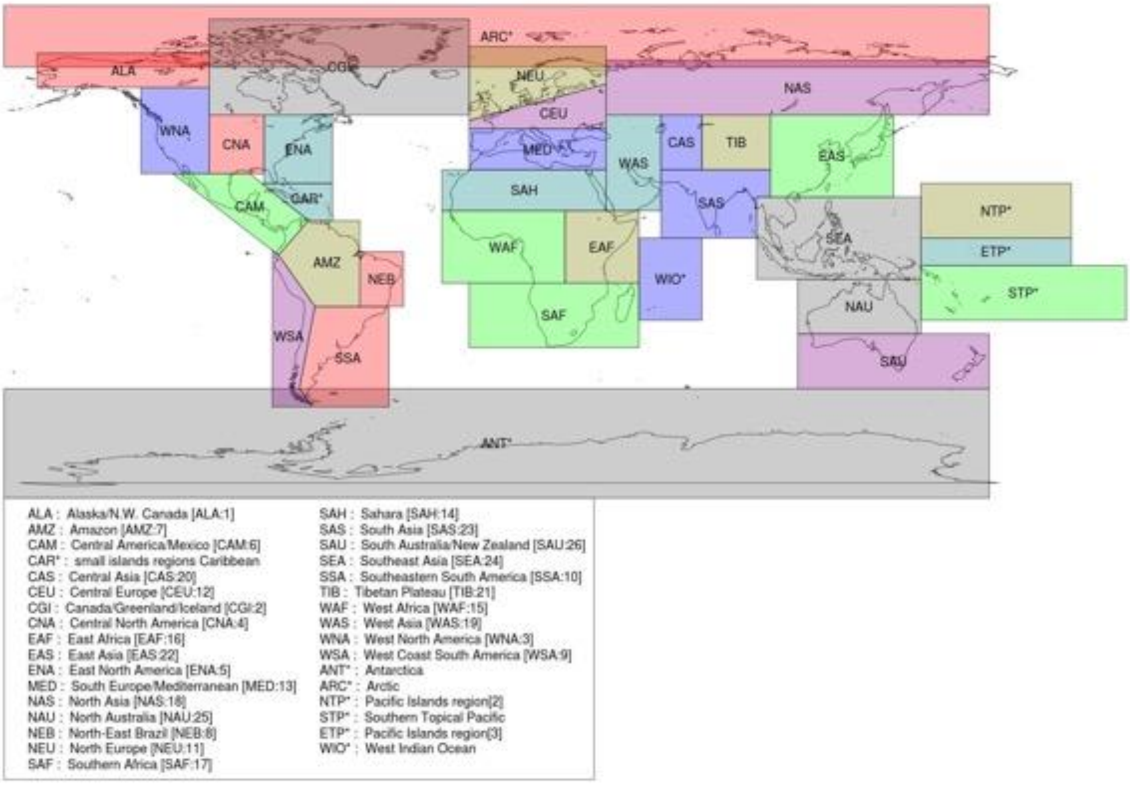

Figure 3.2: Regions used for regional analyses provided in Section 3.3. The choice of regions is based on the IPCC Fifth Assessment Report (AR5, Chapter 14, Christensen et al., 2013) and Annex 1: Atlas) and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, Chapter 3, Seneviratne et al., 2012), including seven additional regions (Arctic, Antarctic and islands) compared to the IPCC SREX report (indicated with asterisks). Analyses for regions with asterisks are provided in the Annex (Annex 3.1 S3-3).

3.3.1 Global changes in climate

There is *high confidence* that the Global Mean Surface Temperature (GMST) warming has reached 0.87°C (±0.10°C *likely* range) above pre-industrial in the 2006-2015 decade (Chapter 1). The AR5 assessed that the globally averaged temperature (combined over land and ocean) displayed a warming of about 0.85°C [0.65°C to 1.06°C] for the period 1880-2012, with a large fraction of the detected global warming being attributed to anthropogenic forcing (Bindoff et al., 2013a; Hartmann et al., 2013; Stocker et al., 2013). While new evidence has highlighted that sampling biases and the choice of approaches to estimate GMST (e.g., using water versus air temperature over oceans; model simulations versus observations-based estimates) can affect estimates of GMST warming (Richardson et al., 2016) (see also Annex 3.1 S3.3), the present assessment is consistent with that of the AR5 regarding a detectable and dominant effect of anthropogenic forcing on observed trends in global temperature (e.g., also confirmed in Ribes et al., 2017). As highlighted in Chapter 1, human-induced warming reached approximately 1°C (±0.2°C *likely* range) in 2017. More background on recent observed trends in global climate is provided in the Annex 3-3.

A global warming of 1.5°C implies warmer mean temperatures compared to pre-industrial times in almost all locations on both land and oceans (*high confidence*) (Figure 3.3). In addition, differences resulting from 1.5°C and 2°C global warming are detectable in mean temperatures in almost all locations on both land and ocean (*high confidence*). The land-sea contrast in temperature warming is important and implies particularly large changes in temperature over land, with larger mean warming than 1.5°C in most land regions (*high confidence*; see Section 3.3.2 for more details). The highest warming of the mean temperature is found in the northern high latitudes (*high confidence*; Figure 3.3, see Section 3.3.2 for more details). Projections for precipitation are more uncertain but highlight significant increases in mean precipitation in the Northern Hemisphere high latitudes at 2°C versus 1.5°C global warming (*medium confidence*) (Figure 3.3). For droughts, changes in evapotranspiration and precipitation timing are also relevant (see Section 3.3.4). Figure 3.4 displays changes in temperature extremes (the hottest day of the year, TXx, and the coldest day of the year TNn) and heavy precipitation (the annual maximum 5-day precipitation, Rx5day). These analyses reveal distinct patterns of changes, with highest changes in TXx in mid-latitude land, and highest changes in TNn in high latitudes (both land and oceans). Differences at 1.5°C versus 2°C are significant across the globe. Changes in heavy precipitation are less robust at the grid-cell scale, but display increases over most land areas.

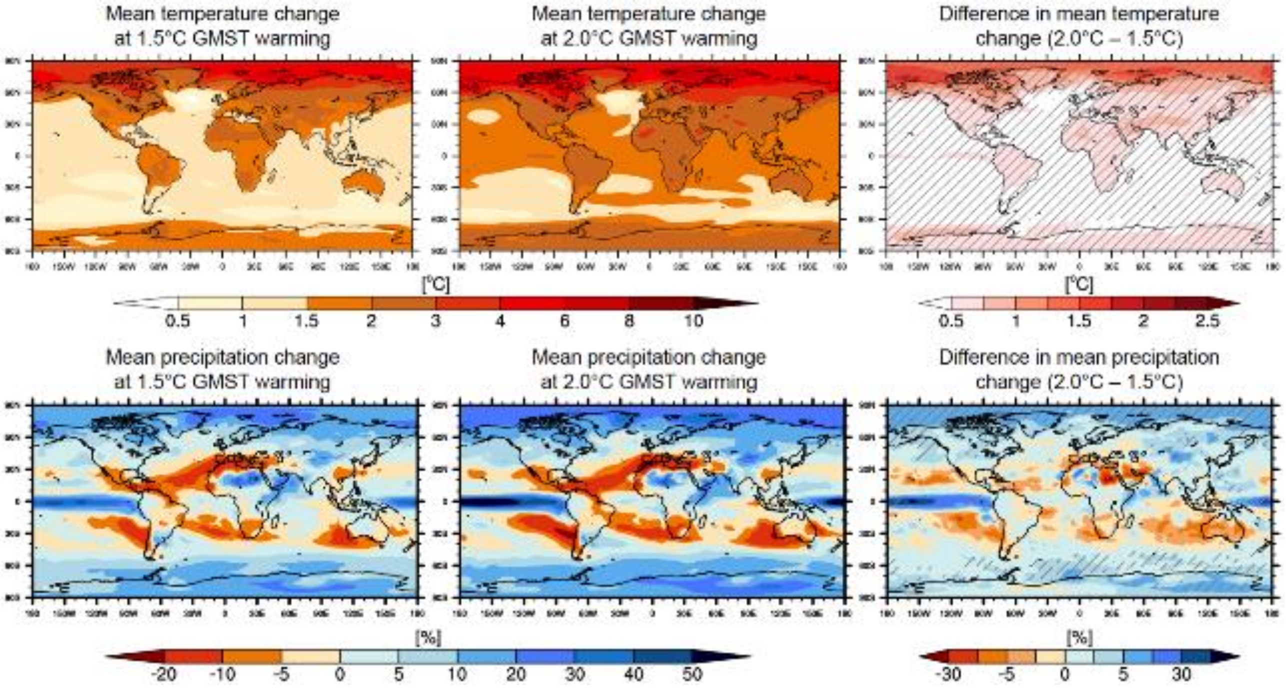

Figure 3.3: Projected mean temperature (top) and mean precipitation changes (bottom) at 1.5°C global warming (left) and 2°C global warming (middle) compared to pre-industrial time period (1861-1880), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Assessed from transient response over 20-year time period at given warming, based on Representative Concentration Pathway (RCP)8.5 Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulations (adapted from Seneviratne et al., 2016, and Wartenburger et al., 2017, see Annex 3.1 S3-3 for more details). Note

that the responses at 1.5°C Global Mean Surface Temperature (GMST) warming are similar for RCP2.6 simulations (see Annex 3.1 S3-3).

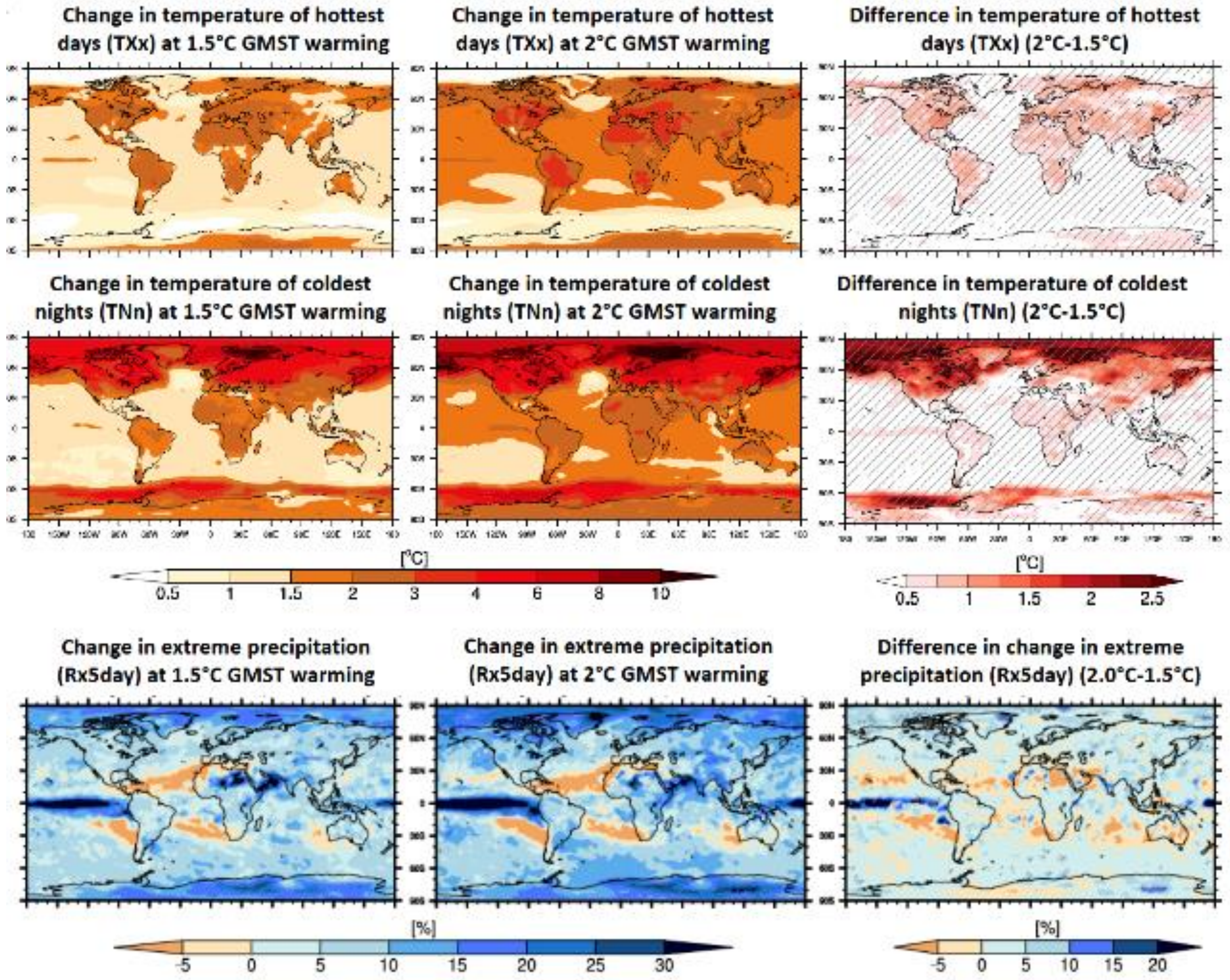

Figure 3.4: Projected change in extreme at 1.5°C global warming (left) and 2°C global warming (middle) compared to pre-industrial time period (1861-1880), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change): temperature of annual hottest day, TXx (top), and annual coldest day, TNn, (middle), and annual maximum 5-day precipitation, Rx5day (bottom). Same underlying methodology and data basis as Figure 3.3 (see Annex 3.1 S3-3 for more details). Note that the responses at 1.5°C Global Mean Surface Temperature (GMST) warming are similar for Representative Concentration Pathway (RCP)2.6 simulations (see Annex 3.1 S3-3).

These projected changes at 1.5°C and 2°C global warming are consistent with the attribution of global observed historical trends in temperature and precipitation means and extremes (Bindoff et al., 2013a) as well as with some observed changes for a recent global warming of 0.5°C (Schleussner et al., 2017), as also addressed in more detail in Sections 3.3.2 and 3.3.3). Attribution studies have shown that there is *high confidence* that anthropogenic forcing has had a detectable influence on trends in global warming (*virtually certain* since the mid 20th century), in land warming on all continents except Antarctica (*likely* since the mid of the 20th century), ocean warming since 1970 (*very likely*) and in increases in hot extremes and decreases in cold extremes since the mid 20th century (*very likely*) (Bindoff et al., 2013a). In addition, there is *medium confidence* that anthropogenic forcing has contributed to increases in mean precipitation in the North-Hemisphere high-latitudes since the mid 20th century and to global-scale increases in heavy precipitation in land regions with sufficient observations over the same time period (Bindoff et al., 2013a). Schleussner et al. (2017) have shown from analyses of recent observed tendencies that changes in temperature extremes and heavy precipitation indices are detectable in observations for the 1991-2010 period compared with 1960-1979, when a global warming of approximately 0.5°C occurred *(high confidence)*. The observed tendencies over that time frame are thus consistent with attributed changes since the mid-20th century (*high confidence*).

The next sections assess changes in several different types of climate-related hazards. It should be noted that the different types of hazards are considered in isolation, but that some regions are projected to be affected by collocated and/or concomitant changes in several types of hazards (for instance sea level rise and heavy precipitation in some regions, possibly leading together to more flooding, or droughts and heatwaves, which can together increase the risk of fire occurrence). Such events, also called compound events, may substantially increase risks in some regions (e.g. (Amir et al., 2014; Van Den Hurk et al., 2015; Martius et al., 2016; Zscheischler et al., 2018). A detailed assessment of physically-defined compound events at 1.5°C vs 2°C global warming was not possible as part of this report, but aspects related to overlapping multi-sector risks are highlighted in Sections 3.4 and 3.5.

3.3.2 Regional temperatures on land, including extremes

3.3.2.1 Observed and attributed changes in regional temperature means and extremes

While the quality of temperature measurements obtained through ground observational networks tend to be high compared to that of measurements for other climate variables (Seneviratne et al., 2012), it should be noted that some regions are undersampled. Cowtan and Way (2014) highlighted issues regarding undersampling being concentrated at the poles and over Africa, which may lead to biases in estimated changes in GMST (see also Annex 3.1 S3-3 and Chapter 1). This undersampling also affects the confidence of assessments regarding regional observed and projected changes in both mean and extreme temperature. Despite this partly limited coverage, the attribution chapter of the AR5 (Bindoff et al., 2013a) and recent papers (e.g., Sun et al., 2016; Wan et al., 2018) assessed that over every continental regions and in many sub-continental regions, anthropogenic influence has made a substantial contribution to surface temperature increases since the mid-20th century.

It is *very likely* that there has been an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights at the global scale on land. It is also *likely* that consistent changes are detectable on continental scale in North America, Europe and Australia. This is consistent with the SREX and AR5 assessments (Seneviratne et al., 2012; Hartmann et al., 2013). There is *high confidence* that these observed changes in temperature extremes can be attributed to anthropogenic forcing (AR5, Bindoff et al., 2013a). As highlighted in Section 3.2, the observational record can be used to assess past changes associated with a global warming of 0.5°C. Schleussner et al. (2017) used this approach to assess observed changes in extreme indices for the 1991-2010 versus the 1960-1979 period, which corresponds to just about 0.5°C GMST difference in the observed record (based on the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) dataset, Hansen et al., 2010). They found that substantial changes due to 0.5°C warming are apparent for indices related to hot and cold extremes, as well as for the Warm Spell Duration Indicator (WSDI). In particular, they identified that one quarter of the land has experienced an intensification of hot extremes (maximum temperature in the hottest day of the year, TXx) by more than 1°C and a reduction of the intensity of cold extremes by at least 2.5°C (minimum temperature in the coldest night of the years, TNn). In addition, that study shows that half of the global land mass has experienced changes in WSDI of more than six days as well as an emergence of extremes outside the range of natural variability (Schleussner et al., 2017). Analyses from Schleussner et al. (2017) for temperature extremes are provided in the Annex 3-3 (Figure S3.6).

3.3.2.2 Projected changes at 1.5°C versus. 2°C in regional temperature means and extremes

There are several lines of evidence available for providing a regional assessment of projected change in temperature means and extremes at 1.5°C versus 2°C global warming (see Section 3.2). These include, analyses of changes in extremes as a function of global warming based on existing climate simulations using the Empirical Scaling Relationship (ESR) and variations therefrom (see Section 3.2 for details about the methodology) (e.g., Schleussner et al., 2017; Dosio and Fischer, 2018; Seneviratne et al., 2018c) dedicated simulations for 1.5°C versus 2°C global warming, for instance based on the Half a degree additional warming, prognosis and projected impacts (HAPPI) experiment (Mitchell et al., 2017) or other model simulations (e.g., Dosio et al., 2018); and analyses based on statistical pattern scaling approaches (e.g. Kharin et al., 2018). Results with these different lines of evidence display qualitatively consistent results regarding changes in temperature means and extremes at 1.5°C global warming compared to pre-industrial climate and 2°C global warming.

There are statistically significant differences in temperature means and extremes at 1.5°C versus 2°C global warming, both in the global average (Schleussner et al., 2016b; Dosio et al., 2018; Kharin et al., 2018), as well as in nearly all inhabited land regions (Wartenburger et al., 2017; Seneviratne et al., 2018c; Wehner et al., 2018) (*high confidence)*. Temperatures over oceans display significant increases between 1.5°C and 2°C global warming (Figures 3.3 and 3.4). A general background on the available evidence on regional changes in temperature means and extremes at 1.5°C versus 2°C global warming is provided in the Annex 3.1 S3-3. As an example, Figure 3.5 shows for the IPCC SREX regions (Figure 3.2) regionally-based analyses of changes in the temperature of hot extremes as a function of warming (corresponding analyses for changes in the temperature of cold extremes are provided in the Annex 3.1 S3-3). As can be seen in these analyses, the mean response of the intensity of temperature extremes in climate models to changes in the global mean temperature is approximately linear and independent of the considered emission scenario (Seneviratne et al., 2016; Wartenburger et al., 2017). Nonetheless, in the case of changes in the number of days exceeding a given threshold, changes are found to be approximately exponential, with higher increases for rare events (Fischer and Knutti, 2015; Kharin et al., 2018); see for example, Figure 3.6. This behavior is consistent with a linear increase in absolute temperature for extreme threshold exceedances (Whan et al., 2015).

As mentioned in Section 3.3.1, there is an important land-sea warming contrast, with stronger warming on land (see also Christensen et al., 2013; Collins et al., 2013; Seneviratne et al., 2016), which implies that regional warming on land is generally higher than 1.5°C even when mean global warming is at 1.5°C. As highlighted in Seneviratne et al. (2016), this feature is generally stronger for temperature extremes (Figures 3.4 and 3.5; Annex 3.1 S3-3). For differences in regional temperature extremes at mean global warming of 1.5°C versus 2°C, this implies differences of as much as 1°C -1.5ºC in some locations, which are thus 2-3 times larger than the differences in global mean temperature. For hot extremes, the strongest warming is found in Central and Eastern North America, Central and Southern Europe, the Mediterranean, Western and Central Asia, and Southern Africa (Figures 3.4 and 3.5). These regions are all characterized by a strong soil-moisture-temperature coupling (Vogel et al., 2017) leading to increased dryness and, consequently, a reduction in evaporative cooling and thus added warming in the projections. Some of these regions also show a wide range of responses to temperature extremes, in particular Central Europe and Central North America, due to discrepancies in the representation of the underlying processes in present climate models (Vogel et al., 2017). For mean temperature and cold extremes, the strongest warming is found in the northern high-latitude regions (*high confidence*). This is due to substantial ice-snow-albedo-temperature feedbacks (Figure 3.3 and Figure 3.4, middle), related to the known 'polar amplification' mechanism (e.g., IPCC, 2013; Masson-Delmotte et al., 2013).

Figure 3.7 displays maps of changes in the Number of Hot Days (NHD) at 1.5°C and 2°C GMST warming. Maps of changes in the number of Frost Days (FD) can be found in the Annex 3.1 S3-3. These analyses reveal clear patterns of changes between the two warming levels, also consistent with analysed changes in heatwave occurrence (e.g., Dosio et al., 2018). For the NHD, the largest differences are found in the tropics due to the lower interannual temperature variability (Mahlstein et al., 2011), and despite the tendency for higher absolute changes in hot temperature extremes in mid-latitudes (Figures 3.4 and 3.5). The emergence of extreme heatwaves is thus earliest in these regions, where they become already widespread at 1.5°C global warming (*high confidence*). These analyses are consistent with other recent assessments. Coumou and Robinson (2013) find that under a 1.5°C warming, already 20% of the global land area, centered in low latitude regions, is projected to experience highly unusual monthly temperatures during boreal summers (a number which nearly doubles for 2°C of global warming).

Figure 3.8 includes an objective identification of "hot spots" / key risks in temperature indices subdivided by regions, based on the ESR approach applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations (Wartenburger et al., 2017). It is noted that results based on the HAPPI multi-model experiment (Mitchell et al., 2017) display similar results (Seneviratne et al., 2018c). The considered regions follow the classification of Figure 3.2 and also include the global land. The figure displays red shading for all instances in which a significant difference is found between regional responses at 1.5°C versus 2°C. Based on these analyses, the following can be stated: Significant changes in responses are found in all regions, for most temperature indices, with the exception of i) the Diurnal Temperature Range (DTR) in most regions, of ii) Ice Days (ID), Frost Days (FD), and Growing Season Length (GSL) in mostly warm regions, and of iii) the minimum yearly value of the Maximum Daily Temperature (TXn) in very few regions. In terms of the sign of the changes, it can be seen that warm extremes display an increase in intensity, frequency and spell length (e.g. increase of the temperature of the hottest day of the year (TXx) in all regions, increase of proportion of days above 90th percentile of Tmax (TX90p) in all regions, increase of the length of the WSDI in all regions), while cold extremes display a decrease in intensity, frequency and spell length (e.g. increase of the temperature of the coldest night of the year (TNn) in all regions, decrease in the proportion of days below the 10th percentile of Tmin (TN10p), decrease in the length of the Cold Spell Duration Index (CSDI) in all regions). Hence, while warm extremes are intensified, it should also be noted that cold extremes become less intense and frequent (but have a higher temperatures) in affected regions.

Overall, large increases in hot extremes happen in many densely inhabited regions (Figure 3.5), both compared to present-day climate and at 2°C versus 1.5°C global warming. For instance, Dosio et al. (2018) concluded based on a modeling study that 13.8% of the world population would be exposed to severe heat waves at least once every 5 years under 1.5°C global warming, with a threefold increase (36.9%) under 2°C warming, i.e. a difference of about 1.7 billion people. They also conclude that limiting global warming to 1.5°C would result in about 420 million fewer people being frequently exposed to extreme heat waves, and about 65 million fewer people being exposed to exceptional heat waves. However, changes in vulnerability were not considered in that study.

In summary, there are statistically significant differences in temperature means and extremes at 1.5°C versus 2°C global warming, both in the global average as well as in near all land regions[1] and the ocean (*likely*). Also, the observational record reveals that substantial changes due to a 0.5°C GMST warming are apparent for indices related to hot and cold extremes, as well as for the WSDI *(likely)*. A warming of 2°C versus 1.5°C leads to more frequent and more intense hot extremes in all land regions[1], as well as to longer warm spells, affecting many densely inhabited regions (*very likely*). Strongest increases in the frequency of hot extremes happens for the rarest events (*very likely*). On the other hand, cold extremes would become less intense and less frequent, and cold spells would be less extended (*very likely*). Temperature extremes on land generally increase more than the global average temperature (*very likely*). Extreme hot days in mid-latitudes display an up to two-fold higher warming than the GMST (*likely*). The highest levels of warming for extreme hot days are found in Central and Eastern North America, Central and Southern Europe, the Mediterranean, Western and Central Asia, and Southern Africa (*likely*). These regions have a strong soil-moisture-temperature coupling in common, leading to increased dryness and, consequently, a reduction in evaporative cooling, although there is substantial model range in the representation of these processes, in particular in Central Europe and Central North America (*likely*). The coldest nights in high-latitudes warm by as much as 1.5°C for a 0.5°C increase in GMST, i.e. a three-fold higher warming (*likely*). The NHD shows the largest differences between 1.5°C and 2.0°C in the tropics because of their low interannual temperature variability (*likely*); the emergence of extreme heatwaves is thus earliest in these regions, where they become already widespread at 1.5°C global warming (*high confidence*). Limiting global warming to 1.5°C instead of 2ºC could result in around 420 million fewer people being frequently exposed to extreme heatwaves, and about 65 million fewer people being exposed to exceptional heatwaves, assuming constant vulnerability (*medium confidence*).

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[1] FOOTNOTE: Using the SREX definition of regions (Figure 3.2)

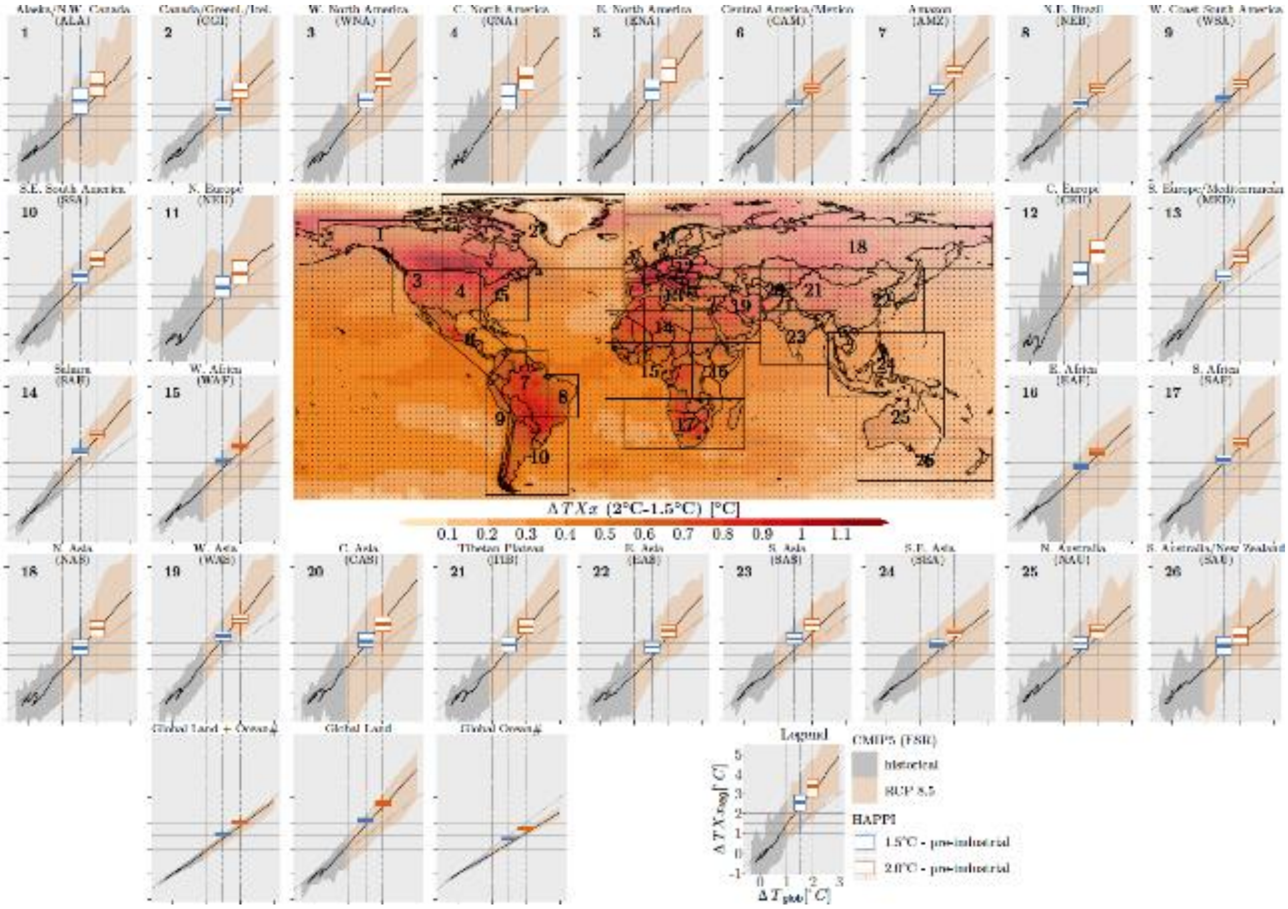


Figure 3.5: Projected changes in annual maximum daytime temperature (TXx) as function of global temperature warming for IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (Figure 3.2), based on empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) data (adapted from Seneviratne et al., 2016, and Wartenburger et al., 2017) together with projected changes from the Half a degree additional warming, prognosis and projected impacts (HAPPI) multi-model experiment (Mitchell et al., 2017, based on analyses in Seneviratne et al., 2018c) (bar plots on regional analyses and central plot, respectively). For analyses for other regions from Figure 3.2 (with asterisks), see Annex 3.1 S3-3. (The stippling indicates significance of the differences of changes in between 1.5°C and 2°C global warming based on all model simulations, using a two-sided paired Wilcoxon test (p = 0.01, after controlling the false discovery rate according to Benjamini and Hochberg, 1995). See Annex 3.1 S3-3 for details.

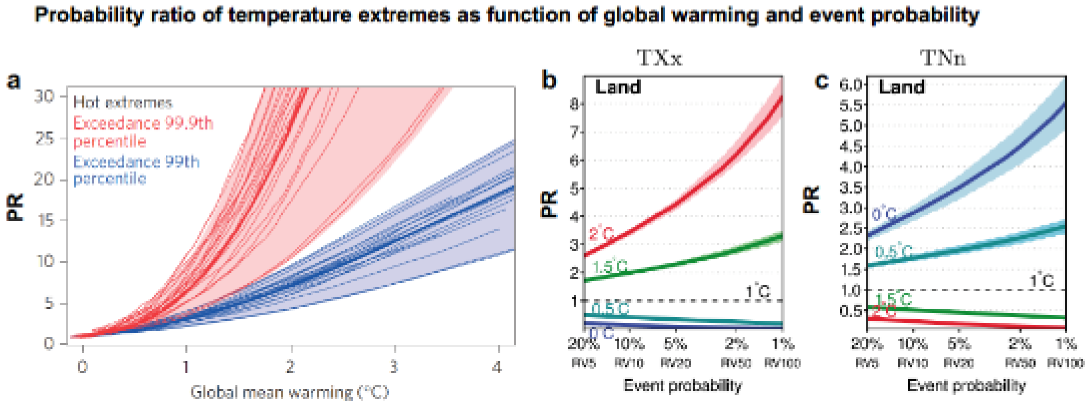


Figure 3.6: Probability ratio (PR) of exceeding extreme temperature thresholds. Left (a): PR of exceeding (blue) 99th and (red) 99.9th percentile of pre-industrial daily temperature at a given warming level relative to pre-industrial conditions averaged across land (from Fischer and Knutti, 2015). Middle (b) and right (c) : PR for hottest day of the year (TXx) and coldest night of the year (TNn) for different event probabilities (with RV indicating return values) in the current climate (1°C warming) ; the shading shows the interquartile (25%-75%) range (from Kharin et al., 2018).

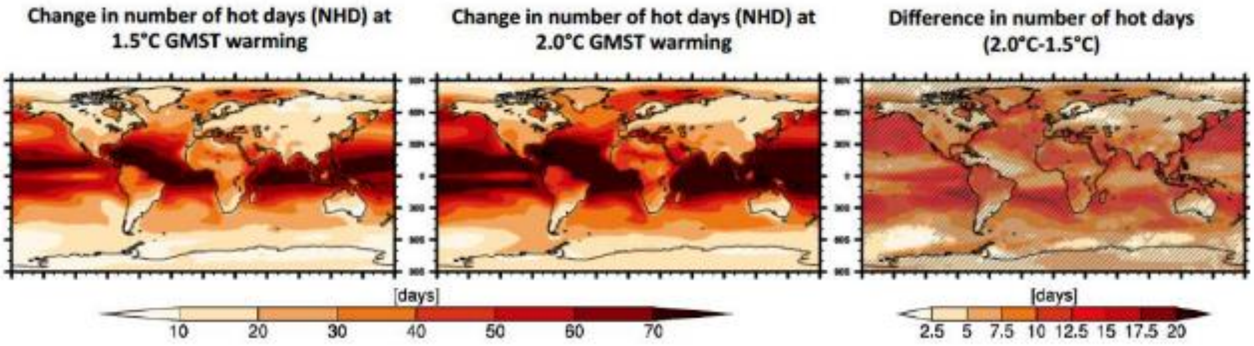
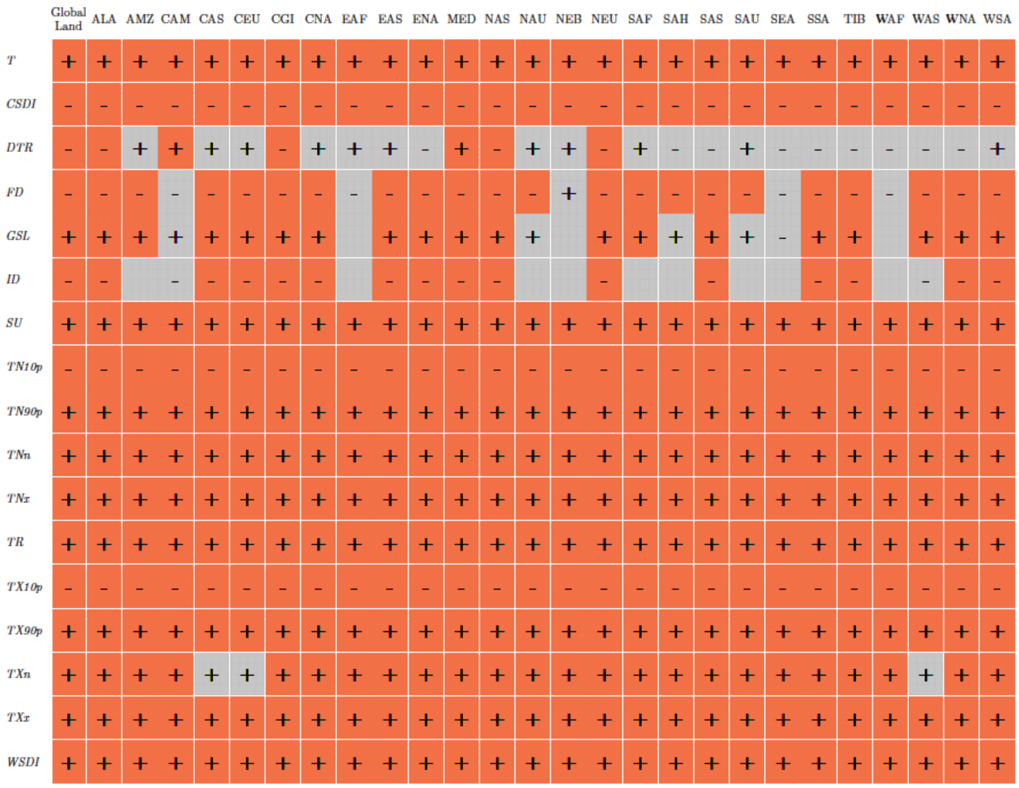


Figure 3.7: Projected change number of hot days (10% warmest days) at 1.5°C global warming (left) and 2°C global warming (middle) compared to pre-industrial time period (1861-1880), and difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Same underlying methodology and data basis as Figure 3.2 (Annex 3.1 S3-3 for more details).



	Global Land	ALA	AMZ	CAM	CAS	CEU	CGI	CNA	EAF	EAS	ENA	MED	NAS	NAU	NEB	NEU	SAF	SAH	SAS	SAU	SEA	SSA	TIB	WAF	WAS	WNA	WSA
T	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
CSDI	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
DTR	-	-	+	+	+	+	-	+	+	+	-	+	-	+	+	-	+	-	-	+	-	-	-	-	-	-	+
FD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	+	-	-	-	-	-	-	-	-	-	-	-	-
GSL	+	+	+	+	+	+	+	+		+	+	+	+	+		+	+	+	+	+	-	+	+		+	+	+
ID	-	-		-	-	-	-	-		-	-	-	-			-			-			-	-		-	-	-
SU	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TN10p	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TN90p	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TNn	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TNx	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TR	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TX10p	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TX90p	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TXn	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
TXx	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
WSDI	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Figure 3.8: Significance of differences of regional mean temperature and range of temperature indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: T: mean temperature; CSDI: Cold Spell Duration Index; DTR: Diurnal Temperature Range; FD: Frost Days; GSL: Growing Season Length; ID: Ice Days; SU: Summer Days; TN10P: Proportion of days with minimum temperature (TN) below 10th percentile of TN; TN90p: Proportion of days with TN higher than 90th percentile TN; TNn: minimum yearly value of TN; TNx: maximum yearly value of TN; TR: Tropical Nights; TX10p: Proportion of days with maximum Temperature (TX) lower than 10th percentile of TX; TX90p: Proportion of days with TX higher than 90th percentile of TX; TXn: minimum yearly value of TX; TXx: maximum yearly value of TX; WSDI: Warm Spell Duration Index. Columns indicate analysed regions and global land (see Figure 3.2 for definition). Significant differences are shown in red shading (increases indicated with + sign, decreases indicated with – sign), insignificant differences are shown in grey shading. Note that decreases in CSDI, FD, ID, TN10p and TX10p are linked to increased temperatures in cold days or nights. Significance is tested using a two-sided paired Wilcoxon test (p=0.01, after controlling the false discovery rate according to Benjamini and Hochberg, 1995) (adapted from Wartenburger et al., 2017).

3.3.3 Regional precipitation, including heavy precipitation and monsoons

This section addresses regional changes in precipitation on land, with a focus on heavy precipitation and consideration of changes to the key features of monsoons.

3.3.3.1 Observed and attributed changes in regional precipitation

Observed global changes in the water cycle, including precipitation, are more uncertain than observed changes in temperature (Hartmann et al., 2013; Stocker et al., 2013). There is *high confidence* that mean precipitation over the mid-latitude land areas of the Northern Hemisphere has increased since 1951 (Hartmann et al., 2013). For other latitudinal zones area-averaged long-term positive or negative trends have *low confidence* due to data quality, data completeness or disagreement amongst available estimates (Hartmann et al., 2013). There is in particular *low confidence* regarding observed trends in precipitation in monsoon regions, based on the SREX report (Seneviratne et al., 2012), the AR5 (Hartmann et al., 2013), as well as on more recent publications (Singh et al., 2014; Taylor et al., 2017; Bichet and Diedhiou, 2018) Annex 3.1 S3-3).

For heavy precipitation, the AR5 (Hartmann et al., 2013), assessed that observed trends displayed more areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation *(likely)*. In addition, it assessed that in land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al., 2013a).

Regarding changes in precipitation associated with a global warming of 0.5°C, the observed record suggests that robust increases in observed precipitation extremes can be identified for annual maximum 1-day precipitation (RX1day) and consecutive 5-day precipitation (RX5day) for GMST changes of this magnitude (Schleussner et al., 2017) (Annex S3.3, Figure S3.7).

3.3.3.2 Projected changes at 1.5°C versus 2°C in regional precipitation

Figure 3.3 (Section 3.3.1) summarizes the projected changes in mean precipitation at 1.5°C versus 2°C. Some regions display substantial changes in mean precipitation between 1.5°C versus 2°C global warming, in particular decreases in the Mediterranean area, including Southern Europe, the Arabian Peninsula and Egypt. Some studies are also available for other regions across the world. For instance, Déqué et al. (2017) investigate the impact of a 2°C global warming on precipitation over tropical Africa and found that average precipitation does not show a significant response due to two compensating phenomena: (a) the number of rain days decreases whereas the precipitation intensity increases, and (b) the rainy season occurs later during the year with less precipitation in early summer and more precipitation in late summer. The assessment found insignificant differences between 1.5°C and 2°C scenarios for tropical Africa, which is consistent with the results of Figure 3.3. For Europe, for 2°C global warming, a robust increase of precipitation over Central and Northern Europe in winter and only over Northern Europe in summer, and decreases of precipitation in Central/Southern Europe in summer, with changes reaching 20% have been reported by Vautard et al. (2014) and is more pronounced than with +1.5°C global warming (Jacob et al., 2018).

For changes in heavy precipitation, Figure 3.9 displays projected changes in the 5-day maximum precipitation (Rx5day) as a function of global temperature increase, using a similar approach as in Figure 3.5. Further analyses are available in the Annex (Annex 3.1 S3-3). These analyses show that projected changes in heavy precipitation are more uncertain than for temperature extremes. However, the mean response of model simulations is generally robust and linear (see also Fischer et al., 2014; Seneviratne et al., 2016). As for temperature this response is also found to be mostly independent of the considered emissions scenario (e.g. Representative Concentration Pathway (RCP)2.6 versus RCP8.5; also Section 3.2). This appears to be a specific feature of heavy precipitation, possibly due to a stronger coupling with temperature, as the scaling of projections of mean precipitation changes with global warming shows some scenario dependency (Pendergrass et al., 2015).

The differences in heavy precipitation are generally small between 1.5°C and 2°C global warming (Figure

3.9 and Annex 3.1 S3-3 Figure S3.10). Some regions display substantial increases, for instance in Southern Asia, but generally in less than 2/3 of the CMIP5 models (Annex 3.1 S3-3, Figure S3.10). Wartenburger et al. (2017) suggests that for Eastern Asia, there are substantial differences in heavy precipitation at 1.5°C versus 2°C. Based on regional climate simulations, Vautard et al. (2014) found a robust increase in heavy precipitation everywhere in Europe and in all seasons, except Southern Europe in summer, consistent with the analysis of Jacob et al. (2014) which used more recent downscaled climate scenarios (EURO-CORDEX) and a higher resolution (12km) for +2°C global warming. There is a consistent agreement in the direction of change for +1.5°C global warming over much of Europe (Jacob et al., 2018). While there are variations between regions, the global tendency for heavy precipitation suggests an increase at 2°C versus 1.5°C (see also Fischer and Knutti, 2015), and Kharin et al., 2018), Figure 3.10, as well as Betts et al., 2018).

The AR5 assessed that the global monsoon, aggregated over all monsoon systems, is *likely* to strengthen, with increases in its area and intensity, while the monsoon circulation weakens (Christensen et al., 2013). There are a few publications that provide more recent evaluations on projections of changes in monsoons for high-emissions scenarios (e.g., Jiang and Tian, 2013; Jones and Carvalho, 2013; Sylla et al., 2015, 2016); Annex S3-3). However, given that a) scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than those assessed in the AR5 and these more recent studies, and b) the fact that there appears to be no specific assessment of changes in monsoon precipitation at 1.5°C versus 2°C global warming in the present literature, and c) that there is *low confidence* in observed trends in monsoons (Section 3.3.3.1), the present assessment is that there is *low confidence* regarding projected changes in monsoons at 1.5°C and 2°C global warming, as well as regarding differences in monsoon responses at 1.5°C versus 2°C.

Similarly, as for Figure 3.8, Figure 3.11 includes an objective identification of “hot spots” / key risks in heavy precipitation indices subdivided by regions, based on (Wartenburger et al., 2017). The considered regions follow the classification of the IPCC SREX report (Figure 3.2) and also include global land areas. The figure displays red shading for all instances in which a significant difference is found between regional responses at 1.5°C versus 2°C. Hot spots displaying statistically significant changes in heavy precipitation between 1.5°C and 2°C global warming are found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, Northern Asia) and high-altitude (Tibetan Plateau) regions, as well as in Eastern Asia (including China and Japan) and in Eastern North America. Results are less consistent for other regions. Note that analyses for meteorological drought (lack of precipitation) are provided in Section 3.3.4.

In summary, observations and projections for mean and heavy precipitation are less robust than for temperature means and extremes (*high confidence*). Observations show that there are more areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation *(likely)*. Several regions display statistically significant differences in heavy precipitation at 1.5°C *vs*. 2°C warming (with stronger increase at 2°C), and there is a global tendency towards increases in heavy precipitation on land between these two temperature levels (*likely*). Overall, regions that display statistically significant changes in heavy precipitation between 1.5°C and 2°C global warming are found in high-latitude (Alaska/Western Canada, Eastern Canada/Greenland/Iceland, Northern Europe, Northern Asia) and high-altitude (Tibetan Plateau) regions, as well as in Eastern Asia (including China and Japan) and in Eastern North America (*medium confidence*). There is *low confidence* in projected changes in heavy precipitation at 1.5°C versus 2°C in other regions.

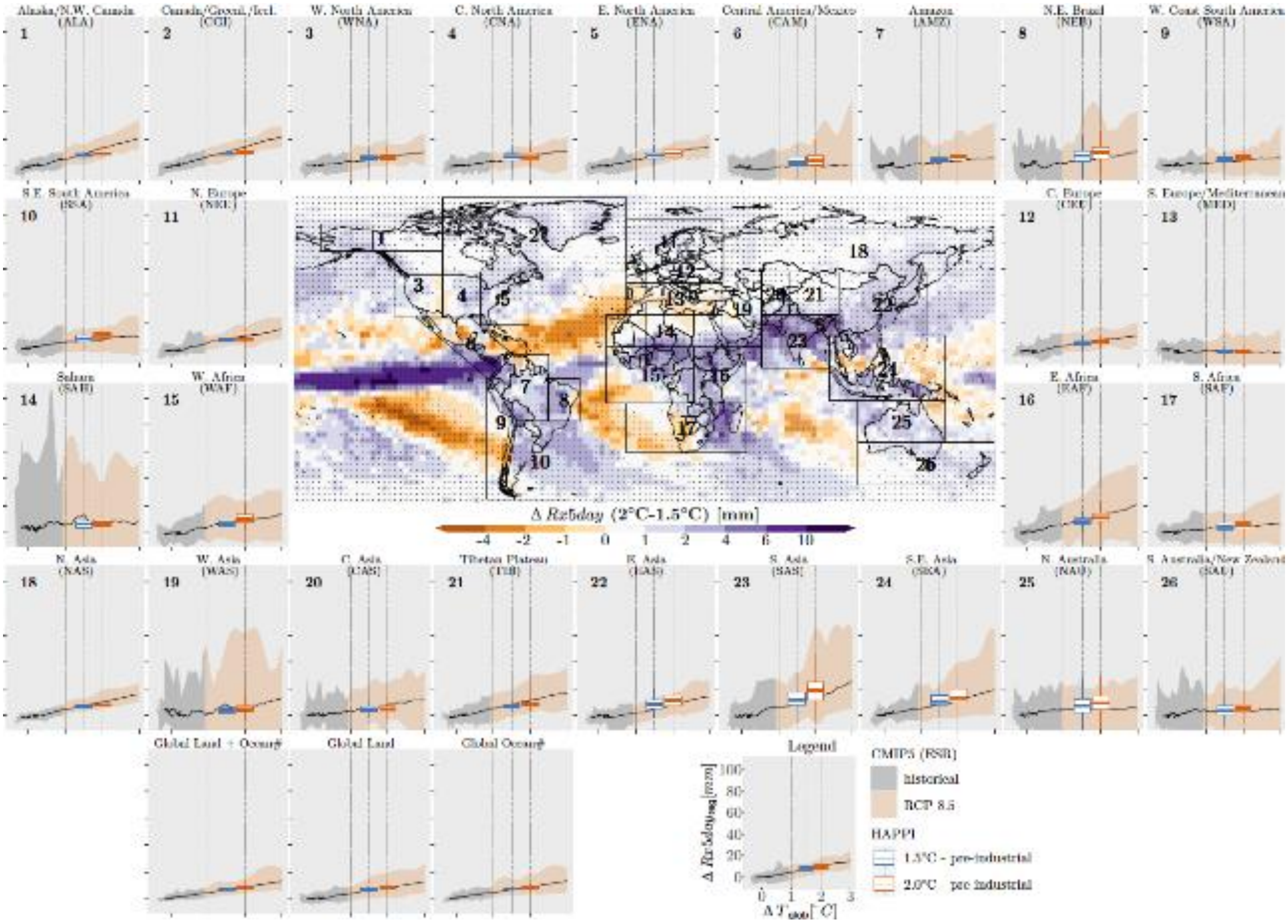


Figure 3.9: Projected changes in annual 5-day maximum precipitation (Rx5day) as function of global temperature warming for IPCC Special Report on the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (Figure 3.2), based on empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) together with projected changes from the HAPPI multi-model experiment (bar plots on regional analyses and central plot). Same data basis and analysis approach as in Figure 3.5 (Annex 3.1 S3-3 for more details).

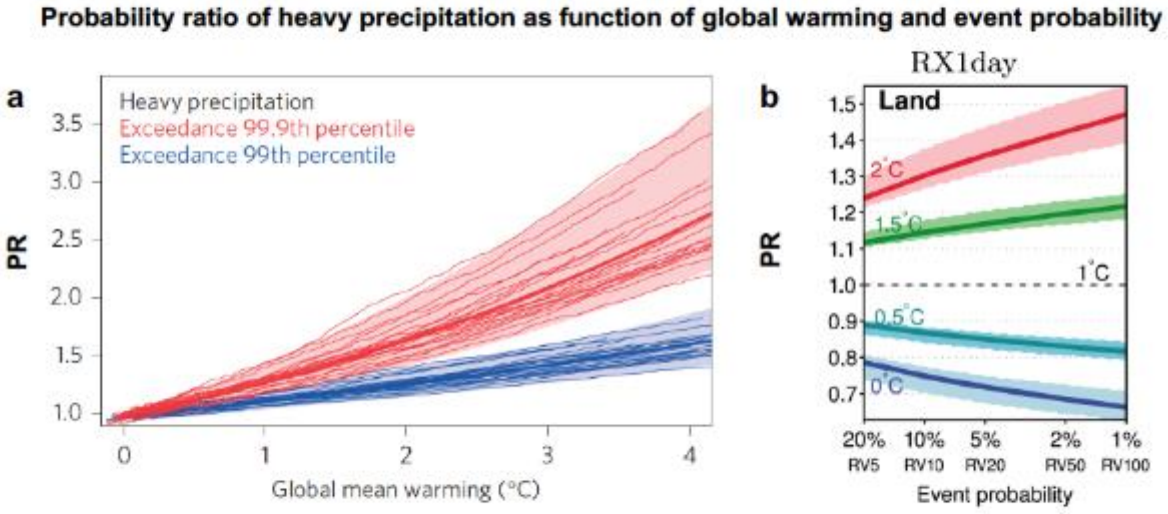
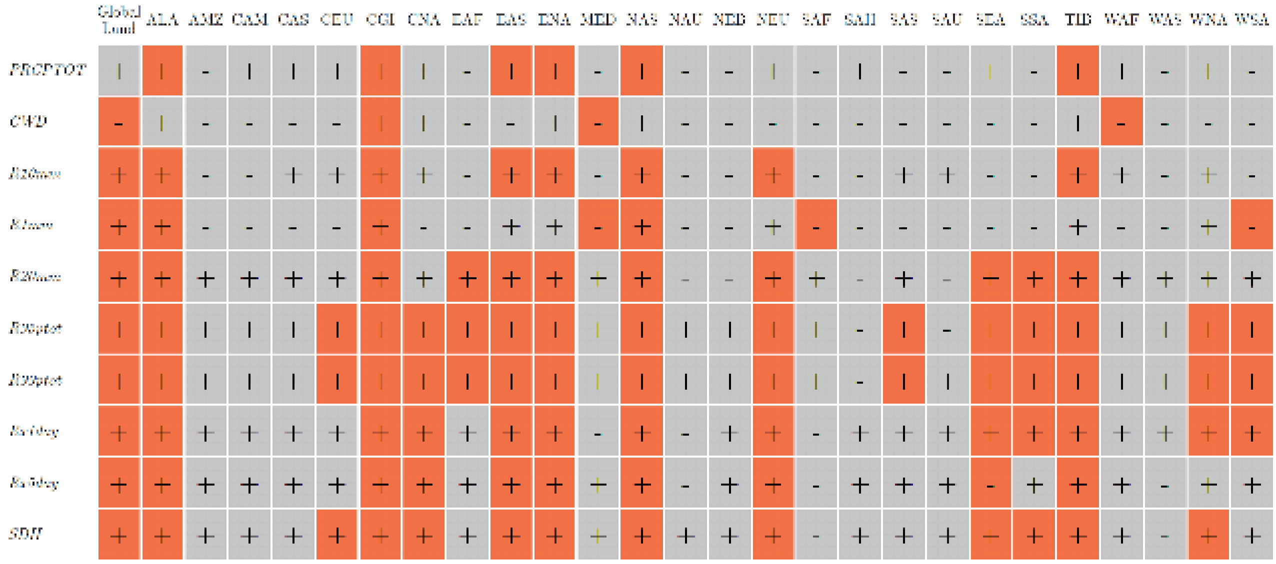


Figure 3.10: Probability ratio (PR) of exceeding extreme preciptiation (heavy precipitation) thresholds. (Left, a): PR of exceeding the (blue) 99th and (red) 99.9th percentile of pre-industrial daily precipitation at a given warming level relative to pre-industrial conditions averaged across land (fromFischer and Knutti, 2015). (Right, b): PR for precipitation extremes (Rx1d) for different event probabilities (with RV indicating return values) in the current climate (1°C warming); the shading shows the interquartile (25%-75%) range (from Kharin et al., 2018).



	Global Land	ALA	AMZ	CAM	CAS	CEU	CGI	CNA	EAF	EAS	ENA	MED	NAS	NAU	NEB	NEU	SAF	SAH	SAS	SAU	SEA	SSA	TIB	WAF	WAS	WNA	WSA
PRCPTOT	|	|	-	|	|	|	|	|	-	|	|	-	|	-	-	|	-	|	-	-	|	-	|	|	-	|	-
CWD	-	|	-	-	-	-	|	|	-	-	|	-	|	-	-	-	-	-	-	-	-	-	|	-	-	-	-
R10mm	+	+	-	-	+	+	+	+	-	+	+	-	+	-	-	+	-	-	+	+	-	-	+	+	-	+	-
R1mm	+	+	-	-	-	-	+	-	-	+	+	-	+	-	-	+	-	-	-	-	-	-	+	-	-	+	-
R20mm	+	+	+	+	+	+	+	+	+	+	+	+	+	-	-	+	+	-	+	-	+	+	+	+	+	+	+
R95ptot	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	-	|	-	|	|	|	|	|	|	|
R99ptot	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	|	-	|	|	|	|	|	|	|	|	|
Rx1day	+	+	+	+	+	+	+	+	+	+	+	-	+	-	+	+	-	+	+	+	+	+	+	+	+	+	+
Rx5day	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	-	+	+	+	-	+	+	+	-	+	+
SDII	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+	-	+	+

Figure 3.11: Significance of differences of regional mean precipitation and range of precipitation indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: PRCPTOT: mean precipitation; CWD: Consecutive Wet Days; R10mm: Number of days with precipitation > 10mm; R1mm: Number of days with precipitation>1mm; R20mm: Number of days with precipitation >20mm; R95ptot: Proportion of rain falling as 95^{th} percentile or higher; R99ptot: Proportion of rain falling as 99^{th} percentile or higher; RX1day: Intensity of maximum yearly 1-day precipitation; RX5day: Intensity of maximum yearly 5-day precipitation; SDII: Simple Daily Intensity Index. Columns indicate analysed

regions and global land (see Figure 3.3 for definition). Significant differences are shown in red shading (increases indicated with + sign, decreases indicated with – sign), insignificant differences are shown in grey shading. Same data basis and analaysis approach as in Figure 3.8 (see Annex 3.1 S3-3 for more details).

3.3.4 Drought and dryness

3.3.4.1 Observed and attributed changes

The IPCC AR5 assessed that there was *low confidence* in the sign of drought trends since 1950 at global scale, but that there was *likely* to be trends in some regions of the world, including increases in drought in the Mediterranean and West Africa and decreases in droughts in central North America and north-west Australia (Hartmann et al., 2013; Stocker et al., 2013). The AR5 assessed that there was *low confidence* in the attribution of global changes in droughts (Bindoff et al., 2013a) and did not provide assessments for the attribution of regional changes in droughts (Bindoff et al., 2013a).

The recent literature does not suggest a necessary revision of this assessment, except in the Mediterranean region. Recent publications based on observational and modeling evidence suggest that human emissions have substantially increased the probability of drought years in the Mediterranean region (Gudmundsson and Seneviratne, 2016; Gudmundsson et al., 2017). There is also new evidence documenting consistent observed drying trends in the Eastern Mediterranean (Syria; see Box 3.2). Based on this evidence, there is *medium confidence* that enhanced greenhouse forcing contributed to increased drying in the Mediterranean region (including Southern Europe, Northern Africa and the Near-East) and that this tendency will thus continue to be increased under higher levels of global warming.

Box 3.1: Sub-Saharan Africa: Changes in Temperature and Precipitation Extremes

Sub-Saharan Africa has experienced the dramatic consequences of climate extremes becoming more frequent and more intense over the past decades (Paeth et al., 2010; Taylor et al., 2017). To reduce the adverse effects of climate change, all African countries signed the Paris Agreement and through their Nationally Determined Contributions (NDCs), they committed to contribute to the global effort of mitigation of Greenhouse Gas (GHG) emissions in the aim to hold global temperature increases to ‘well below 2 degrees’ and to pursue efforts to limit warming to ‘1.5 °C above preindustrial levels’. The target of limiting to 1.5°C above pre-industrial levels is a useful message to share the urgency, but it focused the climate change debate on a temperature threshold (Section 3.3.2), while the potential impacts of these global warming levels at local to regional scales on key sectors such as agriculture, energy, health, etc. remain uncertain in most regions and countries of Africa (Sections 3.3.3, 3.3.4, 3.3.5 and 3.3.6).

Weber et al. (2018) found that at regional scales, temperature increases in Sub-Saharan Africa are projected to be higher than the global mean temperature increase (at global warming of 1.5°C and at 2°C; Section 3.3.2 for further background and analyses of climate model projections). Even if the mean global temperature anomaly is kept below 1.5°C, regions between 15°S and 15°N are projected to experience an increase in hot nights as well as longer and more frequent heat waves (e.g., Kharin et al., 2018). Increases would be even larger if the global mean temperature reaches 2°C of global warming, with significant changes in the occurrence and intensity of temperature extremes in all Sub-Saharan regions (Sections 3.3.1 and 3.3.2; Figures 3.4, 3.5 and 3.8).

West and Central Africa display particularly large increases in the number of hot days, both at 1.5°C and 2°C global warming (Section 3.3.2). This is due to the relatively small interannual present-day variability, which implies that climate-change signals can be detected earlier (Mahlstein et al., 2011, Section 3.3.2). Changes in total precipitation exhibit several uncertainties, mainly in the Sahel (Diedhiou et al., 2018) Section 3.3.3 and Figure 3.8). In the Guinea Coast and Central Africa, a weak change in the total precipitation is noted though it is projected in most models (70%) a decrease of the length of wet spells and a slight increase of heavy rainfall. Western Sahel is projected by most models (80%) to experience the strongest drying with a significant increase in the maximum length of dry spells (Diedhiou et al., 2018). Above 2°C, this region could become more vulnerable to drought and could meet serious food security issues (Salem et al., 2017; Parkes et al., 2018) Cross-Chapter Box 6 and Section 3.4.6). West Africa has thus been identified as a climate-change hot spot with a likelihood of negative impact of climate change in crop yields and production (Cross-Chapter Box 6, Section 3.4.6; Sultan and Gaetani, 2016; Palazzo et al., 2017). Despite uncertainty in future projections of the precipitation in West Africa, which is essential for rain-fed agriculture, a robust evidence of yield loss might emerge. This yield loss is mainly driven by increased mean temperature while potential wetter or drier conditions as well as elevated CO_2 concentrations can modulate this effect (Roudier et al., 2011); see also Cross-Chapter Box 6 and Section 3.4.6). Using Representative Concentration Pathway (RCP)8.5 Cooridnated Regional Climate Downscaling Experiment (CORDEX) scenarios from 25 Regional Climate Models (RCMs) forced with different General Circulation Models (GCMs), Klutse et al. (2018) noted over West Africa a decrease of mean rainfall in models with larger warming at 1.5°C (Section 3.3.4) and Mba et al. (2018) found over Central Africa a lack of consensus in the changes in precipitation (Figure 3.8 and Section 3.3.4), though there is a tendency to a decrease of the maximum length of Consecutive Wet Days (CWD) and a significant increase of the maximum length of Consecutive Dry Days (CDD).

Over southern Africa, models agree in a positive sign of change for temperature, with temperature rising faster at 2°C (1.5ºC-2.5°C) compared to 1.5°C (0.5ºC - 1.5°C). Areas of the south-western region, especially in South Africa and parts of Namibia and Botswana are expected to experience the highest increases in temperature (Engelbrecht et al., 2015; Maúre et al., 2018; Section 3.3.2). The western part of southern Africa is projected to become drier with increasing drought frequency and number of heat waves towards the end of the 21st century (Engelbrecht et al., 2015; Dosio, 2017; Maúre et al., 2018) Section 3.3.4). At 1.5°C, a robust signal of precipitation reduction is found over the Limpopo basin and smaller areas of the Zambezi basin, in Zambia, as well as in parts of Western Cape, in South Africa, while an increase is projected over central and western South Africa as well as in southern Namibia (Section 3.3.4). At 2°C, the region is projected to face robust precipitation decreases of about 10-20% and increases in the length of CDD with longer dry spells projected over Namibia, Botswana, northern Zimbabwe and southern Zambia. Conversely, the length of CWD is projected to decrease with robust signals over Western Cape (Maúre et al., 2018). Projected reductions in stream flow between 5% and 10% in the Zambezi River Basin have been associated with increased evaporation and transpiration rates resulting from rise in temperature (Kling et al., 2014; Section 3.3.5) with issues on hydroelectric power across the southern African region.

Over Eastern Africa, Osima et al. (2018) found that annual rainfall projections show a robust wetting signal over Somalia and a less robust decrease over central and northern Ethiopia (Section 3.3.3). The length of CDD and CWD are projected to increase and decrease respectively (Section 3.3.4). These projected changes could impact the agricultural and water sectors in the region (Cross-Chapter Box 6 in this Chapter and Section 3.4.6).

[END BOX 3.1 HERE]

3.3.4.2 Projected changes in drought and dryness at 1.5°C versus 2°C

There is *medium confidence* in projections of changes in drought and dryness. This is partly consistent with the AR5, which assessed these projections as being '*likely* (*medium confidence*)' (Collins et al., 2013; Stocker et al., 2013). However, given the *medium confidence*, we assess that it does not seem suitable to provide a likelihood statement, consistent with the IPCC uncertainty guidance document (Mastrandrea et al., 2010) and the assessment of the IPCC SREX report (Seneviratne et al., 2012).The technical summary of the AR5 (Stocker et al., 2013) assessed that soil moisture drying in the Mediterranean, Southwest USA and southern African regions was consistent with projected changes in the Hadley circulation and increased surface temperatures and concluded that there was *high confidence* in *likely* surface drying in these regions by the end of this century under the RCP8.5 scenario. However, more recent assessments have highlighted uncertainties in dryness projections due to a range of factors, including variations between considered drought and dryness indices and the effects of enhanced CO_2 concentrations on plant water-use efficiency (Orlowsky and Seneviratne, 2013; Roderick et al., 2015). Overall, projections of changes in drought and dryness for high-emissions scenarios (e.g. RCP8.5 corresponding to about 4 °C global warming) are uncertain in many regions, despite the existence of a few regions displaying consistent drying in most assessments (e.g., Seneviratne et al., 2012; Orlowsky and Seneviratne, 2013). Uncertainty is expected to be even larger for conditions of smaller signal-to-noise ratio such as for global warming levels of 1.5°C and 2°C.

Some published literature is now available on the evaluation of differences in drought and dryness occurrence at 1.5°C and 2°C global warming for a) Precipitation-Evapotranspiration (P-E, i.e. as a general measure of water availability; Wartenburger et al., 2017; Greve et al., 2018), b) soil moisture anomalies (Lehner et al., 2017; Wartenburger et al., 2017), c) consecutive dry days (Schleussner et al., 2016b; Wartenburger et al., 2017), d) the 12-month Standardized Precipitation Index (Wartenburger et al. (2017), e) the Palmer-Drought Severity Index (Lehner et al., 2017), f) annual mean runoff (Schleussner et al., 2016b, see also next section). These analyses are overall consistent, despite the known sensitivity of drought assessment to chosen drought indices (see above paragraph).

Figure 3.12 in Greve et al. (2018) derives the sensitivity of regional changes in precipitation minus evapotranspiration to global temperature changes. The analysed simulations span the full range of available emissions scenarios and the sensitivities are derived using a modified pattern scaling approach. The applied approach assumes linear dependencies on global temperature changes while thoroughly addressing associated uncertainties via resampling methods. Northern high-latitude regions display robust responses towards increased wetness, while subtropical regions display a tendency towards drying but with a large range of responses. While the internal variability and the scenario choice play an important role in the overall spread of the simulations, the uncertainty stemming from the climate model choice usually dominates, accounting for about half of the total uncertainty in most regions (Wartenburger et al., 2017; Greve et al., 2018). The sign of projections, i.e. whether there might be increases or decreases in water availability under higher global warming, is particularly uncertain in tropical and mid-latitude regions. An assessment of the implications of limiting global mean temperature warming to values below (i) 1.5°C or (ii) 2°C shows that opting for the 1.5°C-target might slightly influence the mean response, but could substantially reduce the risk of experiencing extreme changes in regional water availability (Greve et al., 2018).

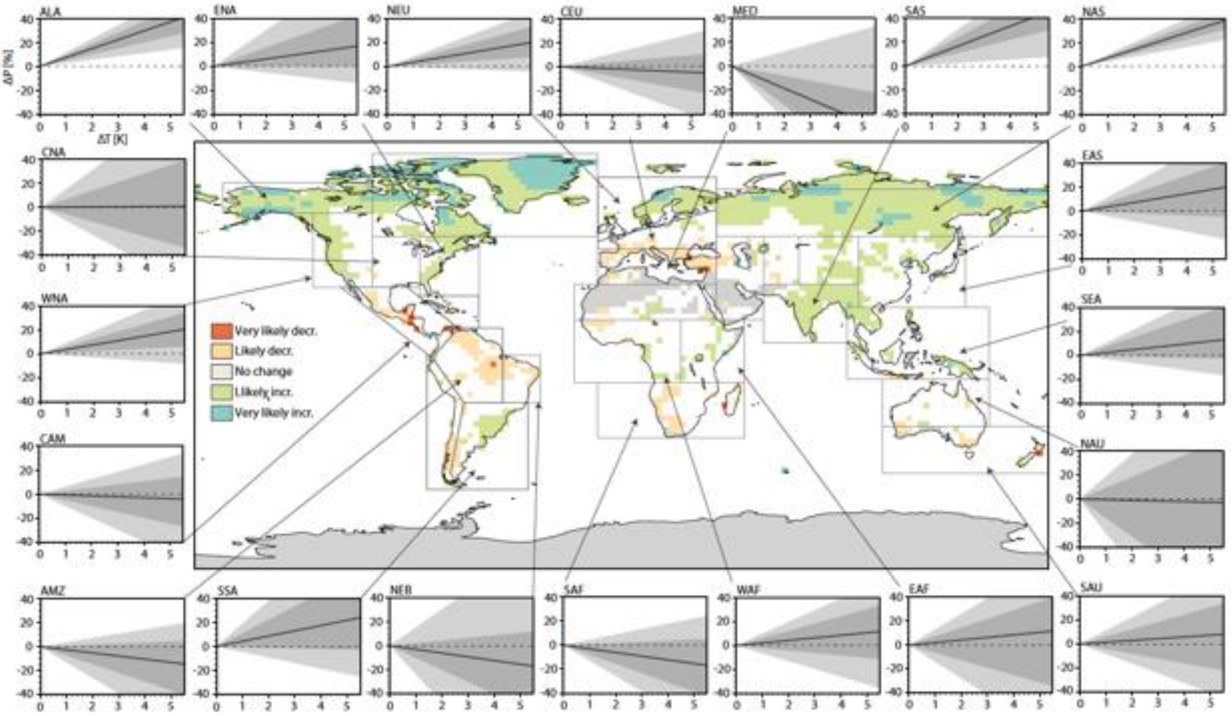


Figure 3.12: Summary of the likelihood of increases/decreases in Precipitation-Evapotranspiration (P-E) in Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations considering all scenarios and a representative subset of 14 climate models (one from each modeling center). Panel plots show the uncertainty distribution of the sensitivity of P-E to global temperature change as a function of global mean temperature change averaged for most IPCC Special Report on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions (see Figure 3.2) outlined in the map (from Greve et al., 2018).

The analysis for the mean response is also qualitatively consistent with results from Wartenburger et al. (2017), which use an ESR (Section 3.2) rather than pattern scaling for a range of drought and dryness indices, as well as with a recent assessment of Lehner et al. (2017) which consider changes in droughts assessed from the soil moisture changes and from the Palmer-Drought Severity Index. We note that these two further publications do not provide a specific assessment for changes in tails of the drought and dryness distribution. The conclusions of (Lehner et al., 2017) are that a) ‘risks of consecutive drought years shows little change in the US Southwest and Central Plains, but robust increases in Europe and the Mediterranean’, and that b) ‘limiting warming to 1.5°C may have benefits for future drought risk, but such benefits are regional, and in some cases highly uncertain’.

Figure 3.13 displays projected changes in CDD as a function of global temperature increase, using a similar approach as in Figures 3.5 (based on Wartenburger et al., 2017). The analyses also include results from the HAPPI experiment (Mitchell et al., 2017). Again, the CMIP5-based ESR estimates and the results of the HAPPI experiment are found to agree well. We note the large disparity of responses depending on the considered regions.

Similarly as for Figures 3.8 and 3.11, Figure 3.14 includes an objective identification of “hot spots” / key risks in dryness indices subdivided by regions, based on (Wartenburger et al., 2017). This analysis reveals the following hot spots of drying, i.e. with increases in CDD, and decreases in P-E, Soil Moisture Anomalies (SMA), and SPI12, with at least two of the indices displaying statistically significant drying: the Mediterranean region (MED; including Southern Europe, northern Africa, and the Near-East) and Southern Africa. However, drying trends are also identified for single indices in Northeastern Brazil and Western South America. In addition, subregional drying trends are projected in the Western Sahel (see also Box 3.1) and in the Amazon region and Central America and Mexico (Fig. 3.12).

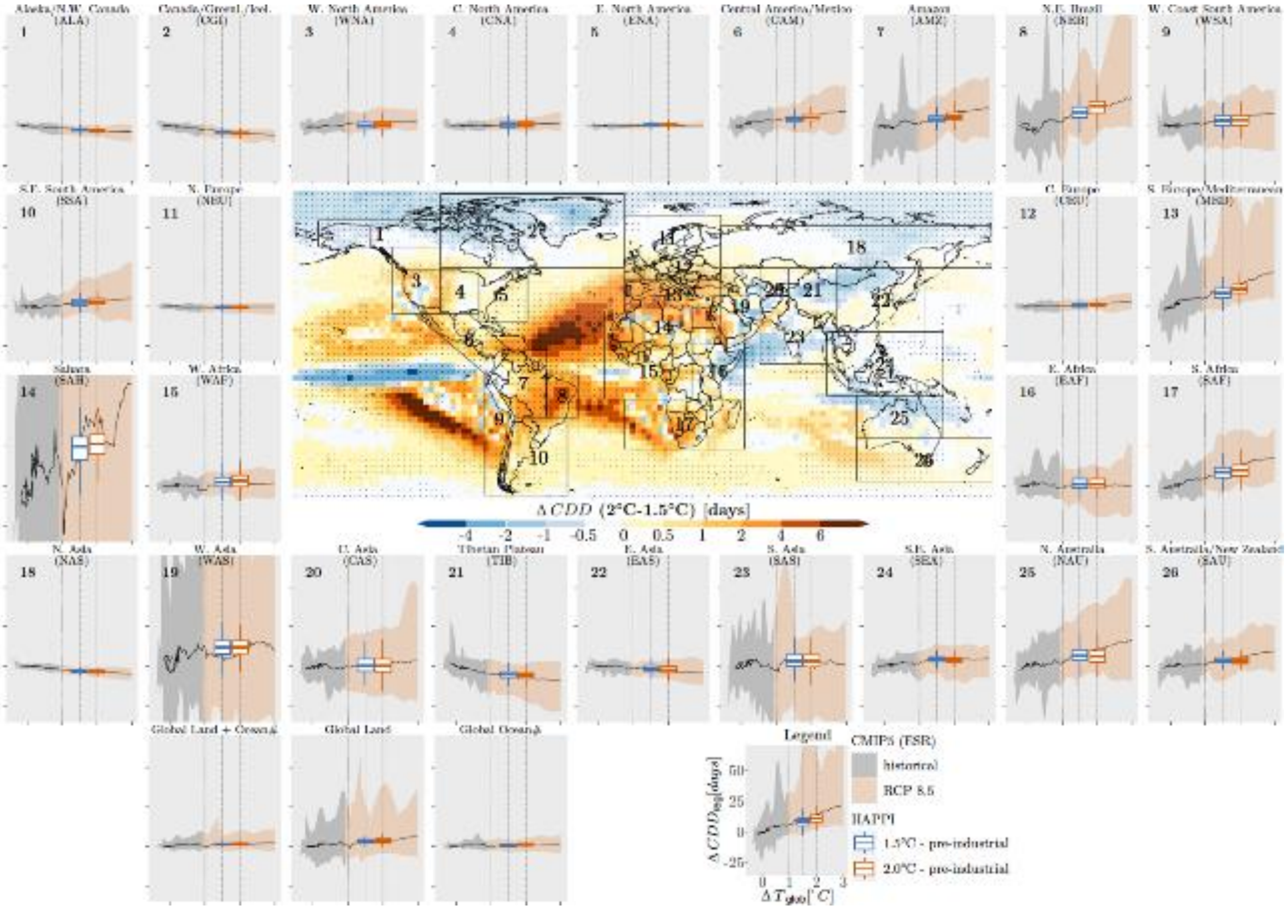
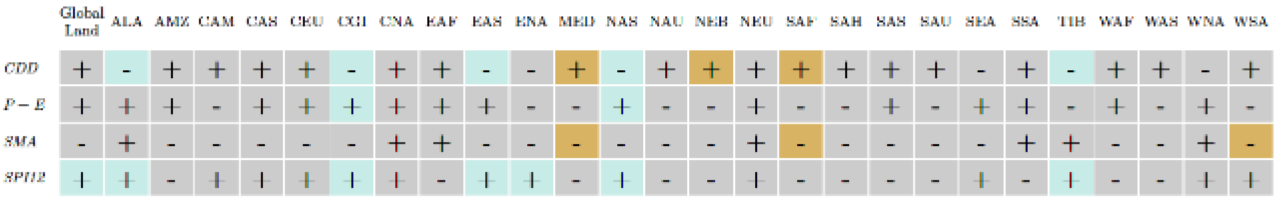


Figure 3.13: Projected changes in consecutive dry days (CDD) as function of global temperature warming for IPCC Special Report on Managng the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regions, based on empirical scaling relationship applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) data together with projected changes from the HAPPI multi-model experiment (bar plots on regional analyses and central plot, respectively). Same data basis and analysis approach as in Figure 3.5 (Annex 3.1 S3-3 for more details).



	Global Land	ALA	AMZ	CAM	CAS	CEU	CGI	CNA	EAF	EAS	ENA	MED	NAS	NAU	NEB	NEU	SAF	SAH	SAS	SAU	SEA	SSA	TIB	WAF	WAS	WNA	WSA
CDD	+	-	+	+	+	+	-	+	+	-	-	+	-	+	+	+	+	+	+	+	-	+	-	+	+	-	+
P − E	+	+	+	-	+	+	+	+	+	+	-	-	+	-	-	+	-	-	+	-	+	+	-	+	-	+	-
SMA	-	+	-	-	-	-	-	+	+	-	-	-	-	-	-	+	-	-	-	-	-	+	+	-	-	+	-
SPI12	+	+	-	+	+	+	+	+	-	+	+	-	+	-	-	+	-	-	-	-	+	-	+	-	-	+	+

Figure 3.14: Similar as Figures 3.8 and 3.11 but for changes in dryness indices. Significance of differences of regional drought and dryness indices between the 1.5°C and 2°C global mean temperature targets (rows). Definition of indices: CDD: Consecutive Dry Days; P-E: Precipitation minus Evaporation; SMA: Soil Moisture Anomalies; SPI12: 12-month SPI. Columns indicate regions and global land (see Figure 3.2 for definitions). Significant differences are shown in light blue/brownshading (increases in indices indicated with + sign, decreases indicated with – sign; the light blue shading indicates decreases in dryness (decreases in CDD, or increases in P-E, SMA or SPI12) and the light brown shading indicates increases in dryness (increases in CDD, or decreases in P-E, SMA or SPI12). Insignificant differences are shown in grey shading. Same data basis and analysis approach as in Figure 3.7 (see Annex 3.1 S3-3 for more details).

Overall, the available literature, consistent with this analysis, reports particularly strong increases in dryness and decreases in water availability in Southern Europe and the Mediterranean when shifting from a 1.5°C to a 2°C global warming (Schleussner et al., 2016b; Lehner et al., 2017; Wartenburger et al., 2017; Greve et al., 2018; Samaniego et al., 2018; Figure 3.13). The fact that this is a region that is also already displaying substantial drying in the observational record (Seneviratne et al., 2012; Sheffield et al., 2012; Greve et al., 2014; Gudmundsson and Seneviratne, 2016; Gudmundsson et al., 2017) provides additional evidence supporting this tendency, suggesting that it is a hot spot of dryness change above 1.5°C (see also Box 3.2). Some of the other identified hot spots, Southern Africa and Northeastern Brazil, are also consistently shown to display drying trends in other publications for higher levels of forcing (e.g., Orlowsky and Seneviratne, 2013), although there are so far to our knowledge no studies reporting observed drying trends in these regions. We thus form the consensus that there are substantial increases in risk of dryness (*medium confidence)* in both the Mediterranean region and South Africa at 2°C versus 1.5°C global warming, because these regions display significant changes in two dryness indicators (CDD and SMA) at these two global warming levels (Figure 3.14). There is *low confidence* elsewhere due to lack of consistency in analyses with different models or different dryness indicators. However, in many regions, there is *medium confidence* that most extreme risks of changes in dryness are avoided at 2°C versus 1.5°C (Figure 3.12).

In summary, in terms of drought and dryness, limiting global warming to 1.5ºC may substantially reduce the probability of extreme changes in water availability in some regions compared to changes for 2°C global warming (*medium confidence*). When shifting from 1.5 to 2°C, available studies and analyses suggest strong increases in dryness and reduced water availability in the Mediterranean region (including Southern Europe, northern Africa, and the Near-East) and in Southern Africa (*medium confidence*). Based on observations and model experiments, a drying trend is already detectable in the Mediterranean region, i.e. for a global warming of less than 1°C (*medium confidence*).

[START BOX 3.2 HERE]

Box 3.2: Mediterranean Basin and the Middle East Droughts

Human society has developed in tandem with the natural environment of the Mediterranean Basin over several millennia, laying the ground for diverse and culturally rich communities. Even if advances in technology may offer some protection from climatic hazards, the consequences of climatic change for inhabitants of the Mediterranean continue to depend on the long term interplay between an array of societal and environmental factors (Holmgren et al., 2016). This makes this region an example of strong vulnerability and various adaptation responses. Previous IPCC assessments and recent publications project regional changes in climate under increased warming, including consistent climate model projections of increased precipitation deficit amplified by strong regional warming (Seneviratne et al., 2012; Christensen et al., 2013; Collins et al., 2013; Greve and Seneviratne, 2015; Section 3.3.3).

A good example of such long history of resilience is the Eastern Mediterranean region, which has exhibited a strong negative trend in precipitation since 1960 (Mathbout et al., 2017) and experienced an intense and prolonged drought episode between 2007 and 2010 (Kelley et al., 2015). This drought was the longest and the most intense in the last 900 years (Cook et al., 2016). Some authors (e.g., Trigo et al., 2010; Kelley et al., 2015) assert that very low precipitation levels have driven a steep decline in agricultural productivity in the Euphrates and Tigris catchment basins, and displaced hundreds of thousands of people, mainly in Syria. Impacts have also been noticed on the water resource (Yazdanpanah et al., 2016) and the crop performance in Iran (Saeidi et al., 2017). Many historical periods of turmoil have coincided with severe droughts, for example the drought which occurred at the end of the Bronze Age, approximately 3200 years ago (Kaniewski et al., 2015). In this instance, a number of flourishing Eastern Mediterranean civilizations collapsed, and rural settlements re-emerged with agro-pastoral activities and limited long-distance trade. This illustrates how some vulnerable regions are forced to pursue drastic adaptive responses, including migration and societal structure changes.

The potential evolution of drought conditions under 1.5°C/2°C warming (Section 3.3.4) can be analyzed by comparing the 2008 drought (high temperature, low precipitation) with the 1960 drought (low temperature, low precipitation) (Kelley et al., 2015). Though the precipitation deficits were comparable, the 2008 drought was amplified by increased evapotranspiration induced by much higher temperatures (a mean increase of 1°C on the 1931-2008 period on Syria) and a large population increase (from 5 million in 1960 to 22 million in 2008). Koutroulis et al. (2013) projects that of the 18% decrease of water availability for Crete under a 2°C global warming at the end of the 21st century, only 6% is due to decreased precipitation (the rest is due to an increase in evapotranspiration). This study and others like it confirm an important risk of extreme drought conditions for the Middle East (even higher in continental locations than in islands) with a 1.5°C global warming (Jacob et al., 2018), consistent with current observed changes (Greve et al., 2014); Section 3.3.4). Risks of drying in the Mediterranean region can be substantially reduced if global warming is limited to 1.5°C compared to 2°C or higher levels of warming (Guiot and Cramer, 2016); see also Section 3.4.3). Higher warming levels may induce strong levels of vulnerability exacerbated by large changes in demography.

[END BOX 3.2 HERE]

3.3.5 Runoff and fluvial flooding

3.3.5.1 Observed and attributed changes in runof and river flooding

There has been progress since the AR5 in identifying historical changes in streamflow and continental runoff. Dai (2016) using available streamflow data shows that long-term (1948–2012) flow trends are statistically significant only for 27.5% of the 200 world's major rivers with negative trends outnumbering the positive ones. Although streamflow trends are mostly non-statistically significant, they are consistent with observed regional precipitation changes. From 1950 to 2012, precipitation and runoff have increased over southeastern South America, central and northern Australia, the central and northeast United States, central and northern Europe, and most of Russia and decreased over most of Africa, East and South Asia, eastern coastal Australia, southeastern and northwestern United States, western and eastern Canada, the Mediterranean region and in some regions of Brazil (Dai, 2016).

A large part of the observed regional trends in streamflow and runoff could have resulted from internal multidecadal and multiyear climate variations, especially the Pacific Decadal Variability (PDV), the Atlantic Multidecadal Oscillation (AMO) and the El Niño-Southern Oscillation (ENSO) although the effect of anthropogenic greenhouse gasses and aerosols could also be important (Hidalgo et al., 2009; Gu and Adler, 2013, 2015; Chiew et al., 2014; Luo et al., 2016; Gudmundsson et al., 2017). Additionally, other human activities can influence the hydrological cycle such as land-use/land-cover change, modifications in river morphology and water table depth, construction and operation of hydropower plants, dikes and weirs, wetland drainage and agricultural practices such as water withdrawal for irrigation. All of these can also have a large impact on runoff at river basin scales although there is less agreement over their influence on global mean runoff (Gerten et al., 2008; Sterling et al., 2012; Hall et al., 2014; Betts et al., 2015; Arheimer et al., 2017). Some studies suggest that increases in global runoff resulting from changes in land-cover or land-use (predominantly deforestation) are counterbalanced by decreases from irrigation (Gerten et al., 2008; Sterling et al., 2012). Likewise, forest and grassland fires can also modify the hydrological response at a watershed scale when the burned area is significant (Versini et al., 2013; Springer et al., 2015; Wine and Cadol, 2016).

Few studies explore observed changes in extreme streamflow and river flooding since the IPCC AR5. Mallakpour and Villarini (2015) analyzed changes of flood magnitude and frequency in Central United States considering stream gauge daily records with at least 50 years of data ending no earlier than 2011. They showed that flood frequency has increased while there was limited evidence of a decrease in flood magnitude in this region. Stevens et al. (2016) found a rise in the number of reported floods in the United Kingdom during the period 1884-2013 with flood events appearing more frequently towards the end of the 20th century. A peak was identified in 2012 when annual rainfall was the second highest in over 100 years. Do et al. (2017) computed the trends in annual maximum daily streamflow data across the globe over the 1966–2005 period. They found decreasing trends for a large number of stations in western North America and Australia, and increasing trends in parts of Europe, eastern North America, parts of South America and southern Africa.

In summary, streamflow trends since 1950 are non-statistically significant in most of the world's largest rivers *(high confidence),* while flood frequency and extreme streamflow increased in some regions *(high confidence).*

3.3.5.2 Projected changes at 1.5°C versus 2°C in runoff and river flooding

Global-scale assessments of projected changes on freshwatr systems generally suggest that areas with either positive or negative changes in mean annual streamflow are smaller for 1.5°C than for 2°C global warming (Betts et al., 2018; Döll et al., 2018). Döll et al. (2018) found that only 11% of the global land area (excluding Greenland and Antarctica) shows statistically significant larger hazard at 2°C than at 1.5°C. Significant decreases are found for 13% of the global land area for both global warming levels, while significant increases are projected to occur for 21% of the global land area for 1.5°C, and rise to between 26% (Döll et al., 2018) and approximately 50% (Betts et al., 2018) for 2°C.

At the regional scale, projected runoff changes in general follow the spatial extent of projected changes in precipitation (see Section 3.3.3). Emerging literature shows runoff projections for different warming levels. For 2°C global warming, an increase in runoff is projected for much of the high northern latitudes, Southeast Asia, East Africa, north-eastern Europe, India, and parts of, Austria, China, Hungary, Norway, Sweden, the northwest Balkans, and Sahel (Schleussner et al., 2016b; Donnelly et al., 2017; Zhai et al., 2017; Döll et al., 2018). Addtionally, decreases are projected in the Mediterranean region, South Australia, Central America and Central and Southern South America (Schleussner et al., 2016b; Donnelly et al., 2017; Döll et al., 2018). Differences between 1.5°C and 2°C would be most prominent in the Mediterranean where the median reduction in annual runoff is expected to be about 9% (likely range 4.5–15.5%) at 1.5°C, while at 2°C warming, runoff could decrease by 17% (likely range 8–25%) (Schleussner et al., 2016b). Consistently, Döll et al. (2018) found that for an increase in global warming from 1.5°C to 2°C, statistically insignificant changes of the mean annual streamflow around the Mediterranean region become significant with decreases of 10–30%. Donnelly et al. (2017) found an intense decrease in runoff along both the Iberian and Balkan coasts as warming level increases.

Basin-scale projections of river runoff at different warming levels are available for many regions. Betts et al. (2018) assessed runoff changes in 21 of the world major river basins at 1.5°C and 2°C global warming (Figure 3.15). They found a general tendency towards increased runoff in the majority of the basins except in the Amazon, Orange, Danube and Guadiana basins where the range of projections indicate decreased mean flows (Figure 3.13). In the case of the Amazon, mean flows are projected to decline by up to 25% for 2°C global warming. Gosling et al. (2017) analyzed the impact of global warming of 1°C, 2°C and 3°C above pre-industrial levels on river runoff at catchment scale, focusing on eight major rivers in different continents: Upper Amazon, Darling, Ganges, Lena, Upper Mississippi, Upper Niger, Rhine and Tagus. Their results show that the sign and magnitude of change with global warming for the Upper Amazon, Darling, Ganges, Upper Niger and Upper Mississippi is unclear, while the Rhine and Tagus may experience decreases in projected runoff and the Lena may increase. Donnelly et al. (2017) analyzed the mean flow response to different warming levels for six major European rivers: Glomma, Wisla, Lule, Ebro, Rhine and Danube. Consistent with the increases in mean runoff in large parts of northern Europe, the Glomma, Wisla and Lule rivers could increase their discharges with global warming while the Ebro could decrease in part due to a decrease in runoff in southern Europe. In the case of the Rhine and Danube rivers, Donnelly et al. (2017) did not find clear results. Projected mean annual runoff of the Yiluo River catchment in northern China will decrease by 22% for 1.5°C and by 21% for 2°C, while the the mean annual runoff for the Beijiang River in southern China, is projected to increase by less than 1% and 3% in comparicon to the studied baseline period for 1.5°C and 2°C respectively (L. Liu et al., 2017). Chen et al. (2017) assessed the future changes of water resources in the Upper Yangtze River basin for the same warming levels and found a slight decrease in the annual discharge for 1.5°C which reverses sign for 2°C. Montroull et al. (2018) studied the hydrological impacts of the main rivers (Paraguay, Paraná, Iguazú and Uruguay) in La Plata basin in South America under 1.5°C and 2°C global warming and for two emission scenarios. The Uruguay basin shows increases in streamflow in all scenarios/warming targets except for the combination of RCP8.5/1.5°C warming. The increase is approximately 15% above the 1981–2000 reference period for 2°C global warming and the RCP4.5 scenario. For the other three rivers the sign of the change in mean streamflow highly depends on the RCP and GCM used.

Marx et al. (2018) analyzed how hydrological low flows in Europe are affected under different global warming levels (1.5°C, 2°C and 3°C). The Alpine region shows the strongest low flow increase from 22% for 1.5°C to 30% for 2°C because of the snow melt contribution, while in the Mediterranean low flows are expected to decrease due to the projected decreases in annual precipitation. Döll et al. (2018) found that extreme low flows in the tropical Amazon, Congo and Indonesian basins could decrease by 10% while in the southwestern part of Russia they could increase by 30% at 1.5°C. For 2°C, projected increases of extreme low flows are exacerbated in the higher northern latitudes and in eastern Africa, India and Southeast Asia while projected decreases intensify in the Amazon basin, Western United States, central Canada, and in Southern and Western Europe, although not in the Congo basin or Indonesia, where models show less agreement.

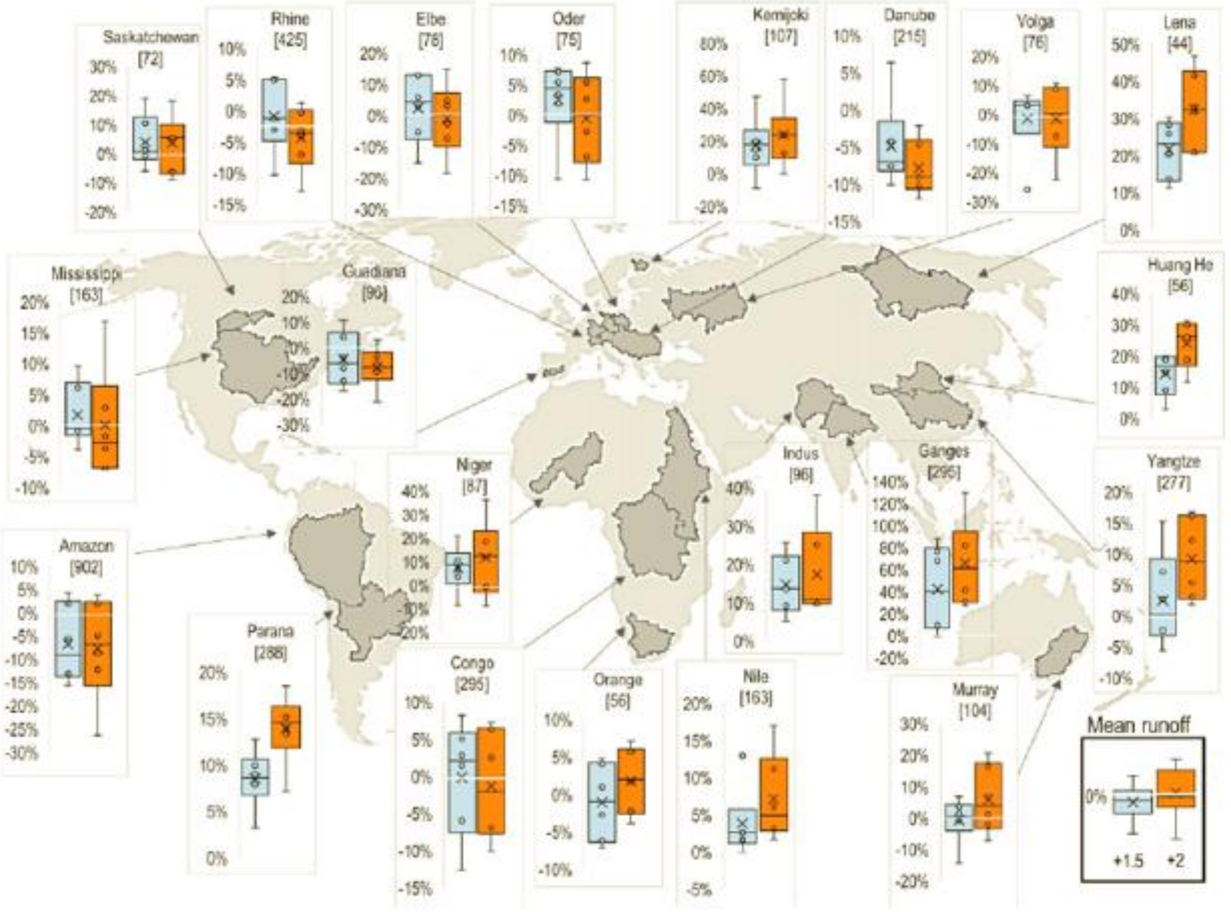


Figure 3.15: Runoff changes in twenty-one of the world major river basins at 1.5°C (blue) and 2°C (orange) global warming simulated by the Joint UK Land Environment Simulator (JULES) ecosystem–hydrology model under the ensemble of six climate projections. Boxes show the 25th and 75th percentile changes, whiskers

show the range, circles show the four projections that do not define the ends of the range, and crosses show the ensemble means. Numbers in square brackets show the ensemble-mean flow in the baseline (millimetres of rain equivalent) (from Betts et al., 2018).

Recent analysis of projections in river flooding and extreme runoff and flows are available for different global warming levels. At the global scale, Alfieri et al. (2017) assessed the frequency and magnitude of river floods and their impacts under 1.5°C, 2°C, and 4°C global warming scenarios. They found that flood events with occurrence interval larger than the return period of present flood protections are projected to increase in all continents under all considered warming levels, leading to widespread increment in the flood hazard. Döll et al. (2018) found that high flows are projected to increase significantly on 11% and 21% of the global land area at 1.5°C and 2°C respectively. Significantly increased high flows are expected to occur in South and Southeast Asia and Central Africa at 1.5°C which intensify under 2°C and include parts of South America.

At continental scale, Donnelly et al. (2017) and Thober et al. (2018) explored climate change impacts on European high flows and/or floods under 1.5°C, 2°C, and 3°C global warming. Thober et al. (2018) identified the Mediterranean region as a hotspot of change with significant decreases of −11% (-13%) in high flows at 1.5°C (2°C) mainly resulting from reduced precipitation (Box 3.2). In Northern regions, high flows are projected to rise between 1%-5% for 1.5°C and 2°C respectively due to increasing precipitation, although floods could decrease by 6% in both scenarios due to less snowmelt. Donnelly et al. (2017) found that high runoff levels could rise in intensity, robustness and spatial extent over large parts of continental Europe, with increasing warming level. For 2°C, flood magnitudes are expected to increase significantly in Europe south of 60°N, except for some regions (Bulgaria, Poland, southern Spain) while they are projected to decrease in most of Finland, northwestern Russia and northern Sweden, with the exception of southern Sweden and some coastal areas in Norway where floods may increase (Roudier et al., 2016). At basin scale, Mohammed et al. (2017) found that floods are projected to be more frequent and flood magnitudes greater at 2°C than at 1.5°C in the Brahmaputra River in Bangladesh.

In coastal regions, increases in heavy precipitation associated with tropical cyclones (Section 3.3.6) combined with increased sea levels (Section 3.3.9) may lead to increased flooding (Section 3.4.5).

In summary, there is *medium confidence* that a global warming of 2°C would lead to an expansion of the area with significant increases in runoff as well as of the area affected by flood hazard compared to conditions at 1.5°C global warming. A global warming of 1.5°C would also lead to an expansion of the global land area with significant increases in runoff (*medium confidence*) as well as to an increase in flood hazard in some regions (*medium confidence*) compared to present day conditions.

3.3.6 Tropical cyclones and extratropical storms

Most recent studies on observed trends in the attributes of tropical cyclones are focusing on the satellite era starting in 1979 (Rienecker et al., 2011), but the study of observed trends is complicated by the heterogeneity of constantly advancing remote sensing techniques and instrumentation during this period (e.g., Landsea et al., 2006; Walsh et al., 2016). Numerous studies towards and beyond AR5 have reported a decreasing trend in the global number of tropical cyclones and/or the globally accumulated cyclonic energy (Emanuel, 2005; Elsner et al., 2008; Knutson et al., 2010; Holland and Bruyère, 2014; Klotzbach and Landsea, 2015; Walsh et al., 2016). A theoretical physical basis for such a decrease to occur under global warming has recently been provided by Kang and Elsner (2015). However Klotzbach (2006), using a relatively short (twenty year) relatively homogeneous remotely sensed record reported no significant trends in global cyclonic activity, consistent with more recent findings of Holland and Bruyère (2014). Such contradictions, in combination with the fact that the almost four-decade long period of remotely sensed observations remains relatively short to distinguish anthropogenically induced trends from decadal and multi-decadal variability, implies that there is only *low confidence* regarding changes in global tropical cyclone numbers under global warming over the last four decades.

Studies on the detection of trends in the occurrence of very intense tropical cyclones (category 4 and 5 hurricanes on the Saffir-Simpson scale) over recent decades have yielded contradicting results. Most studies have reported increases in these systems (Emanuel, 2005; Webster et al., 2005; Klotzbach, 2006; Elsner et al., 2008; Knutson et al., 2010; Holland and Bruyère, 2014; Walsh et al., 2016), and in particular for the North Atlantic, North Indian and South Indian Ocean basins (e.g., Singh et al., 2000; Singh, 2010; Kossin et al., 2013; Holland and Bruyère, 2014; Walsh et al., 2016). In the North Indian Ocean over the Arabian Sea, an increase in the frequency of extremely severe cyclonic storms has been reported and attributed to anthropogenic warming (Murakami et al., 2017). However, to the east over the Bay of Bengal, tropical cyclones and severe tropical cyclones have exhibited decreasing trends over the period 1961-2010, although the ratio between severe tropical cyclones and cyclones is increasing (Mohapatra et al., 2017). Moreover, studies that have used more homogeneous records but that were consequently limited to rather short periods of 20 to 25 years in length, have reported no statistically significant trends or decreases in the global number of these systems (Kamahori et al., 2006; Klotzbach and Landsea, 2015). CMIP5 model simulations of the historical period have also not produced anthropogenically induced trends in very intense tropical cyclones (Bender et al., 2010; Knutson et al., 2010, 2013; Camargo, 2013; Christensen et al., 2013), consistent with the findings of Klotzbach and Landsea (2015). There is consequently *low confidence* in the larger number of studies reporting increasing trends in the global number of very intense cyclones.

GCM projections of the changing attributes of tropical cyclones under high levels of greenhouse gas forcing (3°C to 4°C) are consistently indicating decreases in the global number of tropical cyclones (Knutson et al., 2010, 2015; Sugi and Yoshimura, 2012; Christensen et al., 2013; Yoshida et al., 2017). A smaller number of studies based on statistical downscaling methodologies are contradicting these findings, however, and are indicative of increases in the global number of tropical cyclones under climate change (Emanuel, 2017). Most studies also indicate increases in the global number of very intense tropical cyclones under high levels of global warming (Knutson et al., 2015; Sugi et al., 2017) consistent with dynamic theory (Kang and Elsner, 2015), although a few studies contradict this finding (e.g., Yoshida et al., 2017). Hence, we assess that under 3 to 4 °C of warming *it is more likely than not* (*medium confidence*) that the global number of tropical cyclones would decrease whilst the number of very intense cyclones would increase.

Only two studies have to date directly explored the changing tropical cyclone attributes under 1.5°C versus 2°C of global warming. Using a high resolution global atmospheric model, Wehner et al. (2017) concluded that the differences in tropical cyclone statistics under 1.5°C versus 2°C stabilization scenarios as defined by the HAPPI protocols (Mitchell et al., 2017) are small. Consistent with the majority of studies performed for higher degrees of global warming, the total number of tropical cyclones is projected to decrease under global warming, whilst the most intense (category 4 and 5) cyclones are projected to occur more frequently. These very intense storms are projected to be associated with higher peak wind speeds and lower central pressures under 2°C versus 1.5°C of global warming. The accumulated cyclonic energy is projected to decrease globally from 1.5 to 2 °C, in association with a decrease in the global number of tropical cyclones under progressively higher levels of global warming. It is also noted that heavy rainfall associated with tropical cyclones has been assessed in the IPCC SREX to *likely* increase under increasing global warming (Seneviratne et al., 2012). Two recent articles suggest that there is *high confidence* that global warming for present conditions (i.e. about 1°C of global warming, see Section 3.3.1) has increased the heavy precipitation associated with the 2017 Hurricane Harvey by about 15% or more (Risser and Wehner, 2017; van Oldenborgh et al., 2017). Hence, it can be inferred, under the assumption of linear dynamics, that further increases in heavy precipitation would occur under 1.5°C, 2°C and higher levels of global warming (*medium confidence*). Using a high resolution regional climate model, (Muthige et al., 2018) also explored the effects of different degrees of global warming on tropical cyclones over the southwest Indian Ocean, in transient simulations that downscaled a number of RCP8.5 GCM projections. Decreases in tropical cyclone frequencies are projected under both 1.5ºC and 2°C of global warming. The decreases in cyclone frequencies under 2°C global warming are somewhat larger than under 1.5°C of global warming, but with no further decreases projected under 3°C of global warming. This suggests that 2°C of warming, at least in these downscaling simulations, represent a type of stabilization level in terms of tropical cyclone formation over the southwest Indian Ocean and landfall over southern Africa (Muthige et al., 2018). There is thus *limited evidence* that the global number of tropical cyclones will be less under 2°C of global warming compared to 1.5 °C of warming, but with an increase in the number of very intense cyclones (*low confidence*).

The global response of the mid-latitude atmospheric circulation to 1.5 and 2°C of warming was investigated using the HAPPI ensemble with a focus on the winter season (Li et al., 2018). Under 1.5 °C of global warming a weakening of storm activity over North America, an equatorward shift of the North Pacific jet exit and an equatorward intensification of the South Pacific jet are projected. Under an additional 0.5°C of warming a poleward shift of the North Atlantic jet exit and an intensification on the flanks of the Southern Hemisphere storm track become more pronounced. The weakening of the Mediterranean storm track that is projected under low mitigation emerges in the 2 °C warmer world (Li et al., 2018). The AR5 (Stocker et al., 2013) assessed that under high greenhouse forcing (3°C or 4°C) there is *low confidence* in projections of poleward shifts of the North-Hemisphere storm tracks, while there is *high confidence* that there would be a small poleward shift of the South-Hemisphere storm tracks.In the context of this report, we assess that there is *limited evidence* and *low confidence* in whether any projected signal for higher levels of warming is to be well-manifested under 2°C of global warming.

3.3.7 Ocean circulation and temperature

It is *virtually certain* that the temperature of the upper layers of the ocean (0–700 m) has been increasing at a rate just behind that of the warming trend for the planet. The surface of three ocean basins have warmed over the period 1950–2016 (by 0.11°C, 0.07°C, and 0.05°C per decade for the Indian, Atlantic and Pacific oceans respectively; Hoegh-Guldberg et al., 2014, AR5 Chapter 30), with the greatest changes occurring at the highest latitudes. Isotherms (i.e. lines of equal temperature) of sea surface temperature (SST) are traveling to higher latitudes at rates of up to 40 km per year (Burrows et al., 2014; García Molinos et al., 2015). Long-term patterns of variability make detecting signals due to climate change complex, although the recent acceleration of changes to the temperature of the surface layers of the ocean has made the climate signal more distinct (Hoegh-Guldberg et al., 2014). There is also evidence of significant increases in the frequency of marine heatwaves in the observational record (Oliver et al., 2018), consistent with changes in mean ocean temperatures (*high confidence*). Increasing climate extremes in the ocean are associated with the general rise in global average surface temperature as well as more intense patterns of climate variability (e.g., climate change intensification of ENSO). Increased heat in the upper layers of the ocean is also driving more intense storms and greater rates of inundation, which, together with sea level rise, are already driving significant impacts to sensitive coastal and low-lying areas.

Increasing land-sea temperature gradients, as induced by higher rates of continental warming compared to the surrounding oceans under climate change, have the potential to strengthen upwelling systems associated with the eastern boundary currents (Benguela, Canary, Humboldt and Californian Currents) (Bakun, 1990). Observed trends support the conclusion that a general strengthening of longshore winds has occurred (Sydeman et al., 2014), but are unclear in terms of trends detected in the upwelling currents themselves (Lluch-Cota et al., 2014). Projecting the scale of the changes between 1ºC and 1.5ºC, and 1.5ºC and 2ºC is only informed by the changes over the past change in GMST of 0.5ºC (*low confidence*). However, the weight of evidence from GCM projections of future climate change indicates the general strengthening of the Benguela, Canary and Humboldt upwelling systems under enhanced anthropogenic forcing (D. Wang et al., 2015) is *likely* to occur. This strengthening is projected to be stronger at higher latitudes. In fact, evidence from regional climate modelling is supportive of an increase in long-shore winds at higher latitudes, but at lower latitudes long-shore winds may decrease as a consequence of the poleward displacement of the subtropical highs under climate change (Christensen et al., 2007; Engelbrecht et al., 2009).

It is more likely than not that the Atlantic Meridional Overturning Circulation (AMOC) has been weakening in recent decades, given the detection of the cooling of surface waters in the north Atlantic and evidence that the Gulf Stream has slowed by 30% since the late 1950s (Srokosz and Bryden, 2015; Caesar et al., 2018). There is only *limited evidence* linking the current anomalously week state of AMOC to anthropogenic warming (Caesar et al., 2018). It is *very likely* that the AMOC will weaken over the 21st century. Best estimates and range for the reduction from CMIP5 are 11% (1 to 24%) in RCP2.6 and 34% (12 to 54%) in RCP8.5 (AR5). There is no evidence indicating significantly different amplitudes of AMOC weakening for 1.5°C versus 2°C of global warming.

3.3.8 Sea ice

Summer sea ice in the Arctic has been retreating rapidly in recent decades. During the period 1997 to 2014 for example, the monthly mean sea-ice extent during September decreased on average by 130,000 km² per year (Serreze and Stroeve, 2015). This is about four times as fast as the September sea-ice loss during the period 1979 to 1996. Also sea-ice thickness has decreased substantially, with an estimated decrease in ice thickness of more than 50% in the central Arctic (Lindsay and Schweiger, 2015). Sea-ice coverage and thickness also decrease in CMIP5-model simulations of the recent past, and are projected to decrease in the future (Collins et al., 2013). However, the modeled sea-ice loss in most CMIP5 models is much weaker than observed. Compared to observations, the simulations are weak in terms of their sensitivity to both global mean temperature rise (Rosenblum and Eisenman, 2017) and to anthropogenic CO_2 emissions (Notz and Stroeve, 2016). This mismatch between the observed and modeled sensitivity of Arctic sea ice implies that the multi-model-mean response of future sea-ice evolution probably underestimates the sea-ice loss for a given amount of global warming. To address this issue, studies estimating the future evolution of Arctic sea ice tend to bias correct the model simulations based on the observed evolution of Arctic sea ice in response to global warming. Often based on such bias correction, pre-AR5 and post-AR5 studies agree that for 1.5 °C global warming relative to pre-industrial levels, the Arctic Ocean will maintain a sea-ice cover throughout summer for most years (Collins et al., 2013; Notz and Stroeve, 2016; Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Sigmond et al., 2018). For 2°C global warming relative to pre-industrial levels, chances of an ice-free Arctic during summer are substantially higher (Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Screen et al., 2018; Sigmond et al., 2018). The

Arctic is *very likely* to have experienced at least one ice-free Arctic summer after about 10 years of stabilized warming at 2°C compared to after about 100 years of stabilized warming at 1.5°C (Jahn, 2018; Screen et al., 2018; Sigmond et al., 2018). For a specific given year under stabilized warming of 2°C, studies based on large ensembles of simulations with a single model estimate the likelihood for ice-free conditions as 35% without a bias correction of the underlying model (Sanderson et al., 2017; Jahn, 2018); as between 10% and >99% depending on the observational record used to correct the sensitivity of sea ice decline to global warming in the underlying model (Niederdrenk and Notz, 2018); and as 19% based on a procedure to correct for biases in the climatological sea ice coverage in the underlying model (Sigmond et al., 2018). The uncertainty of the first year of the occurrence of an ice-free Arctic Ocean arising from internal variability is estimated to be about 20 years (Notz, 2015; Jahn et al., 2016).

The more recent estimates of the warming necessary to achieve an ice-free Arctic Ocean during summer are lower than the ones given in AR5 (about 2.6°C-3.1°C relative to preindustrial or 1.6°C-2.1°C global warming relative to the present day), which was similar to the estimate of 3°C relative to preindustrial levels (or 2°C global warming relative to the present day) by Mahlstein and Knutti (2012) based on bias-corrected CMIP3 models. Rosenblum and Eisenman (2016) explain why the sensitivity estimated by Mahlstein and Knutti (2012) might be too low, estimating instead that September sea ice in the Arctic disappears for 2°C relative to preindustrial (or about 1°C global warming relative to the present day), in line with the other recent estimates. Notz and Stroeve (2016) use the observed correlation between September sea-ice extent and cumulative CO_2 emissions to estimate that the Arctic Ocean would become nearly sea-ice-free during September with a further 1000 Gt of emissions, which also implies a sea-ice loss at about 2°C global warming. Some of the uncertainty in these numbers derives from the possible impact of aerosols (Gagne et al., 2017) and of volcanic forcing (Rosenblum and Eisenman, 2016). During winter, little Arctic sea ice is projected to be lost for either 1.5°C or 2ºC global warming (Niederdrenk and Notz, 2018).

Regarding the behavior of Arctic sea ice under decreasing temperatures following a possible overshoot of a long-term temperature target, a substantial number of pre-AR5 studies have found that there is no indication of hysteresis behavior of Arctic sea ice (Holland et al., 2006; Schroeder and Connolley, 2007; Armour et al., 2011; Sedláček et al., 2011; Tietsche et al., 2011; Boucher et al., 2012; Ridley et al., 2012). In particular, the relationship between Arctic sea-ice coverage and GMST is found to be indistinguishable between a warming scenario and a cooling scenario. These results have been confirmed by post-AR5 studies (Li et al., 2013; Jahn, 2018), which implies *high confidence* that an intermediate temperature overshoot has no long-term consequences for Arctic sea-ice coverage.

In the Antarctic, sea ice shows regionally contrasting trends, with for example strongly decreased sea-ice coverage near the Antarctic peninsula and increased sea-ice coverage in the Amundsen Sea (Hobbs et al., 2016). Averaged over these contrasting regional trends, there has been a slow long-term increase in overall sea-ice coverage in the Southern Ocean, with, however, comparably low ice coverage from September 2016 onwards. Collins et al. (2013) have *low confidence* in Antarctic sea ice projections because of the wide range of model projections and an inability of almost all models to reproduce observations such as the seasonal cycle, interannual variability and the long-term slow increase. No studies are hence available to robustly assess the possible future evolution of Antarctic sea ice under low-warming scenarios.

In summary, the probability of a sea-ice-free Arctic Ocean during summer is substantially higher at 2°C compared to 1.5°C global warming relative to pre-industrial levels and it is *very likely* that there will be the least one sea-ice-free Arctic summer after about 10 years of stabilized warming at 2°C, while about 100 years are required for a sea-ice-free Arctic summer at 1.5°C. There is *high confidence* that an intermediate temperature overshoot has no long-term consequences for Arctic sea-ice coverage.

3.3.9 Sea level

Sea level varies over a wide range of temporal and spatial scales, which can be divided into three broad categories. These are Global Mean Sea Level (GMSL), regional variation about this mean, and the occurrence of sea-level extremes associated with storm surges and tides. GMSL has been rising since the late 19th century from the low rates of change that characterized the previous two millennia (Church et al., 2013). Slowing in the reported rate over the last two decades (Cazenave et al., 2014) may be attributable to instrumental drift in the observing satellite system (Watson et al., 2015) and volcanoes (Fasullo et al., 2016). Accounting for the former results in rates (1993 to mid-2014) of between 2.6 and 2.9 mm yr^{-1} (Watson et al., 2015). The relative contributions from thermal expansion, glacier and ice-sheet mass loss, as well as freshwater storage on land, are relatively well understood (Church et al., 2013; Watson et al., 2015) and there attribution is dominated by anthropogenic forcing since 1970 (15±55% before 1950, 69±31% after 1970) (Slangen et al., 2016).

There has been a significant advance in the literature since AR5, which has seen the development of Semi-Empirical Models (SEMs) into a broader emulation-based approach (Kopp et al., 2014; Mengel et al., 2016; Nauels et al., 2017) that is partially based on the results from more detailed, process-based modelling, where available. Church et al. (2013) assigned *low confidence* to SEMs because of their assumption that the relation between climate forcing and GMSL is the same in the past (calibration) and future (projection). Probable future changes in the relative contributions of thermal expansion, glaciers and (in particular) ice sheets invalidate this assumption, however recent emulation-based studies overcome this by considering individual GMSL contributors separately and are therefore employed in this assessment. In this subsection, the process-based literature of individual contributors to GMSL is considered for scenarios close to 1.5ºC and 2ºC before assessing emulation-based approaches.

A limited number of processes-based studies are relevant to GMSL in 1.5ºC and 2ºC worlds. Marzeion et al. (2018) force a global glacier model with temperature-scaled scenarios based on RCP2.6 to investigate the difference between 1.5ºC and 2ºC and find little difference between scenarios in the glacier contribution to GMSL at 2100 (54-97 mm relative to present day for 1.5ºC, and 63-112 mm for 2ºC using a 90% confidence interval). This arises because melt during the remainder of the century is dominated by the response to warming from preindustrial to present-day levels (in turn a reflection of the slow response times of glaciers). Fuerst et al. (2015) make projections of Greenland ice sheet’s contribution to GMSL using an ice-flow model forced by the regional climate model Modèle Atmosphérique Régional (MAR, considered by Church et al., 2013) to be the ‘most realistic’ such model). They obtain an RCP2.6 range of 24-60 mm (1 standard deviation) by the end of the century (relative to 2000 and consistent with the assessment of Church et al. (2013)), however their projections do not allow the difference between 1.5ºC and 2ºC worlds to be evaluated.

The Antarctic ice sheet can contribute both positively and negatively to future GMSL rise by, respectively, increases in outflow (solid ice lost directly to the ocean) and increases in snowfall (due to the increased moisture-bearing capacity of a warmer atmosphere). Frieler et al. (2015) suggest a range of 3.5-8.7 % K^{-1} for this effect, which is consistent with the AR5. Observations from the Amundsen Sea sector of Antarctic suggest an increase in outflow (Mouginot et al., 2014) over recent decades associated with grounding line retreat (Rignot et al., 2014) and the influx of relatively warm Circumpolar Deepwater (Jacobs et al., 2011). Literature on the attribution of these change to anthropogenic forcing is still in its infancy (Goddard et al., 2017; Turner et al., 2017a). RCP2.6-based projections of Antarctic outflow (Levermann et al., 2014; Golledge et al., 2015; DeConto and Pollard, 2016, who include snowfall changes) are consistent with the AR5 assessment of Church et al. (2013) for end-of-century GMSL for RCP2.6, and do not support substantial additional GMSL rise by Marine Ice Sheet Instability or associated instabilities (see Section 3.6). While agreement is relatively good, concerns about the numerical fidelity of these models still exist and this may affect the quality of their projections (Drouet et al., 2013; Durand and Pattyn, 2015). An assessment of Antarctic contributions beyond the end of the century, in particular related to the Marine Ice Sheet Instability, can be found in Section 3.6.

While some literature on process-based projections of GMSL at 2100 is available, it is insufficient to distinguish between emission scenarios associated with 1.5ºC and 2ºC worlds. This literature is, however, consistent with Church et al. (2013) assessment of a *likely* range of 0.28-0.61 m at 2100 (relative to 1986-2005) suggesting that AR5 assessment is still appropriate. Recent emulation-based studies show convergence towards this AR5 assessment (Table 3.1) and offer the advantage of allowing a comparison between 1.5ºC and 2ºC worlds. Table 3.1 presents a compilation of both recent emulation-based and SEM studies.

Table 3.1: Compilation of recent projections for sea level at 2100 (in cm) for Representative Concentration Pathway (RCP)2.6, and 1.5 and 2.0 °C scenarios. Upper and lower limits are shown for the 17-84% and 5-95% confidence intervals quoted in the original papers.

Study	**Baseline**	**RCP2.6**		**1.5ºC**		**2ºC**	
		67%	**90%**	**67%**	**90%**	**67%**	**90%**
AR5	1986-2005	28-61					
Kopp et al. (2014)	2000	37-65	29-82				
Jevrejeva et al. (2016)	1986-2005		29-58				
Kopp et al. (2016)	2000	28-51	24-61				
Mengel et al. (2016)	1986-2005	28-56					
Nauels et al. (2017)	1986-2005	35-56					
Goodwin et al. (2017)	1986-2005		31-59 45-70 45-72				
Schaeffer et al. (2012)	2000		52-96		54-99		56-105
Schleussner et al. (2016b)	2000			26-53		36-65	
Bittermann et al. (2017)	2000				29-46		39-61
Jackson et al. (2018)	1986-2005			30-58 40-77	20-67 28-93	35-64 47-93	24-74 32-117
Sanderson et al. (2017)					50-80		60-90
Nicholls et al. (2018)	1986-2005				24-54		31-65
Rasmussen et al. (2018)	2000			35-64	28-82	39-76	28-96
Goodwin et al. (2018)	1986-2005				26-62		30-69

There is little consensus between the reported ranges of GMSL rise (Table 3.1), in particular at their upper limit, however there is *medium agreement* that GMSL at 2100 would be 0-0.2 m higher in a 2ºC world compared to 1.5 ºC with a most likely value of 0.1 m. There is *medium confidence* in this assessment because of issues associated with both projections of the Antarctic contribution to GMSL that are employed in emulation-based studies (see above) and the issues previously identified with SEMs (Church et al., 2013).

Translating projections of GMSL to the scale of coastlines and islands requires two further steps. The first accounts for regional changes associated with changing water and ice loads (such as Earth's gravitational field and rotation, and vertical land movement), as well as accounting for spatial differences in ocean heat uptake and circulation. The second maps regional sea level on to changes in the return periods of particular flood events to account for effects not included in global climate models such as tides, storm surges and wave setup and runup. Kopp et al. (2014) present a framework to do this and give an example application for nine sites (in the US, Japan, northern Europe and Chile). Of these sites, seven (all except those in northern Europe) experience at least a quadrupling in the number of years in the 21st century with 1-in-100 year floods under RCP2.6 compared to no future sea-level rise. Rasmussen et al. (2018)(2018) use this approach to investigate the difference between 1.5ºC and 2ºC worlds up to 2200. They find that the reduction in the frequency of 1-in-100 year floods in 1.5ºC compared to 2ºC worlds is greatest in the eastern US and Europe, with ESL event frequency amplification being reduced by about a half and with smaller reductions for Small Island Developing States (SIDS). This latter contrasts with the finding of Vitousek et al. (2017) that regions with low variability in extreme water levels (such as SIDS in the tropics) are particularly sensitive to GMSL rise such that a doubling of frequency may be expected for even small (0.1-0.2 m) rises. Schleussner et al. (2011) emulate the AMOC based on a subset of CMIP-class climate models. When forced using global temperatures appropriate to the CP3-PD scenario (1ºC warming at 2100 relative to 2000 or ~2 ºC relative to preindustrial), the emulation suggests an 11% median reduction in AMOC strength at 2100 (relative to 2000) with associated 0.04 m dynamic sea-level rise along the New York City coastline.

In summary, there is *medium confidence* that GMSL rise will be about 0.1 m less by the end of the century in a 1.5°C compared to a 2ºC warmer world. SLR beyond 2100 is discussed in 3.6, however recent literature strongly supports Church et al. (2013)'s assessment that sea level rise will continue well beyond 2100.

[START BOX 3.3 HERE]

Box 3.3: Lessons from Past Warm Climate Episodes

Climate projections and associated risk assessments for a future warmer world are based on climate model simulations. However, Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models do not include all existing earth system feedbacks and may therefore underestimate both rates and extents of changes (Knutti and Sedláček, 2012). Evidence from natural archives of three moderately warmer (1.5ºC-2°C) climate episodes in Earth's past help to assess such long-term feedbacks (Fischer et al., 2018).

While evidence over the last 2000 yr and during the Last Glacial Maximum (LGM) has been discussed in detail in the IPCC Fifth Assessment Report (Masson-Delmotte et al., 2013), the climate system response during past warm intervals was the focus of a recent review paper (Fischer et al., 2018) summarized in this Box. Examples of past warmer conditions (with essentially modern physical geography) include the Holocene Thermal Maximum (HTM) (broadly defined as about10-5 kyr before present (BP), where present is defined as 1950), the Last Interglacial (LIG about 129-116 kyr BP) and the Mid Pliocene Warm Period (MPWP, 3.3-3.0 millions years BP).

The global temperature response to changes in the insolation forcing during the HTM (Marcott et al., 2013) and the LIG (Hoffman et al., 2017) was up to +1°C warmer than preindustrial (1850-1900); high-latitude warming was 2-4°C (Capron et al., 2017), while temperature in the tropics changed little. Both HTM and LIG experienced atmospheric CO_2 levels similar to preindustrial conditions (Masson-Delmotte et al. 2013). During the MPWP, the most recent time period when CO_2 concentrations were similar to present, the global temperature was >1°C and Arctic temperatures about 8°C warmer than preindustrial (Brigham-Grette et al., 2013).

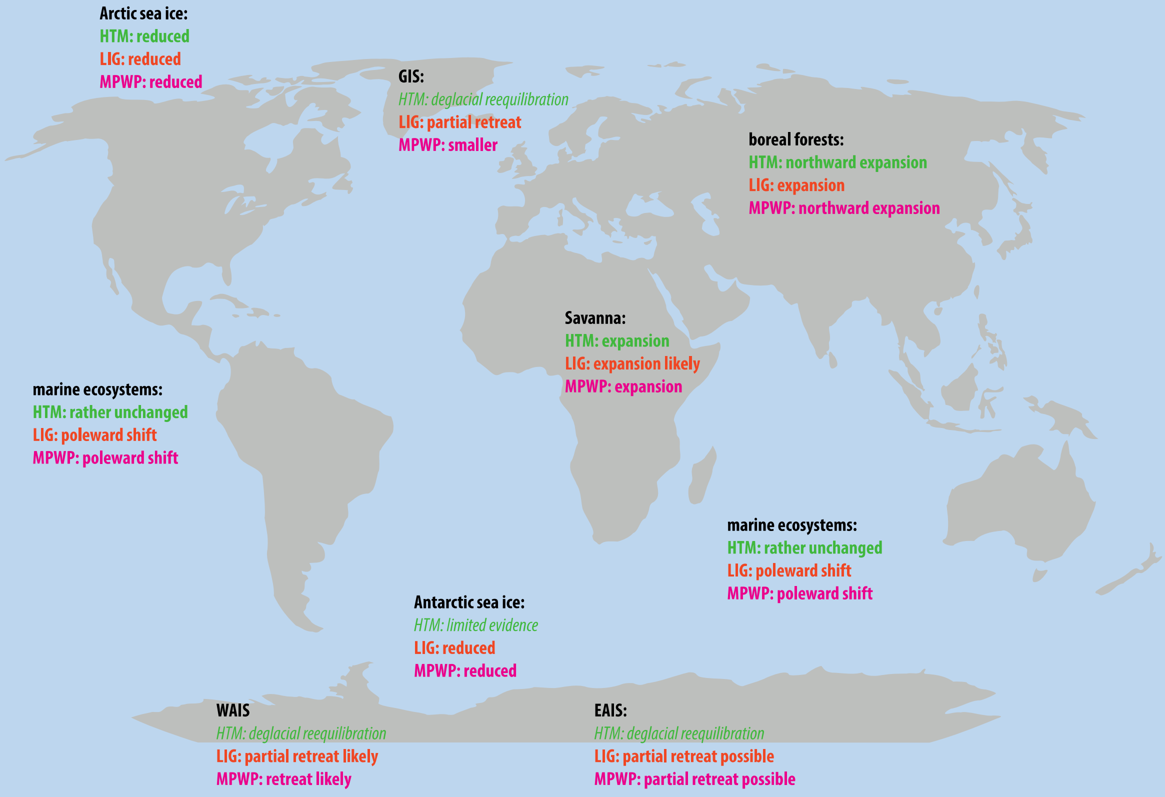
Although imperfect as analogs for the future, these regional changes can inform risk assessments such as the potential for crossing irreversible thresholds or amplifying anthropogenic changes (Box 3.3 Figure 1). For example, HTM and LIG Greenhouse Gas (GHG) concentrations show no evidence of runaway greenhouse gas releases under limited global warming. Transient releases of CO_2 and CH_4 may follow permafrost melting, but may be compensated by peat growth over longer timescales (Yu et al., 2010) . Warming may release CO_2 by enhancing soil respiration, counteracting CO_2 fertilization of plant growth (Frank et al., 2010). Evidence of a collapse of the Atlantic Meridional Overturning Circulation (AMOC) during these past events of limited global warming could not be found (Galaasen et al., 2014).

Ecosystems and biome (major ecosystem types) distributions changed significantly with warming both in the ocean and on land. For example, during past warming events some tropical and temperate forests retreated due to increased aridity, while savannas expanded (Dowsett et al., 2016). Poleward shifts of marine and terrestrial ecosystems, upward shifts in Alpine regions, and reorganisations of marine productivity are also recorded in natural archives (Williams et al., 2009; Haywood et al., 2016).

Past warm events are associated with partial sea ice loss in the Arctic. Limited data on Antarctic sea ice so far preclude firm conclusions about southern-hemisphere sea ice losses (de Vernal et al., 2013).

Reconstructed global sea level rise of 6-9 m during the LIG and possibly > 6m during the MPWP requires a retreat of either the Greenland or Antarctic ice sheets (or both) (Dutton et al., 2015). While ice sheet and climate models allow for a substantial retreat of the West Antarctic Ice Sheet (WAIS) and parts of East Antarctic Ice Sheet (DeConto and Pollard, 2016), direct observational evidence is still lacking. Evidence for ice retreat in Greenland is stronger, although a complete collapse of the Greenland ice sheet during the LIG can be excluded (Dutton et al., 2015). Under modest warming past sea levels rise rates were similar or up to two times larger than observed over the past two decades (Kopp et al., 2013). Given the long timescales involved to reach equilibrium in a warmer world, sea level rise will likely continue for millennia even if warming is limited to 2°C.

Finally, temperature reconstructions from these past warm intervals suggest that current climate models underestimate regional warming at high latitudes (polar amplification) and long-term (multi-millennial) global warming. None of these past warm climate episodes experienced the high speed of change in atmospheric CO_2 and temperatures that we are experiencing today (Fischer et al., 2018).



Box 3.3, Figure 1 : Impacts and responses of components of the Earth System. Summary of typical changes found for warmer periods in the paleorecord as discussed in Fischer et al. (2018) (all statements relative to pre-industrial. Statements in italic indicate that no conclusions can be drawn for the future). Note that significant spatial variability and uncertainty exists in the assessment of each component and, therefore, this figure should not be referred to without reading the source publication in detail. HTM: Holocene Thermal Maximum, LIG: Last Interglacial, MPWP: Mid Pliocene Warm Period

[END BOX 3.3 HERE]

3.3.10 Ocean chemistry

Ocean chemistry includes pH, salinity, oxygen, CO_2, and a range of other ions and gases, which affected by precipitation, evaporation, storms, river run-off, coastal erosion, up-welling, ice formation, and the activities of organisms and ecosystems (Stocker et al., 2013). Ocean chemistry is also changing with global temperature, with impacts projected at 1.5°C and, more so, at 2°C (*high agreement, medium evidence*). Projected changes in the upper layers of the ocean include changes to pH, carbonate ion and oxygen content. Despite its many component processes, ocean chemistry has been relatively stable for long periods of time prior to the Industrial Period (Hönisch et al., 2012). Ocean chemistry is changing under the influence of human activities and rising greenhouse gases (*virtually certain*, Rhein et al., 2013; Stocker et al., 2013). About 30% of CO_2 emitted by human activities, for example, has been absorbed by the ocean where it has combined with water to produce a dilute acid that dissociates and drives ocean acidification (Cao et al., 2007; Stocker et al., 2013). Ocean pH has decreased by 0.1 pH units since the Pre-Industrial Period, which is unprecedented in the last 65 Ma (*high confidence*, Ridgwell and Schmidt, 2010) or even 300 Ma of Earth history (*medium confidence*, Hönisch et al., 2012).

Ocean acidification is most pronounced where temperatures are lowest (e.g. Polar regions) or where CO_2-rich water is brought to the ocean surface by upwelling (Feely et al., 2008). Acidification can also be influenced by effluents from natural or disturbed coastal land use (Salisbury et al., 2008), plankton blooms (Cai et al., 2011), and the atmospheric deposition of acidic materials (Omstedt et al., 2015). These sources may not be directly attributable to climate change, yet may amplify the impacts of ocean acidification (Bates and Peters, 2007; Duarte et al., 2013). Ocean acidification also influences the ionic composition of seawater by changing the organic and inorganic speciation of trace metals (e.g. 20-fold increases in free ion concentrations such as Al) which may have impacts although these are poorly understood (Stockdale et al., 2016).

Oxygen varies regionally and with depth, and is highest in Polar regions and lowest in the eastern basins of the Atlantic and Pacific Oceans, and the northern Indian Ocean (Doney et al., 2014; Karstensen et al., 2015; Schmidtko et al., 2017). Increasing surface water temperatures have reduced oxygen in the ocean by 2% since 1960 with other variables such as ocean acidification, sea level rise, precipitation, wind, and storm patterns playing roles (Schmidtko et al., 2017). Changes to ocean mixing and metabolic rates (due to increased temperature and supply of organic carbon to deep areas) has increased the frequency of ‘dead zones’, areas where oxygen levels no longer support oxygenic life (Diaz and Rosenberg, 2008). Drivers are complex and include both climate change and other factors (Altieri and Gedan, 2015) with increases in tropical as well as temperate regions (Altieri et al., 2017).

Ocean salinity is changing in directions that are consistent with surface temperatures and the global water cycle (i.e. evaporation and inundation). Some regions (e.g. northern oceans and Arctic regions) have decreased salinity (i.e. due to melting glaciers and ice sheets) while others are increasing in salinity due to higher sea surface temperatures and evaporation (AR5 WGII Ch30, Durack et al., 2012). These changes in salinity (density) are also potentially driving changes to large scale patterns of water movement (Section 3.3.8)

3.3.11 Global synthesis

Table 3.2 present a summary of the assessments of global and regional climate changes and associated hazards for this chapter, based on the existing literature. For more detailed observation and attribution in ocean and cryosphere systems please refer to the upcoming IPCC Special Report on the Ocean and Cryophere in a Changing Climate (SROCC) due to be released in 2019.

Table 3.2: Summary of assessments of global and regional climate changes and associated hazards. Confidence and likehood statements are quoted from the relevant chapter text and are omitted where no assessment was made, in which case the IPCC Fifth Assessment Report (AR5) is given where available. Observed impacts and projected risks in natural and human systems. GMST: Global Mean Surface Temperature, AMOC: Atlantic Meridional Overturning Circulation, GMSL: Global Mean Sea Level.

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
GMST anomaly	GMST anomalies were 0.87°C (±0.10°C *likely* range) above pre-industrial (1850-1900) values in the 2006-2015 decade, with a recent warming of about 0.2°C (±0.10°C) per decade (*high confidence*) [Chapter 1]	The observed 0.87°C GMST increase in the 2006-2015 decade compared to pre-industrial (1850-1900) conditions was mostly human-induced (*high confidence*) Human-induced warming reached about 1°C (±0.2°C *likely* range) above pre-industrial levels in 2017 [Chapter 1]	1.5°C	2°C	0.5°C

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
Temperature extremes	Overall decrease in the number of cold days and nighs and an overall increase in the number of warm days and nights at the global scale on land *(very likely)* Continental-scale increase in intensity and frequency of hot days and nights, and decrease in intensity and frequency of cold day and nights, in North America, Europe and Australia. *(very likely)* Increases in frequency or duration of warm spell lengths in large parts of Europe, Asia and Australia (*high confidence (likely)*), as well as on global scale (*medium confidence*) [Section 3.3.2]	Anthropogenic forcing has contributed to the observed changes in the frequency and intensity of daily temperature extremes on the global scale since the mid-20th century *(very likely)* [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights *(very likely)* Warming of temperature extremes highest over land, including nearly all inhabited regions *(high confidence)*, with increases of up to 3°C in mid-latitude warm season, and up to 4.5 in high-latitude cold season (*medium confidence*) Highest increase of frequency of unusually hot extremes in tropical regions (*medium confidence*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights *(very likely)* Warming of temperature extremes highest over land, including nearly all inhabited regions (*high confidence)*, with increases of up to 4°C in mid-latitude warm season, and up to 6°C in high-latitude cold season (*medium confidence*) Highest increase of frequency of unusually hot extremes in tropical regions (*medium confidence*) [Section 3.3.2]	Global-scale increased intensity and frequency of hot days and nights, and decreased intensity and frequency of cold days and nights *(high confidence)* Global-scale increase in length of warm spells and decrease in length of cold spells *(high confidence)* Strongest increase in frequency for rarest and most extreme events (*high confidence*) Particularly large increases in hot extremes in inhabited regions (*high confidence*) [Section 3.3.2]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
Heavy precipitation	More areas with increases than decreases in the frequency, intensity and/or amount of heavy precipitation *(likely)* [Section 3.3.3]	Human influence contributed to global-scale tendency towards increases in the frequency, intensity and/or amount of heavy precipitation events (*medium confidence*) [Section 3.3.3]	Increases in frequency, intensity and/or amount heavy precipitation when averaged on global land, with positive trends in several regions (*high confidence*) [Section 3.3.3]	Increases in frequency, intensity and/or amount heavy precipitation when averaged on global land, with positive trends in several regions (*high confidence*) [Section 3.3.3]	Higher frequency, intensity and/or amount of heavy precipitation when averaded on global on land at 2°C versus 1.5°C (*high confidence)* Several regions are projected to experience increases in heavy precipitation at 2°C warming versus 1.5°C (*high confidence*), in particular in high-latitude and mountainous regions, as well as in Eastern Asia and Eastern North America (*medium confidence*) [Section 3.3.3]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
Drought and dryness	*High confidence* in dryness trends in some regions, especially drying in Mediterranean region (including Southern Europe, Northern Africa and the Near-East) *Low confidence* in drought and dryness trends at global scale. [Section 3.3.4]	*Medium confidence* in attribution of drying trend in Mediterranean region *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on dryness index definition [Section 3.3.4]	*Medium confidence* of drying trends in Mediterranean region. *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on dryness index definition [Section 3.3.4]	*Medium confidence* of drying trends in Mediterranean region and South Africa. *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on dryness index definition [Section 3.3.4]	*Medium confidence* of stronger drying trends in Mediterranean region and South Africa at 2°C versus 1.5°C global warming. *Low confidence* elsewhere, in part due to large interannual variability and longer duration (and thus lower frequency) of drought events, as well as to dependency on dryness index definition [Section 3.3.4]
Runoff & river flooding	Streamflow trends mostly non-statistically significant (*high confidence)* Increase in flood frequency and extreme streamflow in some regions *(high confidence)* [Section 3.3.5]	Not assessed in this report.	Expansion of the global land area with significant increase in runoff (*medium confidence)* Increase in flood hazard in some regions *(medium confidence)* [Section 3.3.5]	Expansion of the global land area with significant increase in runoff (*medium confidence*) Increase in flood hazard in some regions (*medium confidence*) [Section 3.3.5]	Expansion of the global land area with significant increase in runoff (*medium confidence)* Expansion in the area affected by flood hazard *(medium confidence)* [Section 3.3.5]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
Tropical & extra-tropical cyclones	*Low confidence* in robustness of observed changes [Section 3.3.6]	Not meaningful to assess given *low confidence* in changes, which are due to large inter-annual variability, heterogeneity of the observational record and contradictory findings regarding trends in the observational record.	*Low confidence* in manifestation of changes in storm tracks under 2ºC global warming *Limited evidence* that the global number of tropical cyclones will be less under 2°C of global warming compared to 1.5 °C of warming, but with an increase in the number of very intense cyclones (low confidence). [Section 3.3.6]		
Ocean temperature and circulation	*High confidence* in observed warming of upper ocean, with slightly lower rates than global warming Increased occurrence of marine heatwaves *(high confidence)* AMOC has been weakening over recent decades (*more likely than not*) [Sections 3.3.7]	*Limited evidence* attributing the weakening of AMOC in recent decades to anthropogenic forcing	Further increases in ocean temperatures, including more frequent marine heatwaves (*high confidence*) AMOC will weaken over 21st century and substantically so under high levels (higher than 2°C) of global warming (*very likely*)		
Sea ice	Continuing the trends reported in AR4, the annual Arctic sea ice extent decreased over the period 1979–2012. The rate of this decrease was *very likely* between 3.5 and 4.1% per decade (0.45 to 0.51 million	Anthropogenic forcings are *very likely* to have contributed to Arctic sea ice loss since 1979 AR5 Chapter 10 (Bindoff et al., 2013a)	At least one sea-ice-free Arctic summer after about 100 years of stabilized warming *(very likely)* [Section 3.3.8]	At least one sea-ice-free Arctic summer after about 10 years of stabilized warming (*very likely)* [Section 3.3.8]	Probability of sea-ice-free Arctic summer greatly reduced at 1.5°C versus 2°C global warming *(high confidence*) [Section 3.3.8]

	Observed change (recent past versus pre-industrial)	**Attribution of observed change to human-induced forcing (present versus pre-industrial)**	**Projected change at 1.5°C global warming compared to pre-industrial (1.5°C versus 0°C)**	**Projected change at 2°C global warming compared to pre-industrial (2°C versus 0°C)**	**Differences between 2°C and 1.5°C global warming**
	km^2 per decade) AR5 Chapter 4 (Vaughan et al., 2013)		Intermediate temperature overshoot has no long-term consequences for Arctic sea-ice cover (*high confidence*) 3.3.8		
Sea level	It is *likely* that the rate of GMSL has continued to increase since the early 20th century, with estimates that range from 0.000 [–0.002 to 0.002] mm yr^{-2} to 0.013 [0.007 to 0.019] mm yr^{-2} AR5 Chapter 13 (Church et al., 2013)	It is *very likely* that there is a substantial contribution from anthropogenic forcings to the global mean sea level rise since the 1970s AR5 Chapter 10 (Bindoff et al., 2013a)	Not assessed in this report	Not assessed in this report	GMSL rise will be about 0.1 m less at 1.5°C versus 2°C global warming (*medium confidence*) [Section 3.3.9]
Ocean chemistry	Ocean acidification due to increased CO$_2$ has resulted in 0.1 pH unit decrease since the pre-industrial period which is unprecedented in the last 35 Ma (*high confidence*) [Section 3.3.10]	It is *very likely)* that oceanic uptake of anthropogenic CO$_2$ has resulted in acidification of surface waters. [Section 3.3.10]	Ocean chemistry is changing with global temperature with impacts projected at 1.5°C and, more so, at 2°C (*high agreement, medium evidence*) [Section 3.3.10]		

3.4 Observed impacts and projected risks in natural and human systems

3.4.1 Introduction

In Section 3.4, we explore the new literature and update the assessment of impacts and projected risks into the future for a large number of natural and human systems. We also explore adaptation opportunities laying the steps for reducing climate change, preparing the ground for later discussions on the opportunities to tackle both mitigation and adaptation while at the same time recognising the importance of sustainable development and reducing the inequities among people and societies facing climate change.

Working Group II (WGII) of the IPCC Fifth Assessment Report (AR5) provided an assessment of the literature for climate risk for natural and human systems across a wide range of environments, sectors and greenhouse gas scenarios, as well as for particular geographic regions (IPCC, 2014a, 2014b). The comprehensive assessment undertaken by AR5 evaluated the evidence of changes to natural systems, and the impact on human communities and industry. While impacts varied substantially between systems, sectors and regions, many changes over the past 50 years can be attributed to human driven climate change and its impacts. In particular, risks were observed by AR5 to be increasing for natural ecosystems as climate extremes increase in frequency and intensity, as well as those associated with fauna and flora shifting their biogeographical ranges to higher latitudes and altitudes, with consequences for ecosystem services and human dependence. AR5 also reported increasing evidence of changing patterns of disease, invasive species, as well as growing risks for coastal communities and industry, especially important when it comes to sea level rise and human vulnerability.

One of the strong themes that has emerged from AR5 was that previous assessments may have under-estimated how sensitive natural and human systems are to climate change. A more recent analysis of attribution to greenhouse gas forcing at the global scale (Hansen and Stone, 2016) has confirmed that many impacts related to changes in regional atmospheric and ocean temperature can be confidently attributed to anthropogenic forcing, while attribution to anthropogenic forcing of those related to precipitation are by comparison less clear. Moreover there is no strong direct relationship between the robustness of climate attribution and that of impact attribution (Hansen and Stone, 2016). The observed changes in human systems are increased by the loss of ecosystem services (e.g. reduced access to safe water) that are supported by biodiversity (Cramer et al., 2014). Limited research on the risks of warming of +1.5 and +2°C was conducted following AR5 for most key economic sectors and services, for livelihoods and poverty, and for rural areas. For these systems, climate is one of many drivers that result in adverse outcomes. Other factors include patterns of demographic change, socioeconomic development, trade, and tourism. Further, consequences of climate change for infrastructure, tourism, migration, crop yields, and other impacts interact with underlying vulnerabilities, such as for individuals and communities engaged in pastoralism, mountain farming, and artisanal fisheries, to affect livelihoods and poverty (Dasgupta et al., 2014).

Incomplete data and understanding of these lower end climate scenarios has increased the request for greater data and understanding of the projected risks of warming of 1.5°C, and 2°C for reference. This section explores the available literature on the projected risks, impacts and adaptation options, and is supported by additional information and background in Annex 3.1 (S3-4, S3-4-2, S3-4-4, S3-4-7, S3-4-12). A description of the main assessment methods of this chapter is given in Section 3.2.2.

3.4.2 Freshwater resources (quantity and quality)

3.4.2.1 Water availability

WGII AR5 concluded that about 80% of the world's population already suffers from serious threats to its water security as measured by indicators including water availability, water demand, and pollution (Vörösmarty et al., 2010). UNESCO (2011) concluded that climate change can alter the availability of water and threaten water security.

Although physical changes on streamflow and continental runoff that are consistent with climate change have been identified (Section 3.3.5), water scarcity in the past is still less well understood because the scarcity assessment needs to take into account various factors such as the operations of water supply infrastructure and human water use behaviour (Mehran et al., 2017), as well as incorporating green water, water quality, and environmental flow requirements (J. Liu et al., 2017). Over the past century, substantial growth in population, industrial and agricultural activities, and living standards have exacerbated water stress in many parts of the world, especially in semi-arid and arid regions such as California in the US (AghaKouchak et al., 2015; Mehran et al., 2015). Due to changes in climate and water consumption behavior, and particularly the effects of spatial distribution of population growth relative to water resources, the population under water scarcity increased from 0.24 billion (14% of global population) in the 1900s to 3.8 billion (58%) in the 2000s. In that last period (2000s), 1.1 billion people (17% of global population) mostly living in South and East Asia, North Africa and Middle East were facing high water shortage and high water stress (Kummu et al., 2016).

Over the next few decades, and for increases in global mean temperature of less than about 2ºC, the AR5 concluded that changes in population will generally have a greater effect on water resource availability than changes in climate. Climate change, however, will regionally exacerbate or offset the effects of population pressure (Jiménez Cisneros et al., 2014).

The differences in projected changes in runoff under 1.5ºC and 2ºC, particularly those that are regional, are described in Section 3.3.5. Constraining to 1.5ºC instead of 2ºC warming can mitigate the risks on water availability although socio-economic drivers could affect the availability more than the risks posed by the variation in warming levels, while the risks found in regions are not homogeneous (*medium evidence, medium agreement)* (Gerten et al., 2013; Hanasaki et al., 2013; Arnell and Lloyd-Hughes, 2014; Schewe et al., 2014; Karnauskas et al., 2018). Assuming a constant population in these models, Gerten et al. (2013) reveal that an additional 8% of the world population in 2000 will be exposed to new or aggravated water scarcity at 2ºC warming. This value is almost halved - with 50 % larger reliability - when warming is constrained to 1.5ºC. People inhabiting river basins particularly in the Middle East and Near East become newly exposed to chronic water scarcity even if the warming is constrained under 2ºC warming. Many regions especially in Europe, Australia and southern Africa appear to be affected at 1.5ºC if the reduction in water availability is computed for non-water scarce basins in addition to the reductions in water-scarce regions. From a contemporary population of approximately 1.3 billion exposed to water scarcity, about 3% (North America) to 9% (Europe) are prone to aggravated scarcity at 2ºC warming (Gerten et al., 2013). Under the Shared Socioeconomic Pathway (SSP)2 population scenario, about 8% of the global population are projected to experience a severe reduction in water resources under warming of 1.7ºC in 2021-2040, increasing to 14 % of the population under 2.7ºC in 2043-2071, based on either the criteria of discharge reduction >20% or >1 standard deviation (Schewe et al., 2014). Depending on the scenarios of SSP1 to 5, exposure to the increase of water scarcity in 2050 will be globally reduced by 184–270 million people at about 1.5ºC compared to the impacts at about 2ºC. However the variation between socio-economic differences is larger than the variation between warming levels (Arnell and Lloyd-Hughes, 2014).

On many small developing islands, there will be freshwater stress derived from projected aridity change, however, constraining to 1.5ºC warming can avoid a substantial fraction of water stress compared to 2ºC, especially across the Caribbean region, particularly on the island of Hispaniola (Dominican Republic and Haiti) (Karnauskas et al. (2018). Hanasaki et al. (2013) conclude that the projected range of changes in global irrigation water withdrawal (relative to the baseline of 1971-2000) with human configuration fixing non-meteorological variables at the period of about 2000 are 1.1–2.3% and 0.6–2.0% lower at 1.5ºC than at 2ºC, respectively. The same study, Hanasaki et al. (2013) reports on the importance of water use scenarios in water scarcity assessments, but neither quantitative nor qualitative information regarding water use are available. Hanasaki et al. (2013) conclude that the projected ranges of changes in global irrigation water withdrawal with human configuration fixing non-meteorological variables at about 2000 are 1.1–2.3% at about 1.5ºC, which is projected by Geophysical Fluid Dynamic Laboratory (GFDL) model (Representative Concentration Pathway (RCP)2.6 in 2071-2100 and RCP4.5 in 2011-2040), and 0.6‑2.0% at about 2ºC according to the projection using the Hadley Centre New Global Environmental Model (HadGEM) and Model for Interdisciplinary Research on Climate (MIROC) models (RCP4.5 and RCP8.5 in 2011-2040, respectively).

Comparing the impacts on hydropower production at 1.5°C and 2°C, it is found that mean gross potential increases in northern, eastern and western Europe, and decreases in southern Europe (Tobin et al., 2018; Jacob et al., 2018). The Baltic and Scandinavian countries will have the most positive impacts on production. The most negatively impacted are Greece, Spain, and Portugal, although the impacts can be reduced by limiting warming at 1.5°C (Tobin et al., 2018). It is found that, in Greece, Spain and Portugal, a warming of 2°C will decrease hydropower potential below 10%, while limiting to 1.5°C warming will keep the reduction to 5% or less. There is however, substantial uncertainty associated with these results due to a large spread between the climate models (Tobin et al., 2018).

Due to a combination of higher water temperatures and reduced summer river flows, the usable capacity of thermoelectric power plants using river water for cooling is expected to reduce in all European countries (Tobin et al., 2018; Jacob et al., 2018), with the magnitude of decreases being about 5% for 1.5°C and 10% for 2°C for most European countries (Tobin et al., 2018). Greece, Spain, and Bulgaria will have the largest reduction at 2°C (Tobin et al., 2018).

Fricko et al. (2016) assess the direct global energy sector water use across a broad range of energy system transformation pathways in order to identify the water impacts of a 2°C climate policy. This study revealed that there will be substantial divergence in water withdrawal for thermal power plant cooling under a condition in which the distribution of future cooling technology for energy generation is fixed, whereas adopting alternative cooling technologies and water resources will make the divergence considerably smaller.

3.4.2.2 Extreme hydrological events (floods and droughts)

WG II AR5 concluded that socio-economic losses from flooding since the mid-20th century have increased mainly due to greater exposure and vulnerability (*high confidence*; Jiménez Cisneros et al., 2014). There is *low confidence* due to *limited evidence*, however, that anthropogenic climate change has affected the frequency and the magnitude of floods. WGII AR5 also concluded that there is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand (Jiménez Cisneros et al., 2014).

Since the AR5, the number of studies related to river flooding and meteorological drought based on long-term observed data have been gradually increasing. There has been progress since the AR5 in identifying historical changes in streamflow and continental runoff (Section 3.3.5). As a result of population and economic growth, increased exposure of people and assets has caused more damage due to flooding. However, differences in flood risks among regions reflect the balance among the magnitude of the flood, population, their vulnerabilities, the value of assets affected by flooding, and the capacity to cope with flood risks that depend on socio-economic development conditions as well as topography and hydro-climatic conditions (Tanoue et al., 2016). The AR5 assessment concluded that there was *low confidence* in the attribution of global changes in droughts (Bindoff et al., 2013b). However, recent publications based on observational and modeling evidence are supporting a gathering concensus that human emissions have substantially increased the probability of drought years in the Mediterranean region (Sections 3.3.4, Table 3.2).

WGII AR5 assessed that global flood risk will increase in the future partly due to climate change (*limited evidence*, *medium agreement*), with projected changes in the frequency of droughts longer than 12 months being more uncertain, because of their dependence on accumulated precipitation over long periods (Jiménez Cisneros et al., 2014).

Increases in the risks associated with runoff at global scale (*high confidence*), and in flood hazard in some regions (*high confidence*), can be expected at warming of 1.5°C level with an overall increase in the area affected by flood hazard at 2°C (*high confidence*) (see Section 3.3.5). There are studies, however, revealing that socio-economic conditions will exacerbate flood impacts more than global climate change, and the magnitude of the impacts can be larger in some region (Arnell and Lloyd-Hughes, 2014; Winsemius et al., 2016; Alfieri et al., 2017; Arnell et al., 2018; Kinoshita et al., 2018) (*limited evidence, medium agreement*). Assuming constant population sizes, countries representing 73% of the world population will experience increasing flood risk with an average of 580% increase at 4ºC compared to the impact simulated over the baseline period 1976-2005. Such impact is projected to be reduced to 100% increase at 1.5ºC and 170% at 2ºC (Alfieri et al., 2017). Alfieri et al. (2017) reveal that the largest increases in flood risks are found in U.S., Asia, and Europe in general, while decreases are found in only few countries in Eastern Europe and Africa. Alfiere et al (2017) report that the projected changes are not homogeneously distributed on the world land surface. Alfieri et al. (2018) studied the population affected by flood events in European states, specifically Central and Western Europe, and found that the population affected can be limited to 86% for 1.5ºC warming compared to 93% at 2ºC. Under the SSP2 population scenario, Arnell et al. (2018) find that 39% (range 36-46%) of impacts on populations exposed to river flood can be globally avoided at 1.5ºC compared to 2 ºC warming.

Under SSP1-5 scenario, Arnell and Lloyd-Hughes (2014) find that the number of people exposed to increased flooding in 2050 under warming of about 1.5ºC can be reduced by 26–34 million compared to those people exposed to increased flooding associated with 2ºC. Variation between socio-economic differences, however, are larger than the variation between the extent of global warming. Kinoshita et al. (2018) find that a serious increase in potential flood fatality (5.7%) is projected without any adaptation if global warming increases from 1.5ºC to 2ºC, whereas an increase in potential economic loss (0.9%) is relatively small. Nevertheless, the study indicates that socio-economic changes have a stronger contribution to the potentially increased consequences of future floods, and about a half of the increase of potential economic losses is mitigated by autonomous adaptation.

There is limited information about the global and regional projected risks posed by droughts at 1.5ºC and 2ºC. However, hazards by droughts under 1.5ºC can be reduced compared to the hazards at 2ºC (Section 3.3.4). Under constant socio-economic conditions, the population exposed to drought at 2ºC warming is projected to be larger than at 1.5ºC (Smirnov et al., 2016; Sun et al., 2017; Arnell et al., 2018; Liu et al., 2018) (*limited evidence, medium agreement*). Under the same scenario, the global mean monthly number of people expected to be exposed to extreme drought at 1.5ºC in 2021-2040 is projected to be 114.3 million people while 190.4 million people at 2ºC in 2041-2060 (Smirnov et al., 2016) . Under the SSP2 population scenario, Arnell et al. (2018) project that 39% (range 36-51%) of impacts on populations exposed to drought can be globally avoided at 1.5ºC compared to 2ºC.

Liu et al. (2018) study the changes in population exposure to severe droughts in 27 regions and around the globe for 1.5ºC and 2ºC warming using the SSP1 population scenario, compared to the baseline period of 1986-2005, and conclude that urban population exposure in most regions can be decreased at 1.5ºC (350.2±158.8 million) compared to 2ºC (410.7±213.5 million), respectively. Liu et al. (2018) also suggest that more urban populations will be exposed to severe droughts in Central Europe, Southern Europe, the Mediterranean, West Africa, East and West Asia and Southeast Asia, and the number of the affected people will escalate further in these regions at 2ºC. In the Haihe River Basin in China, the proportion of the population exposed to droughts at 1.5ºC is projected to be reduced by 30.4%, but increased by 74.8% at 2°C relative to 339.65 million people in the 1986–2005 period (Sun et al., 2017) .

Alfieri et al. (2018) estimate expected damage from flood at the European level for the baseline period (1976-2005), in which the reported annual figure is 5 billion euro of losses and reveal that relative changes of flood impacts rise with warming levels from 116% at 1.5°C to 137% at 2°C, respectively.

Kinoshita et al. (2018) study the increase of potential economic loss in SSP3 and project that the smaller loss at 1.5°C compared to at 2°C (0.9%) is marginal regardless of whether the vulnerability is fixed at the current level or not. Winsemius et al. (2016) show adaptation measures have the potential to greatly reduce present and future flood damage, by analyzing the differences in results with and without flood protection standard. They conclude that increases in flood induced economic impacts (% Gross Domestic Product, GDP) in African countries are mainly driven by climate change and Africa's growing assets become increasingly exposed to floods. And hence there is greater need for long-term and sustainable investments in adaptation in Africa.

3.4.2.3 Groundwater

WGII AR5 concluded that the detection of changes in groundwater systems, and attribution of those changes to climatic changes, are rare owing to a lack of appropriate observation wells and an overall small number of studies (Jiménez Cisneros et al., 2014).

Since AR5, the number of studies based on long-term observed data continues to be limited. The groundwater-fed lakes in north-eastern central Europe have been affected by climate and land use changes, and show a predominantly negative lake-level trend in 1999–2008 (Kaiser et al., 2014).

WGII AR5 concluded that climate change is projected to reduce groundwater resources significantly in most dry subtropical regions (*robust evidence, high agreement*; Jiménez Cisneros et al., 2014).

In some regions, groundwater is often intensively used to supplement the excess demand, often leading to groundwater depletion. Climate change adds further pressure on water resources and exaggerates human water demands due to increasing temperatures over agricultural lands (Wada et al., 2017). Very few studies project the risks of groundwater depletion under 1.5ºC and 2ºC warming. Under 2ºC warming, impacts posed on groundwater are projected to be greater than at 1.5ºC (*limited evidence, low agreement*; Portmann et al., 2013; Salem et al., 2017).

Portmann et al. (2013) indicate that 2.0% (range 1.1-2.6%) of global land area is projected to suffer from an extreme decrease of renewable groundwater resources of more than 70% at 2ºC, which is clearly mitigated at 1.5ºC. The study also projects that 20% of global land surface is affected by more than 10% groundwater reduction at 1.5ºC with the percentage of the land impacted increasing at 2ºC. In a groundwater-dependent irrigated region in Northwest Bangladesh, the average groundwater level during the major irrigation period (January-April) is projected to decrease in accordance with temperature rise (Salem et al., 2017).

3.4.2.4 Water quality

WGII AR5 concluded that most observed changes to water quality from climate change are from isolated studies, mostly of rivers or lakes in high-income countries, using a small number of variables (Jiménez Cisneros et al., 2014). The AR5 report assessed that climate change is projected to reduce raw water quality, posing risks to drinking water quality with conventional treatment (*medium evidence, high agreement*; Jiménez Cisneros et al. (2014).

Since AR5, studies have detected climate change impacts on several indices of water quality in lakes, watershed and regional (e.g., Patiño et al., 2014; Aguilera et al., 2015; Watts et al., 2015; Marszelewski and Pius, 2016; Capo et al., 2017). Since WGII AR5, the number of studies utilizing RCP scenarios at regional or watershed scale have been gradually increased (e.g., Boehlert et al., 2015; Teshager et al., 2016; Marcinkowski et al., 2017). There are, however, few studies that explore projected impacts on water quality under 1.5ºC versus 2ºC warming. Differences in impacts on water quality between 1.5ºC and 2ºC warming is unclear (Bonte and Zwolsman, 2010; Hosseini et al., 2017) (*limited evidence, low agreement*). The daily probability of exceeding the chloride standard for drinking water taken from Lake IJsselmeer (Andijk, the Netherlands) is projected to increase about five times at 2ºC relative to 1ºC since 1990 (Bonte and Zwolsman, 2010). Mean monthly dissolved oxygen concentrations and nutrient concentrations in the upper Qu'Appelle River (Canada) in 2050-2055 are projected to decrease less at about 1.5ºC warming (RCP2.6 in 2050-2055) compared to about 2ºC (RCP4.5 in 2050-2055) (Hosseini et al., 2017). In the three river basins (Sekong, Sesan, and Srepok in southeast Asia) about 2ºC warming (1.05 ºC increase in the 2030s relative to the baseline peiod 1981-2008, RCP8.5), impacts posed by land-use change on water quality is projected to be greater than at 1.5ºC (0.89 ºC increase in the 2030s relative to the baseline peiod 1981-2008, RCP4.5)(Trang et al., 2017). Under the same warming scenario, Trang et al. (2017) project annual nitrogen (N) and phosphorus (P) yields change in 2030s at about 1.5ºC and about 2ºC as well as with combinations of two land-use change scenarios: 1) conversion of forest to grassland, and 2) of forest to agricultural land. The projected changes in N (P) yield under 1.5ºC and 2ºC scenarios are 7.3 (5.1)% and -6.6 (-3.6)%, whereas under the combination of land-use scenarios are 1) 5.2 (12.6)% and 8.8 (11.7)%, and 2) 7.5 (14.9)% and 3.7(8.8)%, respectively (Trang et al., 2017).

3.4.2.5 Soil erosion and sediment load

WGII AR5 concluded that there is little or no observational evidence that soil erosion and sediment load have been altered significantly due to climate change (*limited evidence, medium agreement*), (Jiménez Cisneros et al., 2014). As studies of climate change impacts on soil erosion have increased where rainfall is an important driver (Lu et al., 2013), studies have increasingly considered other factors such as rainfall intensity (e.g., Shi and Wang, 2015; Li and Fang, 2016), snow melt, and change of vegetation cover due to temperature rise (Potemkina and Potemkin, 2015), and crop management practices (Mullan et al., 2012). WGII AR5 concluded that increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices (Jiménez Cisneros et al., 2014).

While published studies of climate change impacts on soil erosion have increased since 2000 globally (Li and Fang, 2016), few articles have addressed impacts at 1.5ºC and 2ºC warming. The existing studies have found few differences in projected risks posed on sediment load under 1.5ºC and 2ºC (*limited evidence, low agreement*; Cousino et al., 2015; Shrestha et al., 2016). The differences between average annual sediment load under 1.5ºC and 2ºC warmings are not clear because of complex interactions among climate change, land cover/surface and soil management (Cousino et al., 2015; Shrestha et al., 2016). Averages of annual sediment load are projected to be similar under 1.5ºC and 2ºC , in particular in the Great Lakes region in the US as well as in the Lower Mekong region in Southeast Asia (Cousino et al., 2015; Shrestha et al., 2016).

3.4.3 Terrestrial and wetland ecosystems

3.4.3.1 Biome shifts

Latitudinal and elevational shifts of biomes (major ecosystem types) boreal, temperate, and tropical regions have been detected (Settele et al., 2014, AR5) and new studies confirm this (e.g. for shrub encroachment on tundra; Larsen et al., 2014). Attribution studies indicate that anthropogenic climate change has made a greater contribution to these changes than any other factor (Settele et al., 2014, *medium confidence*).

An ensemble of seven Dynamic Vegetation Models driven by projected climates from 19 alternative General Circulation Models (GCMs) (Warszawski et al., 2013 shows 13% (range 8-20%) of biomes transforming at 2°C warming, but only 4% (range 2-7%) doing so at 1°C; suggesting that about 7% may be transformed at 1.5°C, indicating a doubling of the areal extent of biome shifts between 1.5ºC and 2°C warming (Figure 3.15a). A single ecosystem model LPJmL (Gerten et al., 2013) illustrates that biome shifts in the Arctic, Tibet, Himalayas, South Africa and Australia would be avoided by constraining warming to 1.5°C as compared with 2°C (Figure 3.15b). Seddon et al. (2016) quantitatively identified ecologically sensitive regions to climate change in most of the continents from tundra to tropical rainforest. Biome transformation may in some cases be associated with novel climates and ecological communities (Prober et al., 2012).

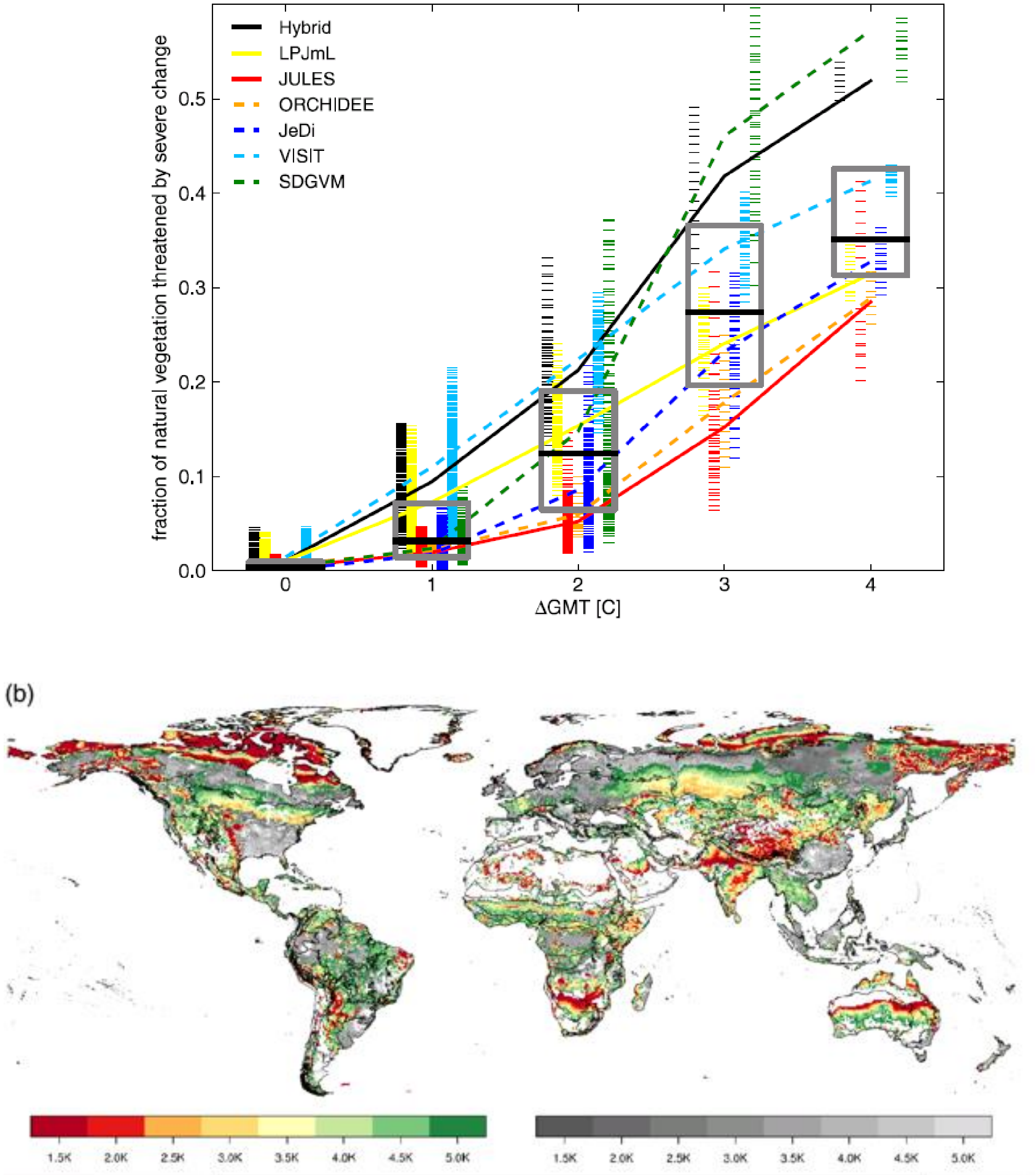


Figure 3.16: (a) Fraction of global natural vegetation (including managed forests) at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems, models, global climate change models

and Representative Concentration Pathways (RCPs). The colours represent the different ecosystem models, which are also horizontally separated for clarity. Results are collated in unit-degree bins, where the temperature for a given year is the average over a 30-year window centred on that year. The boxes span the 25th and 75th percentiles across the entire ensemble. The short, horizontal stripes represent individual (annual) data points, the curves connect the mean value per ecosystem model in each bin. The solid (dashed) curves are for models with (without) dynamic vegetation composition changes. Source: (Warszawski et al., 2013) (b) Threshold level of global temperature anomaly above pre-industrial levels that leads to significant local changes in terrestrial ecosystems. Regions with severe (coloured) or moderate (greyish) ecosystem transformation; delineation refers to the 90 biogeographic regions. All values denote changes found in >50% of the simulations. Source: (Gerten et al., 2013). Regions coloured in dark red are projected to undergo severe transformation under a global warming of 1.5°C while those coloured in light red do so at 2°C; other colors are used when there is no severe transformation unless global warming exceeds 2°C. Note: 1 K = 1ºC

3.4.3.2 Changes in phenology

Advancement in spring phenology of 2.8 ± 0.35 days per decade has been observed in plants and animals in most Northern Hemisphere ecosystems in recent decades (between 30°N and 72°N), and this has been attributed to changes in climate *(high confidence)* (Settele et al., 2014). The rates of change are particularly rapid in the Arctic zone in relation with higher local warming (Oberbauer et al., 2013), but in tropical forests, the phenology changes rather respond to moisture stress (Zhou et al., 2014). While a full review cannot be included here, trends consistent with this earlier finding continue to be detected, including in the flowering times of plants (Parmesan and Hanley, 2015), in the dates of egg laying and migration in birds (newly in China, Wu and Shi, 2016), in the emergence dates of butterflies (Roy et al., 2015), and in the seasonal greening-up of vegetation as detected by satellites (i.e. in the Normalised Difference Vegetation Index, NDVI, Piao et al., 2015).

The potential for de-coupling of species-species interactions due to differing phenological responses to climate change is well established (Settele et al., 2014) for example for plants and their insect pollinators (Willmer, 2012; Scaven and Rafferty, 2013). Now, mid-century projections of plant and animal phenophases in UK (Thackeray et al., 2016) clearly indicate that the timing of phenological events could change more for primary consumers (6.2 days earlier on average) than for higher trophic levels (2.5-2.9 days earlier on average), indicating the potential for phenological mismatch and associated risks for ecosystem functionality in the future, associated with global warming of 2.1-2.7°C above pre-industrial; while differing responses could alter community structure in temperate forests (Roberts et al., 2015). Here, the temperate forest phenology is projected to gain 14.3 days in the near term (2010-2039) and 24.6 days in the medium term (2040-2069), so in first approximation the difference between 2°C and 1.5°C global warming is about 10 days (Roberts et al., 2015). This phenological plasticity is not always adaptive and must be taken cautiously (Duputié et al., 2015), due to accompanying changes in climate variability (risk of frost damage for plants or earlier emergence of insects resulting in mortality during cold spells). Another adaptative response for the plants is expanding their range with increased vigor and altered herbivore resistance in their new range, analogous to invasive plants (Macel et al., 2017).

In summary, limiting warming to 1.5°C as compared with 2°C may avoid a few days of advance in spring phenology and hence decrease the risks of loss of ecosystem functionality due to phenological mismatch between trophic levels, and also of maladaptation coming from the sensitivity of many species to increased climate variability. Nevertheless, this difference between 1.5°C and 2°C warming might be limited for plants able to expand their range.

3.4.3.3 Changes in species range, abundance and extinction

AR5 (Settele et al., 2014) concluded that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming: approximately 17 km per decade poleward and 11 m up in altitude per decade. Recent trends confirm this finding, for example the spatial and interspecific variance in bird populations in Europe and the North America since 1980 were found to be well-predicted by trends in climate suitability (Stephens et al., 2016). Further, a recent meta-analysis of 27 studies concerning a total of 976 species (Wiens, 2016) found that 47% of local extinctions (extirpations) reported across the globe during the 20th century could be attributed to climate change, is significantly higher in tropical regions, for animals and in freshwater habitats. IUCN (2017) lists 305 terrestrial animal and plant species from Pacific island developing nations as being threatened by climate change and severe weather. Due to lags in the responses of some species to climate change, shifts in insect pollinator ranges may result in novel assemblages with unknown implications for biodiversity and ecosystem function (Rafferty, 2017).

Warren et al. (2013) simulated climatically determined geographic range loss under 2°C and 4°C global warming for 50,000 plant and animal species accounting for uncertainty in climate projections and for the potential ability of species to disperse naturally in an attempt to track their geographically shifting climate envelope. This earlier study has now been updated and expanded to incorporate 105,501 species, including 19,848 insects, and finds that a warming of 2°C by 2100 would lead to projected bioclimatic range losses of >50% in 18 (6-35)% of 19,848 insects species, 8 (4-16)% of 12,429 vertebrate species, and 16 (9-28)% of 73,224 plant species studied (Warren et al., 2018b). At 1.5°C this falls to 6 (1-18) % insects, 4 (2-9)% vertebrates and 8 (4-15)% plants. Hence the number of insect species projected to lose over half their geographic range is reduced by two-thirds when warming is limited to 1.5°C as compared with 2°C, while the number of vertebrate and plant species projected to lose over half their geographic range is halved (Warren et al., 2018b). This is consistent with estimates made from an earlier study suggesting that range losses at 1.5°C were significantly lower for plants than those at 2°C warming (Smith et al., 2018). It should be noted that at 1.5°C warming, and if species' ability to disperse naturally to track their preferred climate geographically is inhibited by natural or anthropogenic obstacles, there still remain 10% amphibians, 8% reptiles, 6% mammals, 5% birds, 10% insects and 8% plants which are projected to lose over half their range, while species on average lose 20-27% of their range (Warren et al., 2018b). Since bird and mammal species can disperse more easily, a small proportion can gain range as climate changes, but even at 1.5°C warming the total range loss integrated over all birds and mammals greatly exceeds the integrated range gain (Warren et al., 2018b).

A number of caveats are noted in studies projecting climatic range change, since the approach does not incorporate the effects of extreme weather events and the role of interactions between species; and trophic interactions may locally counteract range expansion of species towards higher altitudes (Bråthen et al., 2018). Also, there is the potential for highly invasive species to become established in new areas as the climate changes (Murphy and Romanuk, 2014), but there is no literature that quantifies this potential for 1.5°C warming.

Pecl et al. (2017) summarize at the global level the consequences (for economic development, livelihoods, food security, human health and culture) of climate-change induced species redistribution and conclude that, even if anthropogenic greenhouse gas emissions stopped today, the effort for human systems to adapt to the most crucial effects of climate-driven species redistribution will be far reaching and extensive. For example, key insect crop pollinator families (Apidae, Syrphidae and Calliphoridae; i.e., bees, hoverflies and blowflies) are shown to retain significantly greater geographic ranges under 1.5°C global warming as compared with 2°C (Warren et al., 2018b). In some cases when species (such as pest and disease species) move into areas which become newly climatically suitable they may become invasive or harmful to human or natural systems (Settele et al., 2014). Some studies are beginning to locate 'refugial' areas where the climate remains suitable in the future for most of the species currently present: for example, (Smith et al., 2018) estimate that 5.5-14% more of the globe's terrestrial land area can act as climatic refugia for plants under 1.5°C warming as compared to 2°C.

There is no literature that directly estimates the proportion of species at increased risk of global (as opposed to local) commitment to extinction as a result of climate change as this is difficult to quantify. However, it is possible to compare the proportions of species at risk of very high range loss in Figure 2 in Warren et al. (2018b) where discernibly lower number of terrestrial species projected to lose over 90% of their range at 1.5°C global warming as compared with 2°C; a link between very high levels of range loss and greatly increased extinction risk may be inferred (Urban, 2015). Hence limiting global warming to 1.5°C as compared with 2°C would be expected to reduce both range losses and associated extinction risks in terrestrial species (*medium confidence*).

3.4.3.4 Changes in ecosystem function, biomass and carbon stocks

WGII AR5 (Settele et al., 2014) concluded that there is *high confidence* that net terrestrial ecosystem productivity at the global scale has increased relative to the preindustrial era and that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, yet there is no clear, consistent signal of a climate change contribution. In the northern latitudes, the productivity change has a lower velocity than the warming possibly because of lack of resource and vegetation acclimation mechanisms (M. Huang et al., 2017). Biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (*high confidence*), but are vulnerable to loss to the atmosphere as a result of projected increases in the intensity of storms, wildfires, land degradation and pest outbreaks (Settele et al., 2014; Seidl et al., 2017). This would contribute to a decrease in the terrestrial carbon sink. Anderegg et al. (2015) show that the total ecosystem respiration, at the global scale, has increased in response to increase of nighttime temperature (1 PgC $year^{-1}$ $°C^{-1}$, p=0.02).

The increase of total ecosystem respiration in spring and autumn, in relation with higher temperature, may turn boreal forest from carbon sink to carbon source (Hadden and Grelle, 2016). This is confirmed for the boreal peatlands where increased temperature may diminish the carbon storage and compromise the stability of the peatland (Dieleman et al., 2016). In addition, J. Yang et al. (2015) showed that fires reduce carbon sink of global terrestrial ecosystems by 0.57 PgC yr^{-1} in ecosystems with high carbon storage, such as peatlands and tropical forests. Consequently for adaptation purposes, it is necessary to enhance carbon sinks, especially in forests which are prime regulators within the water, energy and carbon cycles (Ellison et al., 2017). Soil is also a key compartment for carbon sequestration (Lal, 2014; Minasny et al., 2017) depending on the net biome productivity and the soil quality (Bispo et al., 2017).

The AR5 assessed that there remains large uncertainty in the land carbon cycle behavior in the future (Ciais et al., 2013), with most, but not all, CMIP5 models simulating continued terrestrial carbon uptake under all four RCP scenarios (Jones et al., 2013). Disagreement between models outweighs differences between scenarios even up to 2100 (Hewitt et al., 2016; Lovenduski and Bonan, 2017). Increased CO_2 will drive further increases in land carbon sink (Ciais et al., 2013; Schimel et al., 2015) which could persist for centuries(Pugh et al., 2016). Nitrogen, phosphorus and other nutrients, will limit terrestrial carbon cycle response to both CO_2 and climate (Goll et al., 2012; Yang et al., 2014; Wieder et al., 2015; Zaehle et al., 2015; Ellsworth et al., 2017). Climate change may accelerate plant uptake of carbon (Gang et al., 2015), but also decomposition processes (Todd-Brown et al., 2014; Koven et al., 2015; Crowther et al., 2016). Ahlström et al. (2012) found a net loss of carbon in extra-tropics and largest spread across model results in the tropics. The net effect of climate change is to reduce the carbon sink expected under CO_2 increase alone (Settele et al., 2014). Friend et al. (2014) found substantial uptake of carbon by vegetation under future scenarios when considering the effects of both climate change and elevated CO_2.

There is little published literature examining modelled land carbon changes specifically under 1.5°C warming, but here existing CMIP5 models and published data are used to draw some conclusions. For systems with significant inertia, such as vegetation or soil carbon stores, changes in carbon storage will depend on the rate of change of forcing and so are dependent on the choice of scenario (Jones et al., 2009; Ciais et al., 2013; Sihi et al., 2017). To avoid legacy effects of the choice of scenario we focus on the response of Gross Primary Productivity (GPP) – the rate of photosynthetic carbon uptake – by the models, rather than by changes in their carbon store.

Figure 3.16 shows different responses of the terrestrial carbon cycle to climate change in different regions. The models show a consistent response of increased GPP in temperate latitudes of approximately 2.0 GtC yr^{-1} K^{-1}. Similarly Gang et al. (2015) also projected a robust increase in Net Primary Productivity (NPP) of temperate forests, however Ahlström et al. (2012) show this could be offset or reversed by increases in decomposition. Globally, GPP increases or remains approximately unchanged in most models (Hashimoto et al., 2013). This is confirmed by Sakalli et al. (2017) for Europe using Euro-Cordex regional models under a 2°C global warming for the 2034-2063 period (storage will increase by +5% in soil and by +20% in vegetation). But using the same models, Jacob et al. (2018) showed that limiting warming to +1.5°C instead of +2°C avoids an increase in ecosystem vulnerability of 40-50%.

At the global scale, linear scaling is acceptable for net primary production, biomass burning, and surface runoff and impacts on terrestrial carbon storage will be greater at 2°C than at 1.5°C (Tanaka et al., 2017). If global CO_2 concentrations and temperatures stabilise, or peak and decline, then both land and ocean carbon sinks – which are primarily driven by the continued increase in atmospheric CO_2 – will also decline, and may even reverse (Jones et al., 2016) and so if a given amount of anthropogenic CO_2 is removed from the atmosphere, an equivalent amount of land and ocean anthropogenic CO_2 will be released to the atmosphere (Cao and Caldeira, 2010).

In conclusion**,** ecosystem respiration will increase with temperature, reducing soil carbon storage. Soil carbon storage will be larger if global warming is restricted to 1.5°C, although some of the associated changes will be countered by enhanced gross primary production due to elevated CO_2 concentration (i.e. the ‘fertilization effect’) and higher temperatures, especially at medium and high latitudes (*medium confidence*).

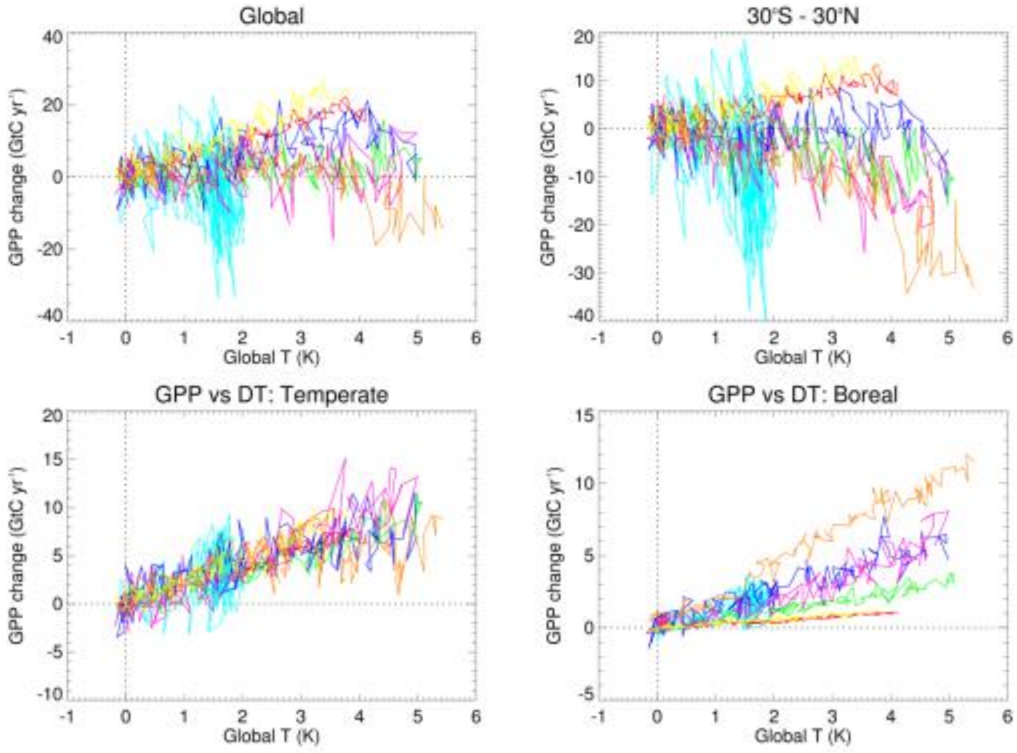


Figure 3.17: The response of terrestrial productivity (Gross Primary Productivity, GPP) to climate change, globally (top left) and for three latitudinal regions: 30°S-30°N; 30-60°N and 60-90°N. Data was used from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (http://cmip-pcmdi.llnl.gov/cmip5/). Seven Earth System Models used: Norwegian Earth System Model (NorESM-ME, yellow); Community Earth System Model (CESM, red); Institute Pierre Simon Laplace (IPLS)-CM5-LR (dark blue); Geophysical Fluid Dynamics Laboratory (GFDL, pale blue); Max Plank Institute-Earth System Model (pink); Hadley Centre New Global Environmental Model 2-Earth System (HadGEM2-ES, orange); Canadian Earth System Model 2 (CanESM2, green). Results are differences in GPP from model simulations with (‘1pctCO_2’) and without (‘esmfixclim1’) the effects of climate change. Data are plotted against global mean temperature increase above pre-industrial from simulations with 1% per year increase in CO_2 (‘1pctCO_2’).

3.4.3.5 Regional and ecosystem-specific risks

A large number of threatened systems including mountain ecosystems, highly biodiverse tropical wet and dry forests, deserts, freshwater systems and dune systems are assessed in the AR5. These include Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succuluent Karoo areas of South Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, it has been shown that impacts accrue with greater warming and thus impacts at 2°C would be expected to be greater than those at 1.5°C (*medium confidence*).

The **High Arctic region**, with tundra-dominated landscapes, has warmed more than the global average over the last century (Settele et al., 2014) (Section 3.3). The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Yang et al., 2016). Both of these processes facilitate conditions for the establishment of woody species in tundra areas. Arctic terrestrial ecosystems are being disrupted by delays in winter onset and mild winters associated with global warming (Cooper, 2014) (*high confidence*). Observational constraints suggest stabilisation at 1.5°C would avoid approximately 2 million km^2 of permafrost compared with stabilisation at 2°C (Chadburn et al., 2017), but the timescale for release of thawed carbon as CO_2 or CH_4 is likely to be many centuries (Burke et al., 2017). In Northern Eurasia, the growing season length is projected to lengthen by about 3-12 days for 1.5°C and 6-16 days for 2°C (*medium confidence*) (Zhou et al., 2018). Aalto et al. (2017) predict a 72% reduction of cryogenic land surface processes in Northern Europe for RCP2.6 in 2040-2069 (corresponding to a global warming of approximately 1.6°C), with only slightly larger losses for RCP4.5 (2°C global warming). Long-term absence of snow reduces vascular plant cover in the understorey by 92%, reduces fine root biomass by 39% (Blume-Werry et al., 2016)

Projected impacts on **forests** as climate changes include increases in the intensity of storms, wildfires and pest outbreaks (Settele et al., 2014), potentially leading to forest dieback (*medium confidence*). Warmer and drier conditions particularly facilitate fire, drought and insect disturbances, while warmer and wetter conditions increase disturbances from wind and pathogens (Seidl et al., 2017). Including disturbances in the simulations may influence productivity changes of European forests in response to climate change (Reyer et al., 2017b). There is additional evidence for attribution of increased forest fire in North America to anthopogenic climate change during 1984-2015, via the mechanism of increasing fuel aridity almost doubling the western US forest fire area compared to what would have been expected in the absence of climate change (Abatzoglou and Williams, 2016). This projection is in line with projected fire risks, which indicate that fire frequency would increase over 37.8% of global land areas during 2010-2039 (Moritz et al., 2012), corresponding to a global warming level of approximately 1.2 ºC; as compared with over 61.9% of the global land area in 2070-2099, corresponding to a warming of approximately 3.5ºC[2] (Table 26-1 in Romero-Lankao et al., 2014) also indicated significantly lower wildfire risks in North America for near term warming (2030-2040, which may be considered a proxy for 1.5ºC) than at 2ºC (*high confidence*).

Amazon tropical forest has been shown to be close to its climatic threshold (Hutyra et al., 2005), but this threshold may move under elevated CO_2 (Good et al., 2011). Future changes in rainfall, especially dry season length, will determine the response of Amazon forest to climate change (Good et al., 2013). The forest may be especially vulnerable to combined pressure from multiple stressors: namely changes in climate and continued anthropogenic disturbance (Borma et al., 2013; Nobre et al., 2016). Modelling (Huntingford et al., 2013) and observational constraints (Cox et al., 2013) suggest large scale forest dieback less likely than suggested under early coupled modelling studies (Cox et al., 2000; Jones et al., 2009). Nobre et al. (2016) estimate climate threshold of 4°C and a deforestation threshold of 40%.

In many places around the world the **savanna** boundary is moving into former grasslands with woody encroachment and tree cover and biomass has increased over the past century due to changes in land management, rising CO_2, climate variability and change (often in combination) (Settele et al., 2014). For the plant species in the Mediterranean region, shift in phenology, range contraction, health decline have been observed because of precipitation decrease and temperature increase (*medium confidence*) (Settele et al., 2014). Recent studies using independent complementary approaches now show that there is a regional-scale

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[2] FOOTNOTE: The approximate temperatures are derived from (Figure 10.5 panel A, Meehl et al. 2007), which indicates an ensemble average projection of 0.7 ºC or 3ºC above 1980-1999, which is itself 0.5ºC above pre-industrial) (Figure 10.5 panel A, Meehl et al. 2007).

threshold in the Mediterranean region between 1.5 ºC and 2ºC warming (Guiot and Cramer, 2016; Schleussner et al., 2016b). Guiot and Cramer (2016) finds that only if global warming is constrained to 1.5ºC can biome shifts unprecedented in the last 10,000 years be avoided (*medium confidence*) – whilst 2ºC warming results in a decrease of 12-15% of the Mediterranean biome area. The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and drier winters. It is projected to lose about 20%, 45% and 80% of its current suitable climate area under 1°C, 2°C and 3°C of global warming compared to 1961-1990, respectively (*high confidence*) (Engelbrecht and Engelbrecht, 2016). In Australia, an increase in the density of trees and shrubs at the expense of grassland species - is occurring across all major Australian ecosystems and is projected to be amplified (NCCARF, 2013). In Central America, Lyra et al. (2017) showed that with a global warming of 3°C in 2100, the tropical rainforest biomass will be reduced by more than 50% with large replacement by savanna and grassland. With a global warming close to 1.5°C in 2050, a biomass decrease 20% is projected (Lyra et al., 2017). If a linear response is assumed, with a global warming of 2°C, we deduced that the decrease may reach 30% (*medium confidence*).

Freshwater ecosystems are considered to be among the most threatened on the planet (Settele et al., 2014). Although peatlands cover only about 3% of the land surface, they hold one-third of the world's soil carbon stock (400 to 600 Pg) (Settele et al., 2014). In the Congo Basin (Dargie et al., 2017) and in the Amazonian Basin (Draper et al., 2014), the peatlands store the equivalent of the tropical forest. But this stored carbon is vulnerable to land use change and future risk of drought, for example in northeast Brazil (*high confidence*) (Figure 3.12, Section 3.3.4.2). At the global scale, they are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Magrin et al., 2014). Wetland salinization, a widespread threat to the structure and ecological functioning of inland and coastal wetlands, is occurring at a high rate and large geographic scale (Herbert et al., 2015). Settele et al. (2014) find that rising water temperatures are projected to lead to shifts in freshwater species distributions and worsen water quality. Some of these ecosystems respond non-linearly to changes in temperature, for example it has been found that the wetland function of the Prairie Pothole region in North America is projected to decline beyond a local warming of 2ºC-3ºC above present (a 1ºC local warming, corresponding to a 0.6ºC global warming) (Johnson and Poiani, 2016). If the ratio of local to global warming remains similar for these small levels of warming, this would indicate a global temperature threshold of 1.2ºC-1.8ºC warming. Hence constraining global warming to approximately 1.5ºC warming would maintain the functioning of the prairie pothole ecosystem in terms of their productivity and biodiversity, but an 20% increase of precipitation can offset a 2°C global warming (*high confidence*) (Johnson and Poiani, 2016).

3.4.3.6 Summary of implications for ecosystem services

In summary, constraining global warming to 1.5ºC rather than 2ºC has strong benefits for terrestrial wetland ecosystems and their services (*high confidence*). These benefits include avoidance of biome transformations, species range losses, increased extinction risks (all *medium confidence*), changes in phenology (*high confidence*), together with projected increases in extreme weather events which are not yet factored into these analyses (Section 3.3) all contribute to disruption of ecosystem functioning and loss of cultural, provisioning and regulating services provided by these ecosystems to humans. Examples of such services include soil conservation (avoidance of desertification), flood control, water and air purification, pollination, nutrient cycling, some sources of food, and recreation.

3.4.4 Oceans systems

The Ocean plays a central role in regulating atmospheric gas concentrations, global temperature and climate. It is also provides habitat to a large number of organisms and ecosystems that provide goods and services that are worth trillions of USD per year (e.g., Costanza et al., 2014; Hoegh-Guldberg et al., 2015). Together with local stresses (Halpern et al., 2015), climate change poses a major threat to an increasing number of ocean ecosystems (e.g. coral reefs: *virtually certain*, WGII AR5) and consequently for many coastal communities who depend on marine resources for food, livelihoods and a safe place to live. Previous sections have described changes in the ocean that include rapid increases in ocean temperature down to at least 700 m (Section 3.3.7). Anthropogenic carbon dioxide has also decreased pH, as well as affected the concentration of ions such as carbonate (Section 3.3.10 and 3.4.4.5), over a similar depth range. Increased ocean temperature has intensified storms (Section 3.3.6), as well as expanded ocean volume and increased sea levels globally (Section 3.3.9) and decreased the extent of polar summer sea ice (Section 3.3.8), as well as the overall solubility of the ocean for oxygen (Section 3.3.10). Importantly, changes in the response to climate change rarely operate in isolation. Consequently, the effect of global warming at 1.5°C versus 2°C, must be considered in the light of multiple, interactive factors that may accumulate and interact over time to produce complex risks, hazards and impacts on human and natural systems.

3.4.4.1 Observed impacts

Physical and chemical changes to the ocean from increasing atmospheric CO_2 and other GHGs are already driving significant changes to ocean systems (*very high confidence*) and will continue to do so at 1.5^{o}C and, more so, at 2^{o}C above the pre-industrial period (Section 3.3.11). These changes have been accompanied by other changes such as ocean acidification and deoxygenation (Levin and Le Bris, 2015). Risks are already significant at current greenhouse gas concentrations and temperatures, and vary significantly between depths, location and ecosystems, with impacts being singular, interactive and/or cumulative (Boyd et al., 2015).

3.4.4.2 Warming and stratification of the surface ocean

As atmospheric greenhouse gasses have increased, the global mean surface temperature (GMST) has reached about 0.87^{o}C above the pre-industrial period, and oceans have rapidly warmed from the ocean surface to the deep sea (Hughes and Narayanaswamy, 2013; Levin and Le Bris, 2015; Yasuhara and Danovaro, 2016; Sweetman et al., 2017) (*high agreement, robust evidence;* Sections 3.3.1.2 and 3.3.7). Marine organisms are already responding to these changes by shifting their biogeographical ranges to higher, relatively cooler latitudes, at rates that range from 0 to 40 km yr^{-1} (Burrows et al., 2014; Chust et al., 2014b; Bruge et al., 2016; Poloczanska et al., 2016) which has consequently affected the structure and function of the ocean, along with its biodiversity and food webs (*high agreement, robust evidence*). Movements of organisms does not necessarily equate to the movement of entire ecosystems. For example, species of reef-building corals have been observed to shift their geographic ranges yet this has not resulted in the shift of entire coral ecosystems (Woodroffe et al., 2010; Yamano et al., 2011) (*medium agreement, medium evidence*). In the case of ‘less mobile’ ecosystems (e.g. coral reefs, kelp forests, intertidal communities), shifts in biogeographical ranges may be limited, with mass mortalities and disease outbreaks increasing in frequency as the exposure to extreme temperatures have increased (Hoegh-Guldberg, 1999; Garrabou et al., 2009; Rivetti et al., 2014; Maynard et al., 2015; Krumhansl et al., 2016; Hughes et al., 2017b) (*high agreement, robust evidence*; see also Box 3.4). These trends will become more pronounced at 1.5^{o}C, and more so at 2^{o}C, above the preindustrial period (Hoegh-Guldberg et al., 2007; Donner, 2009; Frieler et al., 2013; Horta E Costa et al., 2014; Verges et al., 2014; Vergés et al., 2016; Zarco-Perello et al., 2017) and are *likely* to result in decreases in marine biodiversity at the equator and correspondingly increases in biodiversity at higher latitudes (Cheung et al., 2009; Burrows et al., 2014).

While the impacts of relocating species are mostly negative for human communities and industry, there are examples of short-term gains. Fisheries, for example, may expand temporarily at high latitudes in the northern hemisphere as the extent of summer sea ice recedes and NPP increases (*medium agreement, medium evidence;* Cheung et al., 2010; Lam et al., 2016; Weatherdon et al., 2016). High latitude fisheries are not only influenced by the effect of temperature on NPP but are also strongly influenced by the direct effects of changing temperatures on fish and fisheries themselves (Barange et al., 2014; Pörtner et al., 2014; Cheung et al., 2016b; Weatherdon et al., 2016; Section 3.4.4.9). Temporary gains in the productivity of high latitude fisheries are offset against a growing number of examples from low and mid latitudes where increases in sea temperature are driving decreases in NPP, due to the direct effects of elevated temperatures and/or reduced ocean mixing from reduced ocean upwelling (increased stratification; *low to medium confidence;* (Cheung et al., 2010; Ainsworth et al., 2011; Lam et al., 2012, 2014, 2016; Bopp et al., 2013; Boyd et al., 2014; Chust et al., 2014; Hoegh-Guldberg et al., 2014; Poloczanska et al., 2014; Pörtner et al., 2014; Signorini et al., 2015). Reduced ocean upwelling has implications for millions of people and industries that depend on fisheries for food and livelihoods (Bakun et al., 2015; FAO, 2016; Kämpf and Chapman, 2016) although there is *low confidence* in the projection of the size of the consequences at 1.5°C *(low agreement, limited evidence)*. It is also important to appreciate these changes in the context of large-scale ocean processes such as the ocean carbon pump. The export of organic carbon to deeper layers of the ocean increases as NPP changes in the surface ocean, for example, with implications for food webs and oxygen levels (Boyd et al., 2014; Sydeman et al., 2014; Altieri and Gedan, 2015; Bakun et al., 2015; Boyd, 2015).

3.4.4.3 Storms, inundation, and coastal run-off

Storms, wind, waves and inundation can have highly destructive impacts on ocean and coastal ecosystems as well as the human communities that depend on them (IPCC, 2012; Seneviratne et al., 2012). The intensity of tropical cyclones across the world's ocean has increased although the overall number of tropical cyclones has decreased (Elsner et al., 2008; Holland and Bruyère, 2014) (*medium agreement, limited evidence, hence low confidence;* Section 3.3.6). The direct force of wind and waves associated with larger storms, along with changes in storm direction, increase the risks of physical damage to coastal communities as well as ecosystems such as mangroves (*medium agreement, limited evidence*; Long et al., 2016; Primavera et al., 2016; Villamayor et al., 2016; Cheal et al., 2017) and tropical coral reefs (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017). These changes are associated with increases in maximum wind speed, wave height, and the inundation, although trends in these variables vary from region to region (Section 3.3.5, Table 3.2). In some cases, this can lead to increased exposure to related impacts (reduced water quality and sediment run-off; *high agreement, medium evidence*) (Brodie et al., 2012; Wong et al., 2014; Anthony, 2016; AR5-Table 5.1).

Sea level rise also amplifies impacts from observed sea level rise (Section 3.3.9) with robust evidence that storm surge and damage are already penetrating farther inland than a few decades ago, changing conditions for coastal ecosystems and human communities, especially Small Island Developing States (SIDS, Box 3.5) and low-lying coastal communities with issues such as storm surges transforming coastal areas (Section 3.4.5; Brown et al., 2018a). Changes in the frequency of extreme events, such as more intense storms, have the potential (along with other factors such as disease, feed web changes, invasive organisms, and heat stress mortality;(Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016; Clements et al., 2017) to overwhelm the capacity for natural and human systems to recover following disturbances, as has recently been seen for centrally important ecosystems such as tropical coral reefs (Box 3.4), which have changed from coral-dominated ecosystems to asemblages dominated by other organisms such as seaweeds, with changes in associated organisms and ecosystem services (De'ath et al., 2012; Bozec et al., 2015; Cheal et al., 2017; Hoegh-Guldberg et al., 2017; Hughes et al., 2017a, 2017b) (*high agreement, medium evidence*). The impacts of storms are amplified by sea level rise (Section 3.4.5) with substantial challenges today and in the future for cities, delta, and small islands in particular (Section 3.4.5.2 - 3.4.5.4) as well as coastlines and ecosystems (Section 3.4.5.5 – 3.4.5.7).

3.4.4.4 Ocean circulation

The movement of water within the ocean is essential to its biology and ecology as well as the circulation of heat, water and nutrients around the planet (Section 3.3.7). The movement of these factors drives local and regional climates as well as primary productivity and food production. Firmly attributing recent changes in the strength and direction of ocean currents to climate change, however, is complicated by long-term patterns and variability (e.g., Pacific Decadal Oscillation, PDO, Signorini et al., 2015) and the lack of records that match the long-term nature of these changes in many cases (Lluch-Cota et al., 2014). An assessment of literature since the AR5 (Sydeman et al., 2014), however, has concluded that (overall) upwelling-favourable winds have intensified in the California, Benguela, and Humboldt upwelling systems, but have weakened in the Iberian system, over 60 years of records (1946-2012, Section 3.3.7) (*medium agreement, medium evidence*) and are neutral for the Canary upwelling system. These conclusions are consistent with the developing consensus that wind driving upwelling systems are likely to intensify under climate change for most systems (Sydeman et al., 2014; Bakun et al., 2015; Di Lorenzo, 2015) with potentially positive and negative consequences (Bakun et al., 2015).

Changes in ocean circulation can have profound impacts on marine ecosystems by connecting regions and facilitating the entry and establishment of species in areas where they were unknown before (e.g., 'tropicalization' of temperate ecosystems, (Wernberg et al., 2012; Verges et al., 2014; Vergés et al., 2016; Zarco-Perello et al., 2017) as well as the arrival of novel disease agents (Burge et al., 2014; Maynard et al., 2015; Weatherdon et al., 2016) (*medium agreement, limited evidence*). For example, the sea urchin, *Centrostephanus rodgersii*, a herbivore, has been able to reach Tasmania, where it was previously unknown, from the Australian mainland due to a strengthening of the East Australian Current (EAC; *high agreement, robust evidence*) (Ling et al., 2009). As a consequence, the distribution and abundance of kelp forests has rapidly decreased with implications for fisheries and other ecosystem services (Ling et al., 2009). These risks to marine ecosystems are likely to become greater at 1.5^{o}C and further so at 2^{o}C (*medium agreement, medium evidence*, Cheung et al., 2009; Pereira et al., 2010; Pinsky et al., 2013; Burrows et al., 2014).

Changes to ocean circulation can have even larger impacts in terms of scale and impacts. Weakening of the Atlantic Meridional Overturning Circulation (AMOC), for example, is projected to be highly disruptive to natural and human systems as the delivery of heat to higher latitudes via this current system is reduced. Evidence of a slowdown of AMOC has increased since AR5 (Smeed et al., 2014; Rahmstorf et al., 2015a, 2015b; Kelly et al., 2016) yet a strong causal connecton to climate change is missing (*low agreement, limited evidence*; Section 3.3.7).

3.4.4.5 Ocean acidification

Ocean chemistry encompasses a wide range of phenomena and chemical species of which many are integral to the biology and ecology of the ocean (Section 3.3.10) (Gatusso et al., 2014; Hoegh-Guldberg et al., 2014;

Pörtner et al., 2014; Gattuso et al., 2015). While changes to ocean chemistry are likely to be centrally important, the literature on how climate change might influence ocean chemistry over the short and long term is limited (*high agreement, limited evidence*). By contrast, numerous risks from the specific changes associated with ocean acidification have been identified (Dove et al., 2013; Kroeker et al., 2013; Pörtner et al., 2014; Gattuso et al., 2015; Albright et al., 2016) with the consensus that resulting changes to the carbonate chemistry of seawater are having, and are likely to have, fundamental and substantial impacts on a wide variety of organisms and hence ecosystem processes (high agreement, robust evidence) Organisms with shells and skeletons made out of calcium carbonate are particularly at risk, as are the early life history stages of a broad number of organisms and processes such as de-calcification, although some taxa that did not show the same sensitivity to changes in CO_2, pH and carbonate concentrations (Dove et al., 2013; Fang et al., 2013; Kroeker et al., 2013; Pörtner et al., 2014; Gattuso et al., 2015). These risks vary with latitude (i.e. greatest changes at high latitudes) and depths, with the latter involving the rapid shoaling of the aragonite saturation horizon (i.e. where concentrations of calcium and carbonate fall below the saturation point for aragonite, a key crystalline form of calcium carbonate) as CO_2 penetrates deeper as concentrations in the atmosphere increase over time. Under many models and scenarios, the aragonite saturation reaches the surface from 2030 onwards and with poorly understood impacts and consequences for ocean organisms, ecosystems and people (Orr et al., 2005; Roberts et al., 2008; Hauri et al., 2016).

It is also difficult to reliably separate the impacts of ocean warming and acidification, especially under field settings. Ocean waters have increased in sea surface temperature (SST) by approximately 0.9°C and decreased in pH by 0.11 units since 1870-1899 ('preindustrial', Table 1 in Gattuso et al., 2015; Bopp et al., 2013). As CO_2 concentrations continue to increase along with other GHGs, pH will decrease linearly with SST, reaching 1.72°C and a decrease of 0.22 pH units (under RCP4.5) relative to the preindustrial period. These changes are likely to continue given the linear correlation of SST and pH. Experimental manipulation of CO_2, temperature and consequently acidification indicate that these impacts will continue to increase in size and scale as CO_2 and SST continue to increase in tandem (Dove et al., 2013; Fang et al., 2013; Kroeker et al., 2013).

While many risks have been defined through laboratory and mesocosm experiments, there is a growing list of impacts from the field (*medium agreement, medium evidence*) that include community scale impacts on bacterial assemblages and processes (Endres et al., 2014), coccolithophores (K.L.S. Meier et al., 2014), pteropods and polar food webs (Bednaršek et al., 2012, 2014), phytoplankton (Moy et al., 2009; Riebesell et al., 2013; Richier et al., 2014), benthic ecosystems (Hall-Spencer et al., 2008; Linares et al., 2015), seagrass (Garrard et al., 2014), macroalgae (Webster et al., 2013; Ordonez et al., 2014), as well as excavating sponges, endolithic microalgae, and reef-building corals (Dove et al., 2013; Reyes-Nivia et al., 2013; Fang et al., 2014), and coral reefs (Fabricius et al., 2011; Allen et al., 2017; Box 3.4). Some ecosystems such as bathyal areas (200–3000 m) are likely to undergo significant reductions in pH by the year 2100 (0.29 to 0.37 pH units) yet evidence is currently limited despite the potential importance of these areas (Hughes and Narayanaswamy, 2013; Sweetman et al., 2017) (*medium agreement, limited evidence*).

3.4.4.6 Deoxygenation

Oxygen in the ocean is maintained by a series of processes including ocean mixing, photosynthesis, respiration and solubility (Boyd et al., 2014, 2015; Pörtner et al., 2014; Breitburg et al., 2018). Concentrations of oxygen in the ocean are declining (*high agreement, robust evidence*) due to three main factors that relate to climate change: (1) heat related stratification of the water column (less ventilation and mixing), (2) reduced oxygen solubility as ocean temperature increases, and (3) impacts of warming on biological processes that produce or consume oxygen such as photosynthesis and respiration (*high agreement, robust evidence*) (Bopp et al., 2013; Pörtner et al., 2014; Altieri and Gedan, 2015; Deutsch et al., 2015; Schmidtko et al., 2017; Shepherd et al., 2017; Breitburg et al., 2018). Similarly, a range of processes (Section 3.4.11) are also acting synergistically, including non-climate change factors such as run-off and coastal eutrophication (e.g. from coastal farming, intensive aquaculture) leading to increased phytoplankton productivity, which increase the metabolic rate of coastal microbial communities by supplying greater amounts of organic carbon (Altieri and Gedan, 2015; Bakun et al., 2015; Boyd, 2015). Deep sea areas are likely to experience some of the greatest challenges as abyssal seafloor habitats in areas of deep-water formation experiencing decreased water column oxygen concentrations by as much as 0.03 mL L^{-1} by 2100 (Levin and Le Bris, 2015; Sweetman et al., 2017).

The number of 'dead zones' (areas where oxygenic waters have been replaced by hypoxic conditions) has been growing strongly since the 1990s (Diaz and Rosenberg, 2008; Altieri and Gedan, 2015; Schmidtko et al., 2017). While attribution can be difficult due to the complexity of the climate and non-climate change-related processes involved, some impacts related to deoxygenation (*medium agreement, limited evidence*) include the expansion of the Oxygen Minimum Zones (OMZ) (Turner et al., 2008; Carstensen et al., 2014; Acharya and Panigrahi, 2016; Lachkar et al., 2018), physiological impacts (Pörtner et al., 2014), and mortality and/or displacement oxygenic organisms such as fish (Hamukuaya et al., 1998; Thronson and Quigg, 2008; Jacinto, 2011)and invertebrates (Hobbs and Mcdonald, 2010; Bednaršek et al., 2016; Seibel, 2016; Altieri et al., 2017). Deoxygenation interacts with ocean acidification to present substantial and combined challenges for fisheries and aquaculture (*medium agreement, medium evidence*) (Hamukuaya et al., 1998; Bakun et al., 2015; Rodrigues et al., 2015; Feely et al., 2016; S. Li et al., 2016; Asiedu et al., 2017a; Clements et al., 2017; Clements and Chopin, 2017; Breitburg et al., 2018). Deoxygenation is expected to have greater impacts as ocean warming and acidification increase (*high agreement, medium evidence*), with most impacts being larger and more numerous than today (e.g. greater challenges for aquaculture and fisheries from hypoxia), and the number of hypoxic areas continue to increase. Risks from deoxygenation are *virtually certain* to increase as warming continues although our understanding of risks at 1.5^{o}C versus 2^{o}C is incomplete (*high agreement, limited evidence*). Reducing coastal pollution and consequently the export of organic carbon into deep benthic habitats is highly likely to reduce the decline in the oxygen concentrations in coastal waters and in hypoxic areas in general (Breitburg et al., 2018).

3.4.4.7 Loss of sea ice

Sea ice has been a persistent feature of the planet's polar regions (Polyak et al., 2010) and is central to marine ecosystems, people (e.g. food, culture and livelihoods) and industries (e.g. fishing, tourism, oil and gas, and shipping). Summer sea ice in these regions (e.g. Arctic, Antarctic and Southern Ocean), however, has been retreating rapidly in recent decades (Section 3.3.8) with an assessment of the literature revealing that a fundamental transformation is occurring in polar organisms and ecosystems driven by climate change (*high agreement, robust evidence*) (Larsen et al., 2014). These changes are strongly affecting people in the Arctic who have close relationships with sea ice and associated ecosystems, and are facing major adaptation challenges as a result of sea level rise, coastal erosion, the accelerated thawing of permafrost, changing ecosystems and resources, and many other issues (Ford, 2012; Ford et al., 2015).

There is considerable and compelling evidence that a further increase of 0.5°C from today in average global surface temperature will lead to multiple levels of impact on a variety of organisms - from phytoplankton to marine mammals some of the most dramatic changes occurring in the Arctic Ocean and Western Antarctic Peninsula (Turner et al., 2014, 2017b; Steinberg et al., 2015; Piñones and Fedorov, 2016).

The impacts of climate change on sea ice is part of the focus of the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), due to be released in 2019. Therefore, without intending to be comprehensive, there are a range of responses to the loss of sea ice that are occurring and are likely to increase at 1.5°C and 2°C of global warming. Photosynthetic communities such macroalgae, phytoplankton, and microalgae dwelling on the underside of floating sea ice are changing due to increased temperatures, light, and nutrient levels. As sea ice retreats, mixing of the water column increases, and phototrophs have increased access to seasonally high levels of solar radiation (Dalpadado et al., 2014; W.N. Meier et al., 2014) (*medium agreement, medium evidence*). These changes are *very likely* to stimulate fisheries productivity in high latitude regions by mid-century (Cheung et al., 2009, 2010, 2016b; Lam et al., 2014), with evidence of this is already happening for several fisheries species in high latitude regions in the northern hemisphere such as the Bering Sea, although these 'positive' impacts may be relatively short-lived (Hollowed and Sundby, 2014; Sundby et al., 2016). In addition to the impact of climate change on fisheries via impacts on NPP, there are also direct effects of temperature on fish, which may have a range of impacts (Pörtner et al., 2014). Sea ice in Antarctica is undergoing changes that exceed those seen in the Arctic (Maksym et al., 2011; Reid et al., 2015) with increases in sea ice coverage in the western Ross Sea being accompanied by strong decreases in the Bellingshausen and Amundsen seas (Hobbs et al., 2016). While Antarctica is not permanently populated, the ramifications of changes to the productivity of vaste regions such as the Southern Ocean have substantial implications as far as ocean foodwebs and fisheries are concerned.

3.4.4.8 Sea level rise

Mean sea level is increasing (Section 3.3.9) with substantial impacts already being felt by coastal ecosystems and communities (*high agreement, robust evidence*). These changes are interacting with other factors such as larger indundation and storms, which may drive greater storm surge, infrastructure damage, erosion and habitat loss (Church et al., 2013; Stocker et al., 2013; Blankespoor et al., 2014). Coastal wetland ecosystems such as mangroves, sea grasses and salt marshes are under pressure from rising sea level (*medium agreement, medium evidence*, Section 3.4.5) (Di Nitto et al., 2014; Ellison, 2014; Lovelock et al., 2015; Mills et al., 2016; Nicholls et al., 2018) as well as a wide range of other non-climate change related risks and impacts, with on-going loss of wetlands recently estimated at approximately 1% per annum across a large number of countries (Blankespoor et al., 2014; Alongi, 2015). While some ecosystems (e.g. mangroves) may be able to shift shoreward as sea levels increase, coastal development (e.g. coastal building, seawalls, and agriculture) can often interrupt shoreward shifts as does reduced sediment supplies down some rivers due to coastal development (Di Nitto et al., 2014; Lovelock et al., 2015; Mills et al., 2016).

The response to sea level rise challenges for ocean and coastal systems include reducing the impact of other stresses such as those arising from tourism, fishing, coastal development, reduced sediment supply, and unsustainable aquaculture/agriculture in order to build ecological resilience (Hossain et al., 2015; Sutton-Grier and Moore, 2016; Asiedu et al., 2017a). Available literature largely concludes that these challenges will intensify under a 1.5ºC world but will be higher at 2ºC, especially when considered in the context of changes occuring beyond the end of the current century. In some cases, restoration of coastal habitats and ecosystems may be a cost-effective way of responding to changes arising from increasing levels of exposure from rising sea levels, intensifying storms, coastal inundation, and salinization (Section 3.4.5, Box 3.5) (Arkema et al., 2013) although limits of these strategies have been identified (e.g., Lovelock et al., 2015; Weatherdon et al., 2016). These and other issues and options are explored in Section 3.4.5.

3.4.4.9 Projected risks and adaptation options for a global warming of 1.5ºC and 2ºC above pre-industrial levels

Given the space available, it is impossible to be comprehensive, and hence the intention here is to illustrate key risks and adaptation options in the case of the ocean using a number of key examples. This assessment builds on the recent expert consensus of Gattuso and colleagues (Gattuso et al., 2015) by assessing new literature (from 2015-2017) and adjusting the levels of risk in the light of this recent literature. To do this, we use input from the original expert group's assessment (Annex 3.1, S3-4-4) and focus particularly on the implications of global warming of 1.5ºC as compared to 2ºC. A discussion of potential adaptation options is also provided, the details of which will be further explored in later chapters of this special report. This section refers heavily to the review, analysis and literature presented in the Annex 3.1 that accompanies this report.

3.4.4.10 Framework organisms (tropical corals, mangroves and seagrass)

Marine organisms ('ecosystem engineers'), such as seagrass, kelp, oysters, salt marsh species, mangrove and corals, build physical structures or frameworks (i.e. sea grass meadows, kelp forests, oyster reefs, salt marshes, mangrove forests and coral reefs) which form the habitat for large numbers of species (Gutiérrez et al., 2012). These organisms in turn provide food, livelihoods, cultural significance, and services such as coastal protection (Bell et al., 2011, 2017; Cinner et al., 2012; Arkema et al., 2013; Nurse et al., 2014; Wong et al., 2014; Barbier, 2015; Bell and Taylor, 2015; Hoegh-Guldberg et al., 2015; Mycoo, 2017; Pecl et al., 2017).

Risks of climate change impacts for seagrass and mangrove ecosystems have recently been assessed by an expert group led by Short et al. (2016). Impacts of climate change were similar across a range of submerged and emerged plants. Submerged plants such as seagrass were affected mostly by temperature extremes (Arias-Ortiz et al., 2018) and indirectly by turbidity, while emergent communities such as mangroves and salt marshes were most susceptible to sea level variability and temperature extremes, which is consistent with other evidence (Di Nitto et al., 2014; Sierra-Correa and Cantera Kintz, 2015; Osorio et al., 2016; Sasmito et al., 2016), especially in the context of human activities that reduce sediment supply (Lovelock et al., 2015) or interrupt the shoreward movement of mangroves by coastal infrastructure leading to 'coastal squeeze' where coastal ecosystems are trapped between changing ocean conditions and coastal infrastructure (Mills et al., 2016). Projection of the future distribution of seagrasses suggest a poleward shift, with concern that low latitude seagrass communities may contract due to increasing stress levels (Valle et al., 2014).

Present-day risks from climate change (i.e. sea level rise, heat stress, storms and inundation) are medium for seagrass and *high* for reef building corals (Figure 3.20, Annex 3.1 S3-4-4) with evidence of strengthening of concern since the AR5 and the conclusion that tropical corals may be even more vulnerable to climate change than indicated in assessments done in 2014 (Hoegh-Guldberg et al., 2014; Gattuso et al., 2015). The current assessment also took into account the heat wave-related loss of 50% of shallow water corals across hundreds of kilometres of the world's largest continuous coral reef system, the Great Barrier Reef. These large-scale impacts plus the observation of back-to-back bleaching events on the Great Barrier Reef predicted two decades ago (Hoegh-Guldberg, 1999) and arriving sooner than predicted (Hughes et al., 2017b, 2018), suggest that the research community has under-estimated climate risks for coral reefs. General assessment of climate risks for mangroves prior to this special report concluded that they face greater risks from deforestation and unsustainable coastal development than climate change (Alongi, 2008; Hoegh-Guldberg et al., 2014; Gattuso et al., 2015) Recent climate related die-offs (Duke et al., 2017; Lovelock et al., 2017), however, suggest that climate change risks may have been underestimated for mangroves as well.

With the events of the last past 3 years in mind, risks are now considered to be undetectable to moderate (i.e now moderate risks start at 1.3°C as opposed to 1.8ºC, when assessed in 2015). Consequently, when average global warming reaches 1.3°C above pre-industrial period, mangroves risk from climate change will be *moderate*, while there is very *high confidence* that tropical coral reefs will experience high risks of impacts such as very frequent mass mortalities (at least while populations of corals persist). At global warming of 1.8ºC above the preindustrial period, seagrasses are projected to reach moderate to high levels of risk (e.g. sea level rise, erosion, damage from extreme temperatures, storm damage), while risks to mangroves from climate change will remain medium (e.g. risks of not keeping up with SLR; more frequent heat stress mortality) (Figure 3.17).

Tropical coral reefs will reach a *very high risk* of impact at 2ºC (Figure 3.17; Annex 3.1 3.4.4) with most available evidence suggesting that coral dominated ecosystems will be non-existent at this temperature or higher (e.g., coral abundance near zero in most locations, intensifying storms 'flattening' reefs' 3-dimensional structure; Alvarez-Filip et al., 2009) (*high agreement, robust evidence*). Impacts at this point (coupled with ocean acidification) are likely to undermine the ability of tropical coral reefs to provide habitat for the current high levels of biodiversity as well as a range of ecosystem services important for millions of people (e.g., food, livelihoods, coastal protection, cultural services) (Burke et al., 2011).

Strategies for reducing the impact of climate change on framework organisms include reducing non-climate change stresses (e.g. coastal pollution, overfishing, destructive coastal development) in order to increase ecological resilience in the face of accelerating climate change impacts (World Bank, 2013; Ellison, 2014; Anthony et al., 2015; Sierra-Correa and Cantera Kintz, 2015; Kroon et al., 2016; O'Leary et al., 2017) as well protecting locations where organisms may be more robust (Palumbi et al., 2014), or less exposed to climate change (Bongaerts et al., 2010; van Hooidonk et al., 2013; Beyer et al., 2018). This might involve cooler areas due to upwelling or deep-water communities that experience less extreme conditions and impacts, or variable conditions that lead to more resilient organisms. Given the potential value for promoting the survival of coral communities under climate change, efforts for preventing their loss to non-climate stresses is important (Bongaerts et al., 2010; Chollett et al., 2013, 2014; Fine et al., 2013; van Hooidonk et al., 2013; Cacciapaglia and van Woesik, 2015) but see (Chollett et al., 2010; Bongaerts et al., 2017; Beyer et al., 2018; Hoegh-Guldberg et al., 2018).A full understanding of the utility and feasibility of the role of refugia in reducing the loss of ecosystems has yet to be developed (*medium agreement, limited evidence*). There is also interest in *ex situ* conservation approaches involving the restoration of corals via aquaculture (Shafir et al., 2006; Rinkevich, 2014) and 'assisted evolution' to help corals adapt to changing sea temperatures (van Oppen et al., 2015, 2017), although there are numerous challenges that must be surpassed if these remedies are to be cost effective responses to preserving coral reefs under rapid climate change (Hoegh-Guldberg, 2012, 2014a; Bayraktarov et al., 2016) (*low agreement, limited evidence*).

Integrating coastal infrastructure with ecosystems dependent on mangroves, seagrasses and salt marsh such that they are able to shift shoreward as sea levels rise. Maintaining sediment supply to coastal areas will enable mangroves can keep pace with sea level rise (Shearman et al., 2013; Lovelock et al., 2015; Sasmito et al., 2016). For this reason, reducing interventions such as damming rivers may also maintain the sediment supply needed for mangrove habitat, and hence the ability of mangroves to persist without drowning as sea level increases (Lovelock et al., 2015). In addition, integrated coastal zone management should recognize the importance and economic expediency of using natural ecosystems such as mangroves and tropical coral reefs to protect coastal human communities (Arkema et al., 2013; Temmerman et al., 2013; Ferrario et al., 2014; Hinkel et al., 2014; Elliff and Silva, 2017). High levels of adaptation will be required to prevent impacts on food security and livelihoods in general (*medium agreement, medium evidence*). Adaptation options include developing alternative livelihoods and food sources, ecosystem-based management/adaptation such as ecosystem restoration, and constructing coastal infrastructure that reduces the impacts of rising seas and intensifying storms (Rinkevich, 2015; Weatherdon et al., 2016; Asiedu et al., 2017a; Feller et al., 2017). Clearly, these options need to be carefully assessed in terms of feasibility, cost and scalability, as well as in the light of the coastal ecosystems involved (Bayraktarov et al., 2016).

3.4.4.11 Ocean food webs (pteropods, bivalves, krill, and fin fish)

Ocean food webs represent vast interconnected systems that transfer of solar energy and nutrients from phytoplankton to higher trophic levels (including apex predators) as well as through other food web interactions. Here, we take four representative types of marine organisms which are important within food webs across the ocean, and which illustrate the impacts and ramifications of 1.5ºC and 2ºC warming.

Pteropods are small pelagic molluscs that produce a calcium carbonate shell and which are highly abundant in temperate and polar waters, where they form an important link in the food web between phytoplankton and a range of other organisms including fish, whales and birds. The second group, bivalve molluscs (e.g. clams, oysters and mussels) are also filter-feeding invertebrates that underpin important fisheries and aquaculture industries (from the polar to tropical regions) and are important as food sources for a range of organisms including humans. The third group of organisms considered here are a globally significant group of invertebrates known as euphausiid crustaceans (krill), and which are a key food source for many marine organisms and hence a major link between primary producers and higher trophic levels (e.g. fish, mammals, sea birds). Antarctic krill, *Euphausia superba*, are among the most abundant species in mass and are consequently an essential component of polar food webs (Atkinson et al., 2009). The last group, the fin fishes, are vitally important components of ocean food webs, and contribute to the income of coastal communities, industries and nations, and are important to food security and livelihoods of hundreds of millions of people globally (FAO, 2016). Further background to this section is provided in Annex 3.1 (S3-4-4).

There is a moderate risk to ocean food webs under present day conditions (Figure 3.17, *medium to high confidence*). Changing water chemistry and temperature is affecting the ability of pteropods to produce their shells, as well as swim and survive (Roberts et al., 2008; Bednaršek et al., 2016). Shell dissolution is 19-26% higher, for example, in both nearshore and offshore populations since the pre-industrial period (Feely et al., 2016). There is considerable concern as to whether these organisms are declining further, especially given their central importance in ocean food webs (David et al., 2017). Reviewing the literature reveals that pteropods face high risks of impact at 1.5°C and increasing risks of impacts at average global temperatures of 2°C or more above the preindustrial period (*medium agreement, medium evidence*).

As temperatures increase to 1.5˚C and beyond, the risk of impacts from ocean warming and acidification remain moderate to high except in the case of bivalves (mid latitude) where the risks of impacts become high to very high. Ocean warming and acidification are already affecting the life history stages of bivalve molluscs (e.g., Asplund et al., 2014; Mackenzie et al., 2014; Waldbusser et al., 2014; Zittier et al., 2015; Shi et al., 2016; Velez et al., 2016; Q. Wang et al., 2016; Castillo et al., 2017; Lemasson et al., 2017; Ong et al., 2017; X. Zhao et al., 2017). Impacts on adult bivalves include decreased growth, increased respiration, and reduced calcification with larval stages tending to show greater developmental abnormalities and mortality after exposure (Q. Wang et al., 2016; Lemasson et al., 2017; Ong et al., 2017; X. Zhao et al., 2017) (*medium agreement, robust evidence*). Risks accumulate at higher temperatures for bivalve molluscs, with very high risks at 1.8°C or more. This general pattern continues with low latitude fin fish acquiring medium to high risks of impact (*medium agreement, medium evidence)* when average global surface temperatures reach 1.3^{o}C above the pre-industrial period, and very high risks at 1.8^{o}C (Figure 3.17; *medium agreement, medium evidence*).

Large scale changes to food web structure is occurring in all oceans. For example, record levels of sea ice loss in the Antarctic (Notz and Stroeve, 2016; Turner et al., 2017b) translate as a loss of habitat and hence abundance of krill (Piñones and Fedorov, 2016), with negative ramifications for seabirds and whales which feed on krill (Croxall, 1992; Trathan and Hill, 2016). Other influences such as high rates of ocean acidification, coupled with the shoaling of the aragonite saturation horizon, are likely to also play key roles (Kawaguchi et al., 2013; Piñones and Fedorov, 2016). As with many risks associated with impacts at the ecosystem scale, most adaptation options focus on the management of non-climate change stresses from human activities. Reducing non-climate change stresses such as pollution and habitat destruction will be important in efforts to maintain these important food web components. Fisheries management (especially for low latitude fin fisheries that include small scale fisheries) at local to regional scales will be important in reducing stress on food web organisms such as those discussed here, as well as helping communities and industries adapt to changing food web structure and resources (see further discussion of fisheries *per se* below; Section 3.4.6.3). One strategy might be to maintain higher population levels of fished species in order to provide more resilient stocks in the face of challenges driven by climate change (Green et al., 2014; Bell and Taylor, 2015).

3.4.4.12 Key ecosystem services (e.g. carbon uptake, coastal protection, and tropical coral reef recreation)

The ocean provides important services that include the regulation of atmospheric composition via gas exchange across the boundary between ocean and atmosphere, and storage of carbon in vegetation and soils associated with ecosystems such as mangroves, salt marsh, and coastal peatlands, among other components. These include a series of physicochemical processes which are influenced by ocean chemistry, circulation, oceanography, temperature and biogeochemical components, as well as by non-climate activities (Boyd, 2015). The ocean is also a net sink for CO_2 (another important service), absorbing approximately 30% of human emissions from the burning of fossil fuels and modification of land use (IPCC, 2013).

Carbon uptake by the ocean is decreasing (Iida et al., 2015), with risks becoming high as 2^{o}C is approached and prospects of undersaturation of the ocean carbonate system increase (especially for polar oceans; Bopp et al. 2013). Concern is also growing from observations and models regarding changes in ocean circulation (Rahmstorf et al., 2015b); Sections 3.3.7 and 3.4.4.4). Biological components of carbon uptake by the ocean are also changing with observations of changing NPP in equatorial (*medium agreement, medium evidence*) and coastal upwelling systems (*medium agreement, medium evidence*) (Lluch-Cota et al., 2014; Sydeman et al., 2014; Bakun et al., 2015) as well as subtropical gyre systems (Signorini et al., 2015, *low agreement, limited evidence*). There is general agreement that NPP will decline as ocean warming and acidification increase (Bopp et al., 2013; Boyd et al., 2014; Pörtner et al., 2014; Boyd, 2015) (*medium agreement, medium evidence*).

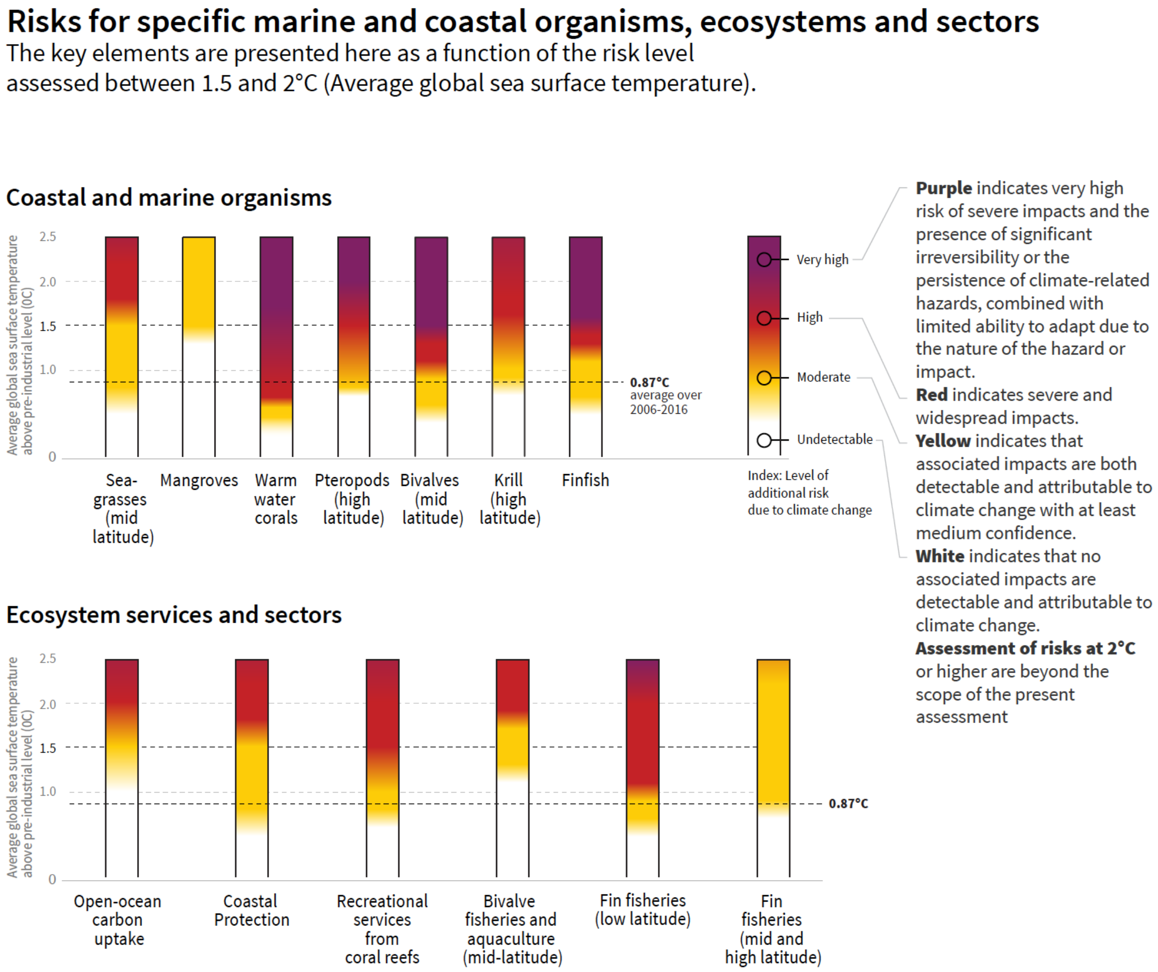
Risks of impacts from reduced carbon uptake, coastal protection, and services contributing to coral reef recreation are moderate at 1.5˚C of warming (*medium agreement, limited evidence*). At 2˚C, risks of impacts associated with changes to carbon uptake remain moderate, while the climate risks associated with reduced coastal protection and recreation on tropical coral reefs are high, especially given the vulnerability of this ecosystem and others (e.g. seagrass, mangroves) to climate change (Figure 3.17). Coastal protection is another service provided by natural barriers such as mangroves, seagrass meadows, coral reefs, and other coastal ecosystems, and which is important for protecting human communities and infrastructure against the impacts associated with rising sea levels, waves and intensifying storms (Gutiérrez et al., 2012; Kennedy et al., 2013; Ferrario et al., 2014; Barbier, 2015; Cooper et al., 2016; Hauer et al., 2016; Narayan et al., 2016). Both natural and human coastal protection have the potential to reduce impacts (Fu and Song, 2017). Tropical coral reefs, for example, provide effective protection by dissipating about 97% of wave energy, with 86% of the energy being dissipated by reef crests alone (Ferrario et al., 2014; Narayan et al., 2016). Mangroves play an important role in coastal protection as well as resources for coastal communities but are already under moderate risk of not keeping up with the sea level rise due to climate change and to contributing factors such as reduced sediment supply or obstacles for the shift shoreward (Saunders et al., 2014; Lovelock et al., 2015). This implies that coastal areas currently protected by mangroves may experience growing risks over time.

Tourism is one of the largest industries globally (Rosselló-Nadal, 2014; Markham et al., 2016; Spalding et al., 2017). A substantial part of the global tourist industry is associated with tropical coastal regions and islands where tropical coral reefs and related ecosystems play important roles (Section 3.4.9.1). Coastal tourism can be a dominant money earner in terms of foreign exchange for many countries, particularly SIDS (Section 3.4.9.1., Box 3.5; Weatherdon et al., 2016; Spalding et al., 2017). The direct relationship between increasing global temperatures, intensifying storms, elevated thermal stress, and the loss of tropical coral reefs has raised concern about the risks of climate change for local economies and industries based on tropical coral reefs. Risks to coral reef recreational services from climate change are considered here as well as in Box 3.5, Section 3.4.9, and Annex 3.1 S3-4-4.

Adapting to the broad global changes in carbon uptake by the ocean are limited and are discussed with respect to the changes in NPP and their implications for fishing industries later in this report. These are broad scale and indirect, with the only other solution at scale being reducing the entry of CO_2 into the ocean. Strategies for adapting to reduced coastal protection involve avoidance of vulnerable areas, managed retreat from threatened locations, and/or accommodation of impacts and loss of services (Bell, 2012; André et al., 2016; Cooper et al., 2016; Mills et al., 2016; Raabe and Stumpf, 2016; Fu and Song, 2017) Within these broad options, there are strategies that involve direct human intervention (e.g. coastal hardening, seawalls and artificial reefs) (Rinkevich, 2014, 2015; André et al., 2016; Cooper et al., 2016; Narayan et al., 2016), while there are others that exploit the opportunities for increasing coastal protection by involving a naturally occurring oyster banks, coral reefs, mangroves, seagrass, and other ecosystems (UNEP-WCMC, 2006; Scyphers et al., 2011; Zhang et al., 2012; Ferrario et al., 2014; Cooper et al., 2016). Natural ecosystems, when healthy, also have the ability to repair themselves after being damaged, which sets them apart from coastal hardening and other human responses that require constant maintenance (Barbier, 2015; Elliff and Silva, 2017). Recognizing and restoring coastal ecosystems in general may be more cost-effective than human structures such as the installation of seawalls and coastal hardening, where natural adaptation (ecosystem-based adaptation) is limited and the costs of creating and maintaining structures is generally expensive (Temmerman et al., 2013; Mycoo, 2017).

Recent studies have increasingly stressed the need for coastal protection to be considered within the context of new ways of managing coastal land, including protecting and ensuring that coastal ecosystems are able to undergo shifts in their distribution and abundance (Clausen and Clausen, 2014; Martínez et al., 2014; Cui et al., 2015; André et al., 2016; Mills et al., 2016)(André et al., 2016). Facilitating these changes will require new tools in terms of legal and financial instruments, as well as integrated planning that involves not only human communities and infrastructure, but also associated ecosystem responses and values (Bell, 2012; Mills et al., 2016). In this regard, the interactions between climate change, sea level rise and coastal disasters are being increasingly informed by models (Bosello and De Cian, 2014) with a widening appreciation of the role of natural ecosystems as an alternative to hardened coastal structures (Cooper et al., 2016). Adaptation options for tropical coral reef recreation include: (1) Protecting and improving biodiversity and ecological function by minimizing the impact of non-climate change stresses (e.g. pollution, overfishing), (2) Ensuring adequate levels of coastal protection by supporting and repairing ecosystems that protect coastal regions, (3) ensuring fair and equitable access to the economic opportunities associated with recreational activities, and (4) seeking and protecting supplies of water for tourism, industry, and agriculture alongside community needs.

In summary, our understanding of systems has increased significantly since AR5, with multiple lines of evidence supporting very significant changes in the structure and function of the ocean and its resident organisms and ecosystems. These changes are occurring today and will get progressively less manageable as temperatures increase to 1.5°C or higher. There is considerable evidence that avoiding 2°C will avoid very substantial damage to ecosystem services and ultimately impacts on human livelihoods, food resources, communities and industries. Figure 3.17 (and additional online material, S3-3.4.4) summarises the additional risks of impacts from global warming for many of the ocean-based organisms, ecosystems and sectors discussed here.



Risks for specific marine and coastal organisms, ecosystems and sectors

The key elements are presented here as a function of the risk level assessed between 1.5 and 2°C (Average global sea surface temperature).

Purple indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impact.

Red indicates severe and widespread impacts.

Yellow indicates that associated impacts are both detectable and attributable to climate change with at least medium confidence.

White indicates that no associated impacts are detectable and attributable to climate change.

Assessment of risks at 2°C or higher are beyond the scope of the present assessment

Figure 3.17: Summary of additional risks of impacts from ocean warming (and associated climate change factors such ocean acidification) for a range of ocean organisms, ecosystem and sectors at 1.0ºC, 1.5ºC and 2.0ºC warming of average sea surface temperature (SST) relative to the preindustrial period. The dotted line (0.87ºC) is a measure of the extent of present day warming. Assessment of changing risk levels and associated confidence were derived from the expert judgement of Gattuso et al., (2015) and the Lead Authors of this Chapter plus the additional input was received from the many reviewers of the ocean systems section of SR1.5. Note: (1) The analysis done here is not intended to be comprehensive. The examples of organisms, ecosystems and sectors discussed here are intended to outline the evidence and projection of impacts and the risks for ocean systems at 1.5º and 2.0ºC relative to 0.87ºC (today). (2) The evaluation of risks by experts did not consider genetic adaptation, acclimatization, or human risk reduction strategies (mitigation and societal adaptation). (3) As discussed elsewhere (3.3.10, 3.4.4.5, Box 3.4; Gattuso et al 2015), ocean acidification is also having impacts on organisms and ecosystems as carbon dioxide increases in the atmosphere. These changes are part of the response reported here although partitioning the effects of the two drivers is difficult at this point in time and hence is not attempted. (4) Confidence levels (L=Low, M=Moderate, H=High, and VH=Very high) were assessed for the position of the transitions from one level of additional climate risk to the next successive level (Gattuso et al. (2015). Three transitions were possible: W-Y (white to yellow), Y-R (yellow to red), and R-P (red to purple), with the colours corresponding to the level of additional risk posed by climate change (see Figure 3.17).

For each of the 13 Ocean 'embers', the levels of confidence for these transitions were assessed (based on level of agreement, extent of evidence) to be: Seagrasses (mid-latitude): W-Y (VH); Y-R (H); R-P(H); Mangroves: W-Y (M); Warm water corals: W-Y (H); Y-R (VH); R-P (VH); Pteropods (high latitude): W-Y (L); Y-R (M); R-P (H); Bivalves (mid-latitude): W-Y (H); Y-R (M); R-P (M), Krill (high latitude): W-Y (M); Y-R (L); R-P (L); Finfish: W-Y (H); Y-R (H); R-P (M); Open ocean carbon uptake: W-Y (H); Y-R (H); Coastal protection: W-Y (M); Y-R (L); R-P (L); Recreational services from coral reefs: W-Y (H); Y-R (M); R-P (M); Bivalve fisheries and aquaculture (mid-latitude): W-Y (H); Y-R (M); Fin fisheries (low latitude): W-Y (H); Y-R (M); R-P (H); and Fin fisheries (high latitude): W-Y (H); Y-R (H); R-P (L)

[START BOX 3.4 HERE]

Box 3.4: Tropical Coral Reefs in a 1.5°C Warmer World

Tropical coral reefs face very high risks (Figure 3.19) of becoming unsustainable as coral dominated ecosystems if warming exceeds 1.5ºC. A 1.5°C world is better for coral reefs than a 2ºC world, in which coral reefs mostly disappear (Donner et al., 2005; Hoegh-Guldberg et al., 2014; Schleussner et al., 2016b; van Hooidonk et al., 2016; Frieler et al., 2017; Hughes et al., 2017a). Even with warming up until today (0.87ºC;Chapter 1), a substantial proportion of coral reefs have experienced large scale mortalities that are causing them to rapidly contract (Hoegh-Guldberg et al., 2014). In the last 3 years alone, large coral reef systems such as the Great Barrier Reef (Australia) have lost as much as 50% of their shallow water corals (Hughes et al., 2017b). These changes are part of a series of heat stress impacts that began in the early 1980s events (Hoegh-Guldberg, 1999).

Coral dominated reefs are found between latitude 30°S and 30°N along coastlines where they provide habitat for over a million species (Reaka-Kudla, 1997). The food, income, coastal protection, cultural context, and many other services for millions of people along tropical coastal areas (Burke et al., 2011; Cinner et al., 2012; Kennedy et al., 2013; Pendleton et al., 2016) are underpinned by a mutualistic symbiosis between reef-building corals and dinoflagellates from the genus *Symbiodinium* (Hoegh-Guldberg et al., 2017). Tropical coral reefs are found down to depth of 150 m and are dependent on light, as distinct from the cold deep-water reef systems that extend down to depths of 2000 m or more. The difficulty in accessing deep-water reef systems also means that the literature on impacts of climate change is limited by comparison to tropical coral reefs (Hoegh-Guldberg et al., 2017). Consequently, this Box focuses on the impacts of climate change on tropical coral reefs, particularly with respect to their prospects under average global surface temperatures of 1.5°C and 2ºC above the pre-industrial period.

The distribution and abundance of coral reefs has decreased by approximately 50% over the past 30 years (Gardner et al., 2005; Bruno and Selig, 2007; De'ath et al., 2012) as a result of pollution, storms, overfishing and unsustainable coastal development (Burke et al., 2011; Halpern et al., 2015; Cheal et al., 2017). More recently, climate change (heat stress; Hoegh-Guldberg, 1999; Baker et al., 2008; Spalding and Brown, 2015; Hughes et al., 2017b) has emerged as the greatest threat to coral reefs with temperatures of just 1°C above the long-term summer maximum for an area (referenced to 1985-1993) over 4-6 weeks being enough to cause mass coral bleaching (loss of the symbiosis) and mortality (*very high confidence*, WGII AR5 Box 18-2, Cramer et al., 2014). Ocean warming and acidification can also slow growth and calcification, making corals less competitive to other benthic organisms such as macroalgae (Dove et al., 2013; Reyes-Nivia et al., 2013, 2014). As corals disappear, so do fish stocks, and many other reef-dependent species, directly impacting industries such as tourism and fisheries, as well as coastal livelihoods for many, often disadvantaged, people (Wilson et al., 2006; Graham, 2014; Graham et al., 2015; Cinner et al., 2016)(Pendleton et al., 2016). These impacts are exacerbated by increasingly intense storms (Section 3.3.6), which physically destroy coral communities and hence reefs (Cheal et al., 2017), and by ocean acidification (Sections 3.3.10 and 3.4.4.5) which can weaken coral skeletons, contribute to disease, and slow the recovery of coral communities after mortality events (Gardner et al., 2005; Dove et al., 2013; Kennedy et al., 2013; Webster et al., 2013; Hoegh-Guldberg, 2014b; Anthony, 2016) (*medium agreement*, *limited evidence*). Ocean acidification also leads to greater activity by decalcifying organisms such as excavating sponges (Kline et al., 2012; Dove et al., 2013; Fang et al., 2013, 2014, Reyes-Nivia et al., 2013, 2014).

Predictions of back-to-back bleaching events (Hoegh-Guldberg, 1999) have become reality over 2015-2017 (e.g., Hughes et al., 2017b) as have projections of declining coral abundance (*high confidence*). Models have also become increasingly capable, and predict the large-scale loss of coral reefs by mid-century under even low emission scenarios (Hoegh-Guldberg, 1999; Donner et al., 2005; Donner, 2009; van Hooidonk and Huber, 2012; Frieler et al., 2013; Hoegh-Guldberg et al., 2014; van Hooidonk et al., 2016). Even achieving emission reduction goals consistent with the ambitious goal of 1.5ºC under the Paris Agreement will result in the further loss of 90% of reef-building corals compared to today, with 99% of corals being lost under warming of 2ºC or more above the pre-industrial period (Frieler et al., 2013; Hoegh-Guldberg, 2014b; Hoegh-Guldberg et al., 2014; Schleussner et al., 2016b; Hughes et al., 2017a).

The assumptions underpinning these assessments are considered to be highly conservative. In some hypothetical cases, ‘optimistic’ assumptions in models include the rapid thermal adaptation by corals (0.2-1.0ºC per decade and 0.4ºC per decade; (Donner et al., 2005; Schleussner et al., 2016b), respectively) as well as very rapid recovery rates from impacts (i.e., 5 years; Schleussner et al., 2016b). Adaptation to climate change at these high rates (if at all) has not been documented and rates of recovery from mass mortality tend to be much longer the time between extreme events (> 15 years; Baker et al., 2008). Probability analysis also reveals that the underlying increases in sea temperatures that drive coral bleaching and mortality are 25% less likely under 1.5°C versus 2ºC (King et al., 2017). Differences between rates of heating suggest the possibility of temporary climate refugia (Caldeira, 2013; van Hooidonk et al., 2013; Cacciapaglia and van Woesik, 2015; Keppel and Kavousi, 2015) which may play an important role in terms of the regeneration coral reefs, especially if these refuges are protected from non-climate change risks. Higher latitude sites are reporting the arrival of reef-building corals, which may deserve focus in terms of limited refugia and coral reef structures, which are likely to be low in biodiversity when compared to tropical reefs today (Kersting et al., 2017). Similar proposals have been made for the potential role of deep water (30 to 150 m) or mesophotic coral reefs (Bongaerts et al., 2010; Holstein et al., 2016) avoiding shallow water extremes (i.e. heat, storms) although the ability of these ecosystems to repopulate damaged shallow water areas may be limited (Bongaerts et al., 2017).

Given the sensitivity of corals to heat stress, even short periods of overshoot (i.e. decades) will be very challenging to coral reefs. Losing 90% of today's coral reefs, however, will remove resources and increase poverty levels across the world's tropical coastlines, highlighting the key issue of equity for the millions of people that depend on these valuable ecosystems (Spalding et al., 2014; Halpern et al., 2015)(Cross Chapter Box 6). Anticipating these challenges to food and livelihoods for coastal communities will become increasingly important, and as will adaptation options such as the diversification of livelihoods and the development of new sustainable industries to reduce the dependency of coastal communities on threatened coastal ecosystems such as coral reefs (Cinner et al., 2012, 2016; Pendleton et al., 2016). At the same time, coastal communities will need to pre-empt changes to other services provided by coral reefs such as coastal protection (Kennedy et al., 2013; Hoegh-Guldberg et al., 2014; Pörtner et al., 2014; Gattuso et al., 2015). Other threats and challenges to coastal living such as sea level rise will amplify challenges from declining coral reefs. Given the scale and cost of these interventions, implementing them earlier rather than later would be expedient.

[END BOX 3.4 HERE]

3.4.5 Coastal and low-lying areas, and sea level rise

Sea level rise (SLR) is accelerating in response to climate change (Section 3.3.9; Church et al., 2013) and is producing significant impacts (*high agreement, robust evidence*). In this section, impacts and projections of sea level rise are reported at global and city scales (Sections 3.4.5.1-3.4.5.2) and for coastal systems

(Sections 3.4.5.3 – 3.4.5.6). For some sectors, there is a lack of precise evidence of change at 1.5°C and 2°C. Adaptation to sea level rise is discussed in Section 3.4.5.7.

3.4.5.1 Global / sub-global scale

Sea level rise (SLR) and other oceanic climate change will result in salinization, flooding and erosion and affect human and ecological systems, including health, heritage, freshwater, biodiversity, agriculture, fisheries and other services (*very high agreement, robust evidence)*. Due to the commitment to SLR, there is an overlapping uncertainty in projections (Schleussner et al., 2016b; Sanderson et al., 2017; Goodwin et al., 2018; Mengel et al., 2018; Nicholls et al., 2018; Rasmussen et al., 2018) of about 0.1 m difference in Global Mean Sea Level (GMSL) rise between 1.5ºC and 2ºC worlds in 2100 (Section 3.3.9, Table 3.3). Exposure and impacts at 1.5°C and 2ºC differ at different time horizons (Schleussner et al., 2016b; Brown et al., 2018a, b; Nicholls et al., 2018; Rasmussen et al., 2018). However, these are distinct from higher rises in temperature (e.g., 4°C or more as discussed in Brown et al., 2018a) over centennial scales. The benefits of climate change mitigation reinforce findings of earlier IPCC reports (e.g., Wong et al., 2014).

Table 3.3 notes the land and people exposed to sea level rise (assuming there is no adaptation or protection at all) using the Dynamic Interactive Vulnerability Assessment (DIVA) model (extracted from Brown et al., 2018a) and Goodwin et al., 2018); Also see Annex 3.1, Table S4). Thus, even with temperature stabilization, exposure increases. In contrast, land area exposed is projected to at least double by 2300 using a RCP8.5 scenario (Brown et al., 2018a). In the 21st century, land area exposed to sea level rise (assuming there is no adaptation or protection at all) is at least an order of magnitude larger than the cumulative land loss due to submergence (which takes into account defences) (Brown et al., 2016, 2018a) regardless of sea level rise scenario. Slower rates of rise due to climate change mitigation may provide greater opportunity for adaptation (*medium confidence*), which can substantially reduce impacts.

Agreeing with WGII AR5 Section 5.4.3.1 (Wong et al., 2014), climate change mitigation may reduce or delay coastal impacts and exposure (*very high confidence, robust evidence*). Adaptation has the potential to substantially reduce risk (Nicholls et al., 2007; Wong et al., 2014; Sections 5.5 and 5.4.3.1; Sections 6.4.2.3 and 6.6,). At 1.5°C in 2100, 31–69 million people world-wide could be exposed to flooding assuming no adaptation or protection at all (and 2010 population values), compared with 32–79 million people at 2ºC in 2100 (Rasmussen et al., 2018) (Annex 3.1, Table S4). As a result, up to 10.4 million more people would be exposed to sea-level rise at 2°C compared with 1.5°C in 2100. With a 1.5°C stabilization scenario in 2100, 55-94 million people / year are at risk from flooding increasing to 115-188 million people per year in 2300 (50th percentile, SSP1-5, no socio-economic change after 2100). This assumes there is no upgrade to present protection levels (Nicholls et al., 2018). The number of people at risk increases by approximately 18% using a 2°C scenario and 266% using a RCP8.5 scenario in 2300 (Nicholls et al., 2018). Through prescribed IPCC Special Report on Emission Scenarios (SRES) SLR scenarios, Arnell et al. (2016) also found people flooded increased substantially after 2ºC without further adaptation from present protection levels, particularly in the second half of the twentieth century.

Coastal flooding by the sea is likely to cost thousands on billions of USD annually, with damage costs under constant protection 0.3–5.0% of global GDP in 2100 for a RCP2.6 scenario (Hinkel et al., 2014). Risks are projected to be highest in south and south-east Asia, assuming there is no upgrade to present protection levels, for all temperatures of climate warming (Arnell et al., 2016; Brown et al., 2016) Countries where at least 50 million people exposed to SLR (assuming no adaptation or protection at all) based on a 1,280 Pg C emission scenario (approximately 1.5°C temperature rise above today's level) include China, Bangladesh, Egypt, India, Indonesia, Japan, Philippines, United States and Vietnam (Clark et al., 2016). Rasmussen et al. (2018) and Brown et al. (2018a) project similar countries at high exposure from SLR. Thus there is *high confidence* that SLR will have significant impacts world-wide in this century and beyond.

3.4.5.2 Cities

Observations of the impacts of SLR are difficult to record due to multiple drivers of change in cities. Rather, there are observations of ongoing or planned adaptation to SLR and extreme water levels, and this will continue (Araos et al., 2016; Nicholls et al., 2018), whilst other cities are yet to prepare (see Section Cross-chapter Box 4.1) (*high confidence, medium to robust evidence*). There are limited observations and analysis of how cities will cope with higher and/or multi-centential SLR, with the exception of Amsterdam, New York and London (Nicholls et al., 2018).

Coastal urban areas are projected to see more exteme water levels due to rising sea levels which may lead to increased flooding and damage of infrastructure from extreme events (unless adaptation is undertaken), plus salinization of groundwater. These impacts may be enhancement through localized subsidence (Wong et al., 2014) causing greater relative SLR. At least 136 mega cities (port cities with a population greater than 1 million in 2005) are at risk from flooding due to SLR (with magnitudes of rise possible under 1.5°C or 2ºC in the 21st century, as indicated in Section 3.3.9) unless further adaptation is undertaken (Hanson et al., 2011; Hallegatte et al., 2013). Many of these cities are located in south and south-east Asia (Hallegatte et al., 2013; Cazenave and Cozannet, 2014; Clark et al., 2016; Jevrejeva et al., 2016). Jevrejeva et al. (2016) report with 2°C of warming by 2040 (for RCP8.5), more than 90% of global coastlines will experience SLR greater than 0.2 m. However, for scenarios where 2°C is stabilized or occurs later in time, this figure is likely to differ due to the commitment to SLR. Raising exisiting dikes helps to protect against SLR substantially reducing risk (whilst acknowledging other forms of adaptation exist). By 2300, dike heights under an unmitigation scenario (RCP8.5) could be more than 2 m higher (on average for 136 mega cities) than under climate change mitigation scenarios at 1.5°C or 2°C (Nicholls et al., 2018). Thus, rising sea levels commits to long-term adaptation in coastal cities. Thus, rising sea levels commits to long-term adaptation in coastal cities (*high confidence*).

3.4.5.3 Small islands

Qualitative physical observations of SLR (and other stresses) include inundation of parts of low-lying islands, land degradation due to saltwater intrusion in Kiribati and Tuvalu (Wairiu, 2017) and shoreline change in French Polynesia (Yates et al., 2013), Tuvalu (Kench et al., 2015, 2018) and Hawaii (Romine et al., 2013). Observations, models and other evidence indicate that unconstrained Pacific atolls have kept pace with SLR with little reduction in size or experienced a net gain in land (Kench et al., 2015, 2018; McLean and Kench, 2015; Beetham et al., 2017). Whilst islands are highly vulnerable to SLR (*high confidence, robust evidence*), they are also reactive to change. Small islands are impacted by multiple climatic stressers, with SLR being more important a stressor to some islands rather than others (Box 3.5, Section 3.4.10, Section 4.3.5.6, Box 4.3, 5.2.1, 5.5.3.3, Box 5.3).

Observations of adaptation to multiple drivers of coastal change, including SLR, include retreat (migration), accommodate and defend. Migration (internal and international) has always been important on small islands (Farbotko and Lazrus, 2012; Weir et al., 2017), with changing environmental and weather conditions (as a planned adaptation strategy) just one factor in the choice to migrate (Campbell and Warrick, 2014) (Sections 3.4.10, 4.3.5.6 and 5.3.2). Whilst flooding may result in migration or relocation for example, Vunidogoloa, Fiji, (McNamara and Des Combes, 2015; Gharbaoui and Blocher, 2016) or Soloman Islands (Albert et al., 2017), in-situ adaptation may be have been tried or preferred, for example stilted housing or raised floors in Tubigon, Bohol, Philippines (Jamero et al., 2017), raised roads and floors in Batasan and Ubay, Phillipines (Jamero et al., 2018) raised platforms for faluw in Leang, Federated States of Micronesia (Nunn et al., 2017). Protective features, such as seawalls or beach nourishment are observed to locally reduce erosion and flood risk, but can have other adverse implcations (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014; Section 29.6.22).

There is a lack of precise, quantitative studies of projected impacts of SLR at 1.5ºC and 2ºC. Small islands are projected to be at risk and very sensitive to coastal climate change and other stressors (high agreement, robust evidence) (Nurse et al., 2014; Benjamin and Thomas, 2016; Ourbak and Magnan, 2017; Brown et al., 2018a; Nicholls et al., 2018; Rasmussen et al., 2018; Section 29.3 and 29.4), such as oceanic warming, SLR (resulting in salinization, flooding and erosion), cyclones and mass coral bleaching and mortality (Section 3.4.4, Box 3.4, Box 3.5). These can have significant socio-economic and ecological implications, such as on health, agriculture and water resources, which have impacts for livlihoods (Sovacool, 2012; Mycoo, 2014, 2017; Nurse et al., 2014). Combinations of drivers causing adverse impacts are important: Storlazzi et al. (2018) found that the impacts of SLR and wave-induced flooding (within a temperature horizon equivalent of 1.5°C) could affect freshwater availability on Roi-Namur, Marshall Islands, but is also dependent on other extreme weather events, such as temperature. Freshwater may also be affected by a 0.40 m rise in sea-level (which may be experienced with a 1.5°C warming) in other Pacific atolls (Terry and Chui, 2012). Whilst SLR is a major hazard for atolls, islands of higher elevation are also threatened given there is often a lot of infrastructure located near to the coast (Kumar and Taylor, 2015; Nicholls et al., 2018). Tens of thousands of people on small islands are exposed to SLR (Rasmussen et al., 2018). Giardino et al. (2018) found that hard defence structures on the island of Ebeye in the Marshall Islands, were effective for longer time periods at the sea level rise associated with 1.5ºC and 2ºC. In Jamacia and St Lucia, SLR and extreme sea levels threaten transport system infrastructure at 1.5°C unless further adaptation is undertaken (Monioudi et al., 2018). slower rates of SLR will provide greater opportunity for adaptation to be successful (*medium agreement*), but will not reduce it substantially enough on islands of the lowest elevation. Migration and/or relocation may be an adaptation option (Section 3.4.10). Thomas and Benjamin (2017) highlight three areas of concern in the context of loss and damage at 1.5°C: a lack of data, gaps in financial assessments, and a lack of targeted policies or mechanisms to address this (Cross-Chapter Box 12 in Chapter 5). Small islands remain vulnerable to SLR (*high confidence*).

3.4.5.4 Deltas and estuaries

Observations of SLR and human influence are felt through salinization leading to mixing in deltas and estuaries, aquifers, flooding (also enhanced by precipitation and river discharge), erosion land degradation, threatening freshwater sources and posing risks to ecosystems and human systems (Wong et al., 2014; Section 5.4). For instance, in the Delaware River Estuary on the USA east coast, upward trends of streamflow adjusted salinity (measured since the 1900s) accounting for the effects of streamflow and seasonal variations have been detected with SLR a potential cause (Ross et al., 2015).

Z. Yang et al. (2015) found that USA future climate scenarios (A1B 1.6°C and B1 2°C in the 2040s) had a greater effect on salinity intrusion than future land use/land cover change in the Snohomish River estuary, Washington state (USA). This resulted in a shift in the salinity both upstream and downstream in low flow conditions. Projecting impacts in deltas needs an understanding of both fluvial discharge and SLR, making projections complex as the drivers operate on different time and spatial scales (Zaman et al., 2017; Brown et al., 2018b) The mean annual flood depth when 1.5°C is first projected to be reached in the Ganges-Brahmaputra delta may be less than the most extreme annual flood depth seen today, taking account of SLR, plus surges, tides, bathymetry and local river flows (Brown et al., 2018b). Furthermore increased river salinity and saline intrusion in the Ganges-Brahmaputra-Meghna is likely with 2°C of warming (Zaman et al., 2017). Salinisation could impact agriculture and food security (Cross-Chapter Box 6). For 1.5°C or 2°C stabilization conditions in 2200, or 2300 plus surges, a minimum of 44% of the the Bangladesh Ganges-Brahmaputra, Indian Bengal, Indian Mahanadi and Ghanese Volta deltas land area (without defences) would be exposed unless sedimentation occurs (Brown et al., 2018b). Other deltas are similarly vulnerable. SLR is one factor affecting deltas, and assessment of numerous geophysical and anthropogenic drivers of geomorphic change is important (Tessler et al., 2018). For example, dike building to reduce flooding and dam building (Gupta et al., 2012) restricts sediment movement and deposition leading to enhanced subsidence, which can occur at a greater rate than SLR (Auerbach et al., 2015; Takagi et al., 2016). Although dikes remain essential to reduce flood risk today, promoting sedimentation is an advisable strategy (Brown et al., 2018b) which may involve nature-based solutions. Transformative decisions regarding the extent of sediment restrictive infrastructure may need to be considered over centennial scales (Brown et al., 2018b). Thus in a 1.5°C or 2°C world, deltas, which are home to millions of people, are highly threatened from SLR and localised subsidence today, and over long time scales (*high confidence, medium evidence*).

3.4.5.5 Wetlands

Observations indicate that wetlands, such as saltmarshes and mangrove forests are disrupted by changing conditions (Wong et al., 2014; Lovelock et al., 2015; Section 5.4.2.4; Section 3.4.4.8), such as total water levels and sediment availability. For example, observations indicated that saltmarshes in Connecticut and New York measured from 1900 to 2012, have accreted with SLR, but have lost marsh surface relative to tidal datums, leading to increased marsh flooding and further accretion (Hill and Anisfeld, 2015). This stimulated marsh carbon storage, and aided climate change mitigation.

Salinisation may lead to shifts in wetland communities and their ecosystems functions, affecting freshwater wetlands (Herbert et al., 2015). Some projections of wetland change, with magnitudes (but not necessarily rates or timing) of SLR analogous at 1.5°C and 2°C, indicate a net loss (e.g., Cui et al., 2015 with a 2.6 mm yr-1 rise (aligning with AR5) in the Yangtze Estuary; Blankespoor et al., 2014) 1 m rise in multiple countries; Arnell et al. (2016) using an A1 SRES scenario of up to 0.48 m by 2050 on a global scale; drowning of 60% of marshes studied world-wide (with a rate of sea-level rise of 4.4 mm yr^{-1}) by 2100 (Crosby et al., 2016), whilst others report a net gain with wetland transgression ((Raabe and Stumpf, 2016) in the Gulf of Mexico). However, the feedback between wetlands and sea level is complex, with parameters such as lack of accommodation space restricting inland migration, or sediment supply and feedback between plant growth and geomorphology (Kirwan and Megonigal, 2013; Ellison, 2014; Martínez et al., 2014; Spencer et al., 2016) still being explored. Reducing global warming from 2oC to 1.5oC will deliver long-term benefits from lower SLR, allowing natural sedimentation rates to more likely keep up with SLR. It remains unclear how wetlands will respond and under what conditions (including other climate parameters) with a rise in 1.5°C and 2°C, simultaneously recognising they have great potential for adaptation and climate change mitigation (medium confidence, medium evidence) (Sections 4.3.2 and 4.3.3.3).

3.4.5.6 Other coastal settings

Numerous impacts have not been quantified at 1.5°C or 2°C but remain important. This includes systems identified in WGII AR5 (Wong et al., 2014; Section 5.4), such as beaches, barriers, sand dunes, rocky coasts, aquifers, lagoons and ecosystems (for the latter, see Section 3.4.4.12). For example, SLR effects erosion and accretion, and therefore sediment movement, instigating shoreline change (Wong et al., 2014; Section 5.4.2.1) which could affect land-based ecosystems. Global observations indicate no overall clear effect of SLR on shoreline change (Le Cozannet et al. (2014) as it is highly site specific (e.g., Romine et al. 2013) Infrastructure or geological constraints reduces shoreline movement causing coastal squeeze (e.g. in Japan, beach losses due to SLR are projected with a RCP2.6 scenario, and are projected to increase under RCP8.5 (Udo and Takeda, 2017)). Compound flooding (the combined risk of flooding from multiple drivers) has increased significantly over the past century in major coastal cities (Wahl et al., 2015) and is likely to increase with further development and SLR at 1.5°C and 2°C unless adaptation is undertaken. Thus SLR rise will have a wide range of adverse effects on coastal zones (*medium confidence*).

3.4.5.7 Adapting to coastal change

Adaptation to coastal change from SLR and other drivers is occurring today (high agreement, robust evidence, see Cross-Chapter Box 9 in Chapter 4) including migration, ecosystem-based adaptation, raising infrastructure and defences, salt-tolerant food production, early warning systems, insurance and education (Wong et al., 2014; Section 5.4.2.1). Climate change mitigation will reduce the rate of SLR this century, decreasing the need for extensive, and in places, immediate adaptation. Adaptation will reduce impacts in human settings (Hinkel et al., 2014; Wong et al., 2014) (*high agreement, robust evidence*), although there is less certainty for ecosystems (Sections 4.3.2, 4.3.3.3). While some ecosystems (e.g., mangroves) may be able to move shoreward as sea levels increase, coastal development (e.g., coastal building, seawalls, and agriculture) often interrupt these transitions (Saunders et al., 2014). Options for responding to these challenges include reducing the impact of other stresses such as those arising from tourism, fishing, coastal development, and unsustainable aquaculture/agriculture. In some cases, restoration of coastal habitats and ecosystems can be a cost-effective way of responding to changes arising from increasing levels of exposure from rising sea levels, intensifying storms, coastal inundation and salinization communities (Arkema et al., 2013; Temmerman et al., 2013; Ferrario et al., 2014; Hinkel et al., 2014; Spalding et al., 2014; Elliff and Silva, 2017).

Since the AR5, planned and autonomous adaptation and forward planning has become more wide-spread (Araos et al., 2016; Nicholls et al., 2018), but continued efforts are required as many localities are in the early stages of adapting or not adapting at all (Araos et al., 2016) (See Cross-Chapter Box 9 in Chapter 4). This is regional and sub-sectoral specific, and also linked to non-climatic factors (Ford et al., 2015; Lesnikowski et al., 2015; Araos et al., 2016). Adaptation pathways (e.g., Ranger et al., 2013; Barnett et al., 2014; Rosenzweig and Solecki, 2014; Buurman and Babovic, 2016) assist long-term thinking, but are not widespread practice despite knowledge of long-term risk (Section 4.2.2). Furthermore, retreat and human migration have increasingly being considered as a management response (Hauer et al., 2016; Geisler and Currens, 2017), with a growing emphasis on green adaptation. There are few studies on the adaptation limits to SLR where transformation change may be required (Wong et al., 2014, Section 5.5.8; Nicholls et al. 2015; Section 4.2.2.3). SLR poses a long-term threat (Section 3.3.9), even with 1.5°C and 2°C of warming centennial scale adaptation remains essential (high confidence, robust evidence).

Table 3.3: Land and people exposed to sea level rise (SLR, assuming no protection at all). Extracted from (Brown et al., 2018a; Goodwin et al., 2018). SSP: Shared Socioeconomic Pathway, wrt: with respect to

Climate scenario	**Impact factor, assuming there is no adaptation or protection at all (50th, [5th-95th percentiles])**	**Year**			
		2050	**2100**	**2200**	**2300**
1.5ºC	Temperature rise wrt 1850–1900 (°C)	1.71 (1.44-2.16)	1.60 (1.26-2.33)	1.41 (1.15-2.10)	1.32 (1.12-1.81)
	SLR (m) wrt 1986-2005	0.20 (0.14-0.29)	0.40 (0.26-0.62)	0.73 (0.47-1.25)	1.00 (0.59-1.55)
	Land exposed (x10^3 km^2)	574 [558-597]	620 [575-669]	666 [595-772]	702 [666-853]
	People exposed, SSP1-5 (millions)	127.9-139.0 [123.4-134.0, 134.5-146.4]	102.7-153.5 [94.8-140.7, 102.7-153.5]	--	133.8-207.1 [112.3-169.6, 165.2 - 263.4]*
2ºC	Temperature rise wrt 1850–1900 (° C)	1.76 (1.51-2.16)	2.03 (1.72-2.64)	1.90 (1.66-2.57)	1.80 (1.60-2.20)
	SLR (m) wrt 1986-2005	0.20 (0.14-0.29)	0.46 (0.30-0.69)	0.90 (0.58-1.50)	1.26 (0.74-1.90]
	Land exposed (10^3 km^2)	575 [558-598]	637 [585-686]	705 [618-827]	767 [642-937]
	People exposed, SSP1-5 (millions)	128.1-139.2 [123.6-134.2, 134.7-146.6]	105.5-158.1 [97.0-144.1, 118.1-179.0]	--	148.3 - 233.0 [120.3-183.4, 186.4-301.8]*

*Population is held static after 2300.

[START BOX 3.5 HERE]

Box 3.5: Small Island Developing States (SIDS)

1.5˚C warming is expected to prove a challenging state for Small Island Developing States (SIDS) that are already experiencing impacts associated with climate change. At 1.5˚C, compounding impacts from interactions between climate drivers may contribute to loss of, or change in, critical natural and human systems (*high agreement*, *medium evidence*). There are a number of reduced risks at 1.5˚C versus 2˚C, particularly when coupled with adaptation efforts (*high agreement*, *medium evidence*).

Changing climate hazards for SIDS at 1.5°C

Mean surface temperature is projected to increase in SIDS at 1.5˚C (*high agreement*, *robust evidence*). The Caribbean region will experience 0.5°C –1.5˚C warming compared to 1971–2000 baseline, with greatest warming over larger land masses (Taylor et al., 2018). Under the Representative Concentration Pathway (RCP)2.6 scenario, the western tropical Pacific is projected to experience warming of 0.5°C –1.7°C relative to 1961–1990. Extreme temperatures will also increase, with potential for elevated impacts as a result of comparably small natural variability (Reyer et al., 2017a). Compared to the 1971–2000 baseline, up to 50% of the year are projected to be under warm spell conditions in the Caribbean at 1.5˚C with a further increase by up to 70 days at 2˚C (Taylor et al., 2018).

Changes in precipitation patterns, freshwater availability and drought sensitivity differ between small island regions (*high agreement, medium evidence*). Some western Pacific and the northern Indian Ocean islands may see increased freshwater availability, while islands in most other regions are projected to see a substantial decline (Holding et al., 2016; Karnauskas et al., 2016). For several SIDS, approximately 25% of the overall freshwater stress projected under 2°C at 2030 can be avoided by limiting global warming to 1.5°C (Karnauskas et al., 2018). In accordance with an overall drying trend, an increasing drought risk is projected for Caribbean SIDS (Lehner et al., 2017) and moderate to extreme drought conditions are projected to be about 9% longer on average for 2°C versus 1.5°C for islands in this region (Taylor et al., 2018).

Projected changes in the ocean system at higher warming targets (Section 3.4.4), including potential changes in circulation (Section 3.3.7) and increases in both surface temperatures (Section 3.3.7) and ocean acidification (Section 3.3.10) suggest steadily increasing risks for SIDS associated with warming levels close to and exceeding 1.5°C.

Differences in global sea level between 1.5°C and 2°C depend on the time scale considered and will fully materialize only after 2100 (Section 3.3.9). Projected changes in regional sea level are similarly time dependent, but generally found to be above global average for tropical regions including small islands (Kopp et al., 2014; Jevrejeva et al., 2016). Sea level related threats for SIDS, for example, from salinisation, flooding, permanent inundation, erosion and pressure on ecosystems, will therefore persist well beyond the 21st century even under 1.5°C warming (Section 3.4.5.3; Nicholls et al., 2018). Prolonged interannual sea level inundations may increase throughout the tropical Pacific with ongoing warming and in the advent of increased frequency of extreme La Niña events, exacerbate coastal impacts of projected global mean Sea Level Rise (SLR; Widlansky et al., 2015). Changes to frequency of extreme El Niño and La Niña events may also increase the frequency of droughts and floods in South Pacific islands (Cai et al., 2012; Box 4.2; Section 3.5.2)

Extreme precipitation in small island regions is often linked to tropical storms and contributes to the climate hazard (Khouakhi et al., 2017). Similarly, extreme sea levels for small islands, particularly in the Caribbean, are linked to tropical cyclone occurrence (Khouakhi and Villarini, 2017). Under a 1.5˚C stabilization scenario, there is a projected decrease in the frequency of weaker tropical storms and an increase in the number of intense cyclones (Section 3.3.6, Wehner et al., 2017). There are insufficient studies to assess differences in tropical cyclone statistics for 1.5°C versus 2°C (Section 3.3.6). There are considerable differences in the adaptation responses to tropical cyclones across SIDS (Cross-Chapter Box 11 in Chapter 4).

Impacts on key natural and human systems

Projected increases in aridity and decreases in freshwater availability at 1.5°C, along with additional risks from SLR and increased wave-induced run-up, might leave several atoll islands uninhabitable (Storlazzi et al., 2015; Gosling and Arnell, 2016). Changes in availability and quality of freshwater linked to a combination of changes to climate drivers may adversely impact SIDS' economies (White and Falkland, 2010; Terry and Chui, 2012; Holding and Allen, 2015; Donk et al., 2018). Growth-rate projections based on temperature impacts alone indicate robust negative impacts on GDP per capita growth for SIDS (Petris et al., 2018, Section 3.4.7.1, Section 3.4.9.1, Section 3.5.4.9). These impacts are reduced considerably under 1.5°C but may be increased by escalating risks from climate related extreme weather events and SLR (Section 3.4.5.3, Section 3.4.9.4, Section 3.5.3)

Marine systems and associated livelihoods in SIDS face higher risks at 2°C as compared to 1.5°C (*high agreement, medium evidence*). Mass coral bleaching and mortality are projected to increase due to interactions between rising ocean temperatures, ocean acidification, and destructive waves from intensifying storms (Section 3.4.4, Box 3.4, Section 5.2.3). At 1.5°C, approximately 70–90% of global coral reefs are projected to be at risk of long-term degradation due to coral bleaching, increasing to 99% at 2°C (Schleussner et al., 2016b). Warmer temperatures are also related to an increase in coral disease development, leading to coral degradation (Maynard et al., 2015). For marine fisheries, limiting warming to 1.5°C decreases the risk of species extinction and declines in maximum catch potential, particularly for small islands in tropical oceans (Cheung et al., 2016a).

Long term risks of coastal flooding and impacts on population, infrastructure and assets are projected to increase with higher levels of warming (*high agreement, robust evidence*). Tropical regions including small islands are expected to experience the largest increases in coastal flooding frequency with the frequency of extreme water-level events in small islands projected to double by 2050 (Vitousek et al., 2017). Wave driven coastal flooding risks for reef-lined islands may increase as a result of coral reef degradation and SLR (Quataert et al., 2015). Exposure to coastal hazards is particularly high for SIDS, with a significant share of population, infrastructure and assets at risk (Scott et al., 2012; Kumar and Taylor, 2015; Rhiney, 2015; Byers et al., 2018; Section 3.4.9, Section 3.4.5.3). Limiting warming to 1.5°C instead of 2°C spares the inundation of lands currently home to 60,000 individuals in SIDS by 2150 (Rasmussen et al., 2018). However, such estimates do not take into account shoreline response (Section 3.4.5) or adaptation.

Risks of impacts across sectors are higher at 1.5°C as compared to the present, and will further increase at 2°C (*high agreement, medium evidence*). Projections indicate that at 1.5°C there will be increased incidents of internal migration and displacement (Albert et al., 2017, Sections 3.5.5, 4.3.6, 5.2.2), limited capacity to assess loss and damage (Thomas and Benjamin, 2017) and substantial increases in risk to critical transportation infrastructure from marine inundation (Monioudi et al., 2018). The difference between 1.5°C and 2°C might exceed limits for normal thermoregulation of livestock animals and result in persistent heat stress for livestock animals in SIDS (Lallo et al., 2018).

At 1.5C limits to adaptation will be reached for several key impacts in SIDS resulting in residual impacts and loss and damage (Cross-Chapter Box 12 in Chapter 5, Section 1.1.1). There are a number of reduced risks when limiting temperature increase to 1.5°C versus 2°C, particularly when coupled with adaptation efforts that take into account sustainable development (Mycoo, 2017; Thomas and Benjamin, 2017; Section 3.4.2, Box 4.3, Section 5.6.3.1, Box 5.3). Region-specific pathways for SIDS exist to address climate change (Section 5.6.3.1, Box 5.3, Box 4.6, Cross-Chapter Box 11 in Chapter 4).

[END BOX 3.5 HERE]

3.4.6 Food, nutrition security and food production systems (including fisheries and aquaculture)

3.4.6.1 Crop production

Quantifying the observed impacts of climate change for food security and food production systems requires assumptions about the many non-climate variables that interact with climate change variables. Implementing specific strategies can partly or greatly alleviate the climate change impacts on these systems (Wei et al., 2017), whilst the degree of compensation is mainly dependent on geographical area and crop type (Rose et al., 2016). Despite these issues, recent studies confirm that observed climate changes have already affected crop suitability in many areas, resulting in changes in the production levels of the main agricultural crops. These impacts are evident in many areas of the world ranging from Asia (C. Chen et al., 2014; Sun et al., 2015; He and Zhou, 2016) to America (Cho and McCarl, 2017) and Europe (Ramirez-Cabral et al., 2016), particularly affecting typical local crops cultivated in specific climate conditions (e.g., Mediterranean crops like olive and grapevine, (Moriondo et al., 2013a, b).

Temperature and precipitation trends have reduced crop production and yields, with the most negative impacts on wheat and maize (Lobell et al., 2011), whilst the effects on rice and soybean yields are less clear and may be positive or negative (Kim et al., 2013; van Oort and Zwart, 2018). Warming has resulted in positive effects on crop yield in some high-latitude areas (Jaggard et al., 2007; Supit et al., 2010; Gregory and Marshall, 2012; C. Chen et al., 2014; Sun et al., 2015; He and Zhou, 2016; Daliakopoulos et al., 2017), also suggesting the possibility of more than one harvest per year (B. Chen et al., 2014; Sun et al., 2015). Climate variability was found to explain more than 60% of the of maize, rice, wheat and soybean yield variations in the main global breadbaskets areas (Ray et al., 2015), with variation in the percentage according to crop type and scale (Moore and Lobell, 2015; Kent et al., 2017). Climate trends explain also change in the lengthening of the growing season, where greater modifications were found in the northern latitude areas (Qian et al., 2010; Mueller et al., 2015).

The rise in tropospheric ozone has already reduced yields of wheat, rice, maize, and soybean ranging from 3% to 16% globally (Van Dingenen et al., 2009). Some studies found that increases in atmospheric CO_2 concentrations would be expected to increase yields by enhancing radiation and water use efficiencies (Elliott et al., 2014; Durand et al., 2017). In open-top chamber experiments at elevated CO_2 and 1.5°C warming, maize and potato yields were observed to increase by 45.7% and 11%, respectively (Singh et al. 2013; Abebe et al., 2016). However, observations of actual crop yield trends indicate that reductions as a result of climate change remain more common than crop yield increases, despite increased atmospheric CO_2 concentration (Porter et al., 2014). For instance, McGrath and Lobell (2013) indicated that production stimulation at increased atmospheric CO_2 concentration was mostly driven by differences in climate and crop species, whilst yield variability due to elevated CO_2 was only about 50–70% of the variability due to climate. However, importantly, the faster growth rates induced by elevated CO_2 often coincided with lower protein values in several important C3 cereal grains (Myers et al., 2014) although perhaps not always for C4 grains such as sorghum under drought conditions (De Souza et al., 2015). Elevated CO_2 concentrations of 568–590 ppm alone (a range that corresponds approximately to RCP6 in the 2080s and hence a warming of 2.3–3.3°C (van Vuuren et al., 2011a, WGI Table 12.2) alone reduced the protein, micronutrient, and B vitamin content of the 18 rice cultivars grown most widely grown in southeast Asia, where it is a staple food source, by an amount sufficient to create nutritional-related health risks for 600 million people (Zhu *et al.* 2018). Overall, the effects of increased CO_2 concentration alone during the 21st century are therefore expected to have a negative impact on global food security (*medium confidence*).

Crop yields in the future will also be affected by projected changes in temperature and precipitation. Studies of major cereals showed that maize and wheat yields begin to decline with 1°C –2°C of local warming and under nitrogen stress conditions at low latitudes (Porter et al., 2014; Rosenzweig et al., 2014) (*high confidence*). A few studies since the AR5 have focused on the impacts on cropping systems for scenarios where global mean temperatures increase within 1.5°C. (Schleussner et al., 2016b) projected that constraining warming to 1.5ºC rather than 2ºC would avoid significant risks of tropical crop yield declines in West Africa, South East Asia, and Central and South America. Ricke et al. (2015) highlighted that cropland stability declines rapidly between 1ºC and 3ºC warming, whilst Bassu et al. (2014) suggested that an increase of air temperature negatively influence the modeled maize yield response of –0.5 t ha^{-1} per degree Celsius, as also reported by Challinor et al. (2014) for tropical regions. Niang et al. (2014) projected significantly lower risks to crop productivity in Africa at 1.5ºC compared to 2ºC warming. Lana et al. (2017) indicated that the impact of temperature increases on crop failure of maize hybrids was much greater as temperatures increase to +2°C compared to 1.5°C (*high confidence*). J. Huang et al. (2017) found that limiting warming at +1.5 °C compared to +2°C, maize yield losses would be reduced over drylands. Although Rosenzweig et al. (2017, 2018) did not find a clear distinction between yield declines or increases in some breadbasket regions between the two temperature levels, these studies generally did find declines in breadbasket regions when the effects of CO_2 fertilization were excluded. Iizumi et al. (2017) found lower maize and soybean yields reduction at +1.5°C than at +2°C, higher rice production at +2°C than at +1.5°C warming and no clear differences for wheat at global mean basis. These results were largely consistent with other studies (Faye et al., 2018; Ruane et al., 2018). In the western Sahel and southern Africa, moving from 1.5°C to 2°C warming was projected to result in further reduction of maize, sorghum and cocoa cropping areas suitability as well as yield losses especially for C3, only partially compensated by rainfall change (Läderach et al., 2013; World Bank, 2013; Sultan and Gaetani, 2016).

Some studies found a significant reduction in global production of wheat rice, maize, and soybean of 6.0 ± 2.9%, 3.2 ± 3.7%, 7.4 ± 4.5% and 3.1%, respectively, for each degree Celcius increase in global mean temperature (Asseng et al. 2015; C. Zhao et al., 2017). Similarly, Li et al. (2017) indicated a significant reduction in rice yields by about 10.3% in the greater Mekong sub-region (*medium confidence*). Large rice and maize yield losses are to be expected in China due to climate extremes (Wei et al., 2017; Zhang et al., 2017) (*medium confidence*).

Crop production is also negatively affected also by a factor generally excluded from the aforementioned studies, that is the increase in both direct and indirect climate extremes. Direct extremes include changes in rainfall extremes (Rosenzweig et al., 2014), increases in hot nights (Welch et al., 2010; Okada et al., 2011)); extremely high daytime temperature (Schlenker and Roberts, 2009; Jiao et al., 2016, Lesk et al., 2016); drought (Jiao et al., 2016; Lesk et al., 2016), heat stress (Deryng et al., 2014, Betts et al., 2018), flood (Betts et al., 2018; Byers et al., 2018), chilling damage, (Jiao et al., 2016), while indirect effects include the spread of pest and diseases (van Bruggen et al., 2015, Jiao et al., 2014), which can also have detrimental effects on cropping systems.

Taken together, the findings of studies on the effects of changes in temperature, precipitation, changes in CO_2 concentration and extreme weather events indicate that a global warming of 2°C is projected to result in a greater reduction in global crop yields and global nutrition than a global warming of 1.5°C (*high confidence*, Section 3.6).

3.4.6.2 Livestock production

Studies of climate change impacts on livestock production are few in number. Climate change is expected to directly affect yield quantity and quality (Notenbaert et al., 2017), beside indirectly impacting the livestock sector through feed quality changes and spread of pests and diseases (Kipling et al., 2016) (*high confidence*). Increased warming and its extremes are expected to cause changes in physiological processes in livestock (i.e., thermal distress, sweating and high respiratory rates) (Mortola and Frappell, 2000) and to have detrimental effects on animal feeding, growth rates (André et al., 2011; Renaudeau et al., 2011; Collier and Gebremedhin, 2015) and reproduction (De Rensis et al., 2015). Wall et al. (2010) observed reduced milk yields and increased cow mortality as the impact of heat stress on dairy cow production over some UK regions, whilst reduction in water supply might increase cattle water demand (Masike and Urich, 2008). Generally, heat stress can be responsible for domestic animal mortality increase and economic losses (Vitali et al., 2009), affecting a wide range of reproductive parameters (e.g., embryonic development and reproductive efficiency in pigs, Barati et al., 2008; ovarian follicle development and ovulation in horses, Mortensen et al., 2009).

Much attention has also been dedicated to ruminant diseases (e.g., liver fluke, Fox et al., 2011; blue-tongue virus, Guis et al., 2012; Foot-and-Mouth Disease (FMD), Brito et al. (2017); or zoonotic diseases, Njeru et al., 2016; Simulundu et al., 2017).

Future climate change impacts on livestock are expected to increase. In temperate climates, warming is expected to lengthen forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al., 2010; Hatfield et al., 2011; Izaurralde et al., 2011). Similar studies confirmed decrease in forage quality both for natural grassland in France (Graux et al., 2013) and sown pastures in Australia (Perring et al., 2010). Water resources availability for livestock are expected to decrease due to increased runoff and reduced groundwater resource. Increased temperature will likely induce changes in river discharge and basins water amount, leading human and livestock populations to experience water stress especially over the driest areas (Palmer et al., 2008) (i.e., sub-Saharan Africa and South Asia) (*medium confidence*). Elevated temperatures are also expected to increase methane production (M.A. Lee et al., 2017; Knapp et al., 2014). Globally, a decline in livestock of more 7.5-9.6% is expected at about 2°C warming, with associated economic losses of between $9.7 and $12.6 billion (Boone et al., 2017).

3.4.6.3 Fisheries and aquaculture production

Global fisheries and aquaculture contribute a total of 88.6 and 59.8 million tons from capture and aquaculture (FAO, 2016), playing an important role in food security of a large number of countries (McClanahan et al., 2015; Pauly and Charles, 2015) and resulting essential to meet the protein demand of a growing global population (Cinner et al., 2012, 2016; FAO, 2016; Pendleton et al., 2016). A steady increase in the risks associated with bivalve fisheries and aquaculture at mid-latitude is coincident with increases in temperature, ocean acidification, introduced species, disease and other drivers (Lacoue-Labarthe et al., 2016; Clements et al., 2017; Clements and Chopin, 2017; Parker et al., 2017). Sea level rise and storm intensification pose a risk to hatcheries and other infrastructure (Callaway et al., 2012; Weatherdon et al., 2016), whilst others risks are associated with the invasion of parasites and pathogens (Asplund et al., 2014; Castillo et al., 2017). Human actions have reduced the risks from these factors which are expected to be more likely moderated under RCP2.6 and very high under RCP8.5 (Gattuso et al., 2015). The climate related risks for fin fish (Section 3.4.4) are producing a number of challenges for small scale fisheries (e.g., (Kittinger, 2013; Pauly and Charles, 2015; Bell et al., 2017). Recent literature (2015–2017) described growing threats from the rapid shifts in the biogeography of key species (Poloczanska et al., 2013, 2016; Burrows et al., 2014; García Molinos et al., 2015) and the ongoing rapid degradation of key ecosystems such as coral reefs, seagrass and mangroves (Section 3.4.4; Box 3.4). The acceleration of these changes, coupled with non-climate stresses (e.g., pollution, overfishing, unsustainable coastal development), drive many small-scale fisheries well below the sustainable harvesting levels required to maintain these resources as a source of food (McClanahan et al., 2009, 2015; Cheung et al., 2010; Pendleton et al., 2016). As a result, projections of climate change and the growth in human population increasingly project scenarios that include shortages of fish protein for many regions (e.g., Pacific Ocean, Bell et al., 2013; 2017); Indian Ocean, for example, (McClanahan et al., 2015). Mitigation of these risks involves marine spatial planning, fisheries repair, sustainable aquaculture, and the development of alternative livelihoods (Kittinger, 2013; McClanahan et al., 2015; Song and Chuenpagdee, 2015; Weatherdon et al., 2016). Other threats concern the increasing incidence of alien species and diseases (Kittinger et al., 2013; Weatherdon et al., 2016).

Risks of climate change related impacts on low latitude fin fisheries are low today, but are expected to reach very high levels under all RCPs especially at low latitudes (*high confidence*) by 1.1ºC. Projections for mid to high latitude fisheries include increases in fishery productivity in some cases (Cheung et al., 2013; Hollowed et al., 2013; Lam et al., 2014; FAO, 2016). These are associated with the biogeographical shift of species towards higher latitudes (Fossheim et al., 2015) which brings benefits as well as challenges (e.g., increased risk of disease and invasive species). Factors underpinning the expansion of fisheries production to high latitude locations include warming, increased light levels and mixing due to retreating sea ice (Cheung et al., 2009), resulting in substantial increases in primary productivity and fish harvesting in the North Pacific and North Atlantic (Hollowed and Sundby, 2014).

Present day risks for mid latitude bivalve fisheries and aquaculture are low up to 1.3ºC, *moderate* at 1.3ºC, and *moderate* to *high* up to 1.9ºC (Figure 3.17). For instance, Cheung et al. (2016a), simulating the loss in fishery productivity at 1.5°C, 2ºC and 3.5°C above the preindustrial period, found that the potential global catch for marine fisheries will *likely* decrease by more than 3 million metric tons for each degree of warming. Low latitude finfish fisheries have higher risks of impacts, with present day risks being moderate and becoming high risks at 1.5˚C and 2˚C. High latitude fisheries are undergoing major transformations, and while production is increasing, present day risk is moderate, and remains at moderate at 1.5˚C and 2˚C (Figure 3.3).

Adaptation measures can be applied to shellfish, large pelagic fish resources and biodiversity and include options such as protecting reproductive stages and brood stock from periods of high Ocean Acidification (OA), stock selection for high tolerance to OA (Ekstrom et al., 2015; Rodrigues et al., 2015; Handisyde et al., 2016; Lee, 2016; Weatherdon et al., 2016; Clements and Chopin, 2017) (*high confidence*), redistribution of highly migratory resources (Pacific tuna) (*high confidence*), governance instruments such as international fisheries agreements (Lehodey et al., 2015; Matear et al., 2015), protection and regeneration of reef habitats, reduction of coral reefs stresses and development of alternative livelihoods (e.g., aquaculture, Bell et al., 2013, 2017).

Cross-Chapter Box 6: Food Security

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Climate change influences food and nutritional security through its effects on food availability and quality, access, and distribution (Paterson and Lima, 2010; Thornton et al., 2014; FAO, 2016). More than 815 million people were undernourished in 2016; 11% of the world's population, with higher proportions of populations in Africa (20%), southern Asia (14.4%) and the Caribbean (17.7%), with recent decreases in food security (FAO et al., 2017). Overall, food security is expected to be reduced at 2°C warming compared to 1.5°C warming, due to projected impacts of climate change and extreme weather on crop nutrient content and yields, livestock, fisheries and aquaculture (Sections 3.4.4.12 and 3.4.3.6), and land use (cover type and management) (*high confidence;* Section 3.4.6). The impacts of climate change on yield, area, pests, price, and food supplies are projected to have major implications for sustainable development, poverty eradication, inequality, and the ability for the international community to meet the United Nations Sustainable Development Goals (SDGs; Cross-Chapter Box 4 in Chapter 1)

Goal 2 of the SDGs aims to end hunger, achieve food security, improve nutrition, and promote sustainable agriculture by 2030. This builds on the Millennium Development Goal (MDG); efforts to achieve Goal 1 reduced the proportion of undernourished people in low- and middle-income countries from 23.3% in 1990 to 12.9% in 2015. Climate change threatens the possibility of achieving SDG 2 and could reverse the progress made. Food security and agriculture are also critical to other aspects of sustainable development, including eradicating poverty (SDG 1), health and wellbeing (SDG 3), clean water (SDG 6), decent work (SDG 8) and the protection of ecosystems on land and water (SDG 14 and SDG 15) (UN, 2015, 2017; Pérez-Escamilla, 2017).

Increasing global temperatures pose large risks to food security globally and regionally, especially at low latitude areas (Cheung et al., 2010; Rosenzweig et al., 2013; Porter et al., 2014; Rosenzweig and Hillel, 2015; Lam et al., 2016) with warming of 2°C projected to result in a greater reduction in global crop yields and global nutrition than a global warming of 1.5°C (*high confidence*, Section 3.4.6) owing to the combined effects of changes in temperature, precipitation, and changes in extreme weather events and in CO_2 concentrations. Climate change can exacerbate malnutrition, reducing nutrient availability and quality of food products (Cramer et al., 2014; Springmann et al., 2016); *medium confidence*). Generally, vulnerability to decreases in water and food availability is reduced at 1.5°C versus 2°C (Cheung et al., 2016a; Betts et al., 2018) , whilst at 2°C these are expected to be exacerbated especially in regions such as the African Sahel, the Mediterranean, central Europe, the Amazon, and western and southern Africa (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018) (*high confidence*).

Rosenzweig et al. (2018) and Ruane et al. (2018) report that the higher CO_2 concentrations at 2^{o}C caused positive effects in some regions compared to 1.5^{o}C. Production can also benefit from warming in higher latitudes with fertile soils, crop, and grassland, in contrast to the situation at low latitudes (Section 3.4.6) and similar benefits could arise for high latitude fisheries production (*high confidence*; Section 3.4.6.3). Studies exploring regional climate change risks on crop production are strongly influenced by the use of alternative regional climate change projections and the assumed strength of CO_2 fertilisation effects (Section 3.6) which are uncertain. For C3 crops, theoretically advantageous CO_2 fertilisation effects may not be realized in the field; further, they are often accompanied by losses in protein and nutrient content of crops (Section 3.6) and hence these projected benefits may not be realized. In addition, some micronutrients such as iron and zinc will be less accumulated and less available in food (Myers *et al.*, 2014). Together, the impacts on protein availability may take as many as 150 million people into protein deficiency by 2050 (Medek *et al.*, 2017). However, short-term benefits could arise for high latitude fisheries production as waters warm, sea ice contracts and primary productivity increases due to climate change (Cheung et al., 2010; Hollowed and Sundby, 2014; Lam et al., 2016; Sundby et al., 2016; Weatherdon et al., 2016) (*high confidence*; Section 3.4.6.3).

Factors affecting projections of food security include variability in regional climate projections, climate change mitigation (where this affects land use; see Section 3.6 and Crosss-Chapter Box 7) and biological responses (McGrath and Lobell, 2013; Elliott et al., 2014; Pörtner et al., 2014; Durand et al., 2017; AR5 6.5.1) (*medium confidence*; Section 3.4.6.1), extreme events (droughts, floods) (Rosenzweig et al., 2014; Wei et al., 2017) (*high confidence*; Sections 3.4.6.1, 3.4.6.2), financial volatility (Kannan et al., 2000; Ghosh, 2010; Naylor and Falcon, 2010; HLPE, 2011) and the distributions of pests and disease (van Bruggen et al., 2015; Jiao et al., 2014). Changes in temperature and precipitation are projected to increase global food prices by 3–84% by 2050 (IPCC, 2013). Differences in price impacts of climate change are accompanied by differences in land use change (Nelson et al., 2014b), energy policies and food trade (Mueller et al., 2011; Wright, 2011; Roberts and Schlenker, 2013). Fisheries and aquatic production systems (aquaculture) face similar challenges to those of crop and livestock sectors (Asiedu et al., 2017a, b; Utete et al., 2018; Section 3.4.6.3). Human influences on food security include demography, food wastage, diet shift, incomes and prices, storage, health status, trade patterns, conflict, and access to land and government or other assistance (Chapters 4 and 5). Across all these systems, the efficiency of adaptation strategies is uncertain, because it is strongly linked with future economic and trade environments and their response to changing food availability (Lobell et al., 2011; von Lampe et al., 2014; d'Amour et al., 2016; Wei et al., 2017) (*medium confidence*).

Climate change impacts on food security can be reduced through adaptation (Hasegawa et al., 2014). While climate change is very likely to decrease agricultural yield, the consequences could be reduced substantially at 1.5ºC with appropriate investment (Neumann et al., 2010; Muller, 2011; Roudier et al., 2011), awareness-raising to help inform farmers of new technologies for maintaining yield, and strong adaptation strategies and policies that develop sustainable agricultural choices (Sections 4.3.2 and 4.5.3). In this regard, initiatives such as 'climate smart' food production and distribution systems may assist adaptation via technologies and adaptation strategies for food systems (Lipper et al., 2014; Martinez-Baron et al., 2018; Whitfield et al., 2018) as well as meet mitigation goals (Harvey et al., 2014).

K.R. Smith et al. (2014) concluded that climate change will negatively affect childhood undernutrition and stunting through reduced food availability, and will negatively affect undernutrition-related childhood mortality and increase disability-adjusted life years lost, with the largest risks in Asia and Africa (Ishida et al., 2014; Hasegawa et al., 2016; Springmann et al., 2016; Annex 3.1 Table S11). Studies comparing the health risks associated with food insecurity at 1.5°C and 2°C concluded that risks are higher and the globally undernourished population larger at 2°C (Hales et al., 2014; Ishida et al., 2014; Hasegawa et al., 2016). Climate change impacts on dietary and weight-related risk factors were projected to increase mortality due to global reductions in food availability and consumption of fruit, vegetables, and red meat (Springmann et al., 2016). Further, temperature increases are reducing the protein and micronutrient content of major cereal crops, which is expected to further affect food security (Myers et al., 2017) (Zhu et al. 2018).

Strategies for improving food security often do so in complex settings such as the Mekong River Basin in South-East Asia. The Mekong is a major food bowl (Smajgl et al., 2015) yet is also a climate change hotspot (de Sherbinin, 2014; Lebel et al., 2014). It is also a useful illustration of the complexity of adaptation choices and actions in a 1.5˚C world. Climate projections indicate increased annual average temperatures and precipitation (Zhang et al., 2016) and increased flooding and related disaster risks (T.F. Smith et al., 2013; Ling et al., 2015; Zhang et al., 2016). Sea level rise and saline intrusion are ongoing risks to agricultural systems (Renaud et al., 2015). The main climate impacts in the Mekong will be on ecosystem health through salinity intrusion, biomass reduction, and biodiversity losses (Le Dang et al., 2014; Smajgl et al., 2015); agricultural productivity and food security (Smajgl et al., 2015); livelihoods such as fishing and farming (D. Wu et al., 2013); and disaster risk (D. Wu et al., 2013; Hoang et al., 2016) with implications for human mortality and economic and infrastructure losses.

Adaptation imperatives and costs in the Mekong will be higher under increased temperatures via impacts on agriculture and aquaculture, hazard exposure, and infrastructure. Adaptation measures to meet food security include greater investment in crop diversification and integrated agriculture-aquaculture practices (Renaud et al., 2015), improving water use technologies (e.g., irrigation, pond capacity improvement, rainwater harvesting), soil management, crop diversification, and strengthening allied sectors such as livestock rearing and aquaculture (ICEM, 2013). Ecosystem-based approaches, such as integrated water resources management, demonstrate successes in mainstreaming adaptation into existing strategies (Sebesvari et al., 2017). However, some of these adaptive strategies can have negative impacts that deepen the divide between land-rich and land-poor farmers (Chapman et al., 2016). Construction of high dikes for example has enabled triple-cropping with benefits for land-wealthy farmers but increasing debt for land-poor farmers (Chapman and Darby, 2016).

Institutional innovation has happened through the establishment of the Mekong River Commission (MRC) in 1995, an intergovernmental body between Cambodia, Lao PDR, Thailand and Viet Nam. The MRC has facilitated impact assessment studies, regional capacity building, and local project implementation (Schipper et al., 2010), although mainstreaming of adaptation into development policies has lagged behind needs (Gass et al., 2011). Existing adaptation interventions can be strengthened through improving flexibility of institutions dealing with land use planning and agricultural production, improved monitoring of saline intrusion, and setting up early warning systems that can be accessed by the local authorities or farmers (Renaud et al., 2015; Hoang et al., 2016; Tran et al., 2018). It is critical to identify and invest in synergistic strategies from an ensemble of infrastructural options (e.g., building dikes); soft adaptation measures (e.g., land-use change) (Smajgl et al., 2015; Hoang et al., 2018); combinations of top-down government-led (e.g., relocation) and bottom-up household strategies (e.g., increasing house height) (Ling et al., 2015); and community-based adaptation initiatives that merge scientific knowledge with local solutions (Gustafson et al., 2016, 2017; Tran et al., 2018). Critical attention needs to be given to strengthening social safety nets and livelihood assets whilst ensuring that adaptation plans are mainstreamed into broader development goals (Sok and Yu, 2015; Kim et al., 2017). The complexity of environmental, social and economic pressure on people in the Mekong River Basin highlights the complexity of climate impacts and adaptation in this region, and the fact that costs are likely to be much lower at 1.5ºC than 2ºC.

[END BOX X-B 3.1 HERE]

3.4.7 Human health

Climate change adversely affects human health by increasing exposure and vulnerability to climate-related stresses, and decreasing the capacity of health systems to manage changes in the magnitude and pattern of climate-sensitive health outcomes (Cramer et al., 2014; Hales et al., 2014). Changing weather patterns are associated with shifts in the geographic range, seasonality, and intensity of transmission of selected climate-sensitive infectious diseases (e.g., Semenza and Menne, 2009), and increasing morbidity and mortality are associated with extreme weather and climate events (e.g., K.R. Smith et al., 2014). Health detection and attribution studies conducted since the AR5 provided evidence using multi-step attribution that climate change is negatively affecting adverse health outcomes associated with heatwaves; Lyme disease in Canada; and *Vibrio* emergence in northern Europe (Mitchell, 2016; Mitchell et al., 2016; Ebi et al., 2017). The IPCC AR5 concluded there is *high* to *very high confidence* that climate change will lead to greater risks of injuries, disease and death due to more intense heatwaves and fires; increased risks of undernutrition; and consequences of reduced labor productivity in vulnerable populations (K.R. Smith et al., 2014).

3.4.7.1 Projected risk at 1.5°C and 2°C

Annex 3.1, Tables S7, S8 and S9 (based on Ebi et al., 2018) summarize the projected risks to human health of warming of 1.5°C and 2°C from studies of temperature-related morbidity and mortality, air quality and vector borne diseases assessed in and since the AR5. Other climate-sensitive health outcomes, such as diarrheal diseases, mental health and the full range of sources of poor air quality, were not considered because of the lack of projections of how risks could change at 1.5°C and 2°C. Few projections were for specific temperatures above pre-industrial temperature; Annex 3.1, Table S6 provides the conversions used to translate risks projected at particular time slices to temperature change (Ebi et al., 2018).

Temperature-related morbidity and mortality: The magnitude of projected heat-related morbidity and mortality is greater at 2°C than at 1.5°C (*very high confidence*) (Doyon et al., 2008; Jackson et al., 2010; Hanna et al., 2011; Huang et al., 2012; Petkova et al., 2013; Hajat et al., 2014; Hales et al., 2014; Honda et al., 2014; Vardoulakis et al., 2014; Garland et al., 2015; Huynen and Martens, 2015; Li et al., 2015; Schwartz et al., 2015; L. Wang et al., 2015; Guo et al., 2016; T.T. Li et al., 2016; Chung et al., 2017; Kendrovski et al., 2017; Arnell et al., 2018; Mitchell, 2018). The number of people exposed to heat events is projected to be greater at 2°C than at 1.5°C (Russo et al., 2016; Mora et al., 2017; Byers et al., 2018; Harrington and Otto, 2018; King et al., 2018). The extent to which morbidity and mortality increase varies by region, presumably because of acclimatization, population vulnerability, the built environment, access to air conditioning and other factors (Russo et al., 2016; Mora et al., 2017; Byers et al., 2018; Harrington and Otto, 2018; King et al., 2018). Populations at highest risk include older adults, children, women, those with chronic diseases, and people taking certain medications (*very high confidence*). Assuming adaptation takes place reduces the projected magnitude of risks (Hales et al., 2014; Huynen and Martens, 2015; Li et al., 2016b).

In some regions, cold-related mortality is projected to decrease with warmer temperatures, although increases in heat-related mortality generally are projected to outweigh any reductions in cold-related mortality with warmer winters, with the heat-related risks increasing with greater degrees of warming (Huang et al., 2012; Hajat et al., 2014; Vardoulakis et al., 2014; Gasparrini et al., 2015; Huynen and Martens, 2015; Schwartz et al., 2015).

Occupational health: Higher ambient temperatures and humidity levels place additional stress placed on individuals engaging in physical activity. Safe work activity and worker productivity during the hottest months of the year would be increasingly compromised with additional climate change (*medium agreement, low evidence*) (Dunne et al., 2013; Kjellstrom et al., 2013, 2017; Sheffield et al., 2013; Habibi Mohraz et al., 2016). Patterns of change may be complex; for example, at 1.5°C, there could be about a 20% reduction in areas experiencing severe heat stress in East Asia, compared to significant increases in low latitudes at 2°C (Lee and Min, 2018). The costs of preventing workplace heat-related illnesses through worker breaks suggest the difference in economic loss between 1.5°C and 2°C could be approximately 0.3% global GDP in 2100 (Takakura et al., 2017). In China, taking into account population growth and employment structure, high temperature subsidies for employees working on extremely hot days are projected to increase from 38.6 billion yuan yr^{-1} in 1979–2005 to 250 billion yuan yr^{-1} in the 2030s (about 1.5°C) (Zhao et al., 2016).

Air quality: Because ozone formation is temperature dependent, projections focusing only on temperature increase generally conclude that ozone-related mortality will increase with additional warming, with the risks higher at 2°C than at 1.5°C (*high confidence*) (Heal et al., 2013; Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016; Dionisio et al., 2017; J.Y. Lee et al., 2017); Annex 3.1 Table S.8) reductions in precursor emissions would reduce future ozone concentrations (and associated mortality). Changes in projected PM-related mortality could increase or decrease, depending on climate projections and emissions assumptions (Tainio et al., 2013; Likhvar et al., 2015; Silva et al., 2016; Table S8).

Malaria: Recent projections of the potential impacts of climate change on malaria globally and for Asia, Africa, and South America (Annex 3.1 Table S9) confirm that weather and climate are among the drivers of the geographic range, intensity of transmission, and seasonality of malaria, and that the relationships are not necessarily linear, resulting in complex patterns of changes in risk with additional warming (*very high confidence*) (Ren et al., 2016; Song et al., 2016; Semakula et al., 2017). Projections suggest the burden of malaria could increase with climate change because of a greater geographic range of the *Anopheles* vector, longer season, and/or increase in the number of people at risk, with larger burdens with greater amounts of warming, with regionally variable patterns (*high agreement, medium evidence*). Vector populations are projected to shift with climate change, with expansions and reductions depending on the degree of local warming, the ecology of the mosquito vector, and other factors (Ren et al., 2016).

***Aedes* (mosquito vector for dengue fever, chikungunya, yellow fever, and Zika virus):** Projections of the geographic distribution of *Aedes aegypti* and *Ae. albopictus* (principal vectors) or of the prevalence of dengue fever generally conclude there will be an increase in the number of mosquitos and a larger geographic range at 2° than at 1.5°C and beyond than at present, and suggest more individuals at risk of dengue fever, with regional differences (*high confidence*) (Fischer et al., 2011; Colón-González et al., 2013; Fischer et al., 2013; Bouzid et al., 2014; Ogden et al., 2014a; Mweya et al., 2016). The risks increase with greater warming. Projections suggest that climate change will expand the geographic range of chikungunya, with greater expansions with higher degrees of warming (Tjaden et al., 2017).

Other vector-borne diseases: Increased warming in North America and Europe could result in latitudinal and altitudinal expansions of regions climatically suitable for West Nile Virus transmission, particularly along the current edges of its transmission areas, and extension of the transmission season, with the magnitude and pattern of changes varying by location and degree of warming (Semenza et al., 2016). Most projections conclude that climate change will expand the geographic range and seasonality of Lyme and other tick-borne diseases in parts of North America and Europe (Ogden et al., 2014b; Levi et al., 2015). The changes are larger with greater warming and under higher greenhouse gas emission pathways. Projections of the impacts of climate change on leishmaniosis and Chagas disease indicate climate change could increase or decrease future health burdens, with greater impacts at higher degrees of warming (González et al., 2014; Ceccarelli and Rabinovich, 2015).

In summary, warming of 2°C poses greater risks to human health than warming of 1.5°C, often with the risks varying regionally, and with a few exceptions (*high confidence*). There is *very high confidence* that each additional unit of warming will increase heat-related morbidity and mortality, and that adaptation would reduce the magnitude of impacts. There is *high confidence* that ozone-related mortality will increase if precursor emissions remain the same, and that warmer temperatures will affect the transmission of some infectious diseases, with increases and decreases projected depending on disease (e.g., malaria, dengue, West Nile virus, and Lyme disease), region, and degree of temperature change.

3.4.8 Urban areas

There is new literature on urban climate change and its differential impacts on and risks for infrastructure sectors —energy, water, transport, buildings— and vulnerable populations, including those living in informal settlements (UCCRN, 2018). However, there is limited literature on the risks of warming of 1.5°C and 2°C in urban areas. Heat-related extreme events (Matthews et al., 2017), variability in precipitation (Yu et al., 2018) and sea-level rise can directly affect urban areas (Bader et al., 2018; Dawson, et al., 2018; Section 3.4.5). Indirect risks may arise from interactions between urbanization and natural systems.

Future warming and urban expansion could lead to more extreme heat stress (Argüeso et al., 2015; Suzuki-Parker et al., 2015). At 1.5°C, twice as many megacities (such as Lagos, Nigeria and Shanghai, China) could become heat-stressed, exposing more than 350 million more people to deadly heat by 2050 under midrange population growth. Without considering adaptation options, such as cooling from more reflective roofs, and overall characteristics of urban agglomerations in terms of landuse, zoning and building codes (UCCRN, 2018), at 2°C warming, Karachi (Pakistan) and Kolkata (India) could expect annual conditions equivalent to the deadly 2015 heatwaves (Akbari et al., 2009; Oleson et al., 2010; Matthews et al., 2017). Warming of 2°C is expected to increase the risks of heatwaves in China's urban agglomerations (Yu and Zhai, 2018). Stabilising at 1.5 °C warming could decrease extreme temperature-related mortality compared with stabilisation at 2°C for key European cities, assuming no adaptation and constant vulnerability (Jacob et al., 2018; Mitchell et al., 2018). Holding temperature change to below 2°C, taking Urban Heat Islands (UHI) into consideration, could result in a substantial increase in the occurrence of deadly heatwaves in cities, with the impacts similar at 1.5°C and 2°C, with both substantially larger than under the present climate (Matthews et al., 2017; Yu et al., 2018).

For extreme heat events, an additional 0.5°C of warming implies a shift from the upper-bounds of observed natural variability to a new global climate regime (Schleussner et al., 2016b), with differential implications for the urban poor (Revi et al., 2014; Jean-Baptiste et al., 2018; UCCRN, 2018). Adverse impacts of extreme events could arise in tropical coastal areas of Africa, South America, and South East Asia (Schleussner et al., 2016b), with large informal settlements and other vulnerable urban populations, and with vulnerable assets, including urban infrastructure—energy, water, transport, and buildings (McGranahan et al., 2007; Hallegatte et al., 2013; Revi et al., 2014; UCCRN, 2018). Mediterranean water stress is projected to increase from 9% at 1.5°C to 17% at 2°C compared to 1986-2005. Regional dry spells are projected to expand from 7% at 1.5°C to 11% at 2°C. Sea-level rise is expected to be lower for 1.5°C than 2°C, lowering risks for coastal metropolitan agglomerations (Schleussner et al., 2016b).

Increases in the intensity of UHI could exacerbate warming of urban areas, with projections ranging from a 6% decrease to a 30% increase for a doubling of CO_2 (McCarthy et al., 2010). Increases in population and city size, in the context of a warmer climate, are projected to increase UHI (Georgescu et al., 2012; Argüeso et al., 2014; Conlon et al., 2016; Kusaka et al., 2016; Grossman-Clarke et al., 2017).

Climate models are better at projecting implications of greenhouse gas forcing on physical systems than assessing differential risks associated with achieving a specific temperature target (James et al., 2017). These challenges in managing risks are amplified when combined with the scale of urban areas and assumptions about socio-economic pathways (Krey et al., 2012; Kamei et al., 2016; Yu et al., 2016; Jiang and Neill, 2017).

In summary, in the absence of adaptation, in most cases, warming of 2°C poses greater risks to urban areas than warming of 1.5°C, depending on the vulnerability of the location (coastal or non-coastal), infrastructure sectors (energy, water, transport), levels of poverty and the mix of formal and informal settlements.

3.4.9 Key economic sectors and services

Climate change will affect tourism, energy systems, and transportation through direct impacts on operations (e.g., sea level rise) and through impacts on supply and demand, with the risks varying significantly across geographic region, season, and time. Projected risks also depend on assumptions with respect to population growth, the rate and pattern of urbanization, and investments in infrastructure. Table S10 in Annex 3.1 summarizes the cited publications.

3.4.9.1 Tourism

The implications of climate change for the global tourism sector are far-reaching and are impacting sector investments, destination assets (environment and cultural), operational and transportation costs, and tourist demand patterns (Scott et al., 2016a; Scott and Gössling, 2018). Since the AR5, observed impacts on tourism markets and destination communities continue to be not well analyzed, despite many analogue conditions (e.g., heatwaves, major hurricanes, wild fires, reduced snow pack, coastal erosion, coral reef bleaching) that are anticipated to occur more frequently with climate change. There is some evidence that observed impacts on tourism assets (environmental and cultural heritage) is leading to the development of 'last chance' tourism markets, where travellers visit destinations before they are substantially degraded by climate change impacts or to view the impacts of climate change on landscapes (Lemelin et al., 2012; Stewart et al., 2016; Piggott-McKellar and McNamara, 2017).

There is limited research on the differential risks of 1.5° versus 2°C temperature increase and resultant environmental and socio-economic impacts in the tourism sector. The translation of these changes in climate resources for tourism into projections of tourism demand remains geographically limited to Europe. Based on analyses of tourist comfort, summer and spring-autumn tourism in much of Western Europe may be favored by 1.5°C warming, with negative effects projected for Spain, Cyprus (decrease of 8% and 2% overnight stays, respectively) and most coastal regions of the Mediterranean (Jacob et al., 2018). Similar geography of potential tourism gains (central and northern Europe) and reduced summer favorability (Mediterranean countries) are projected under 2°C (Grillakis et al., 2016). Considering potential changes in natural snow only, winter overnight stays at 1.5°C are projected to decline by 1–2% in Austria, Italy, and Slovakia, with an additional 1.9 million overnight stays lost under 2°C warming (Jacob et al., 2018). Using an econometric analysis of the relationship between regional tourism demand and climate conditions, Ciscar et al. (2014) projected a 2°C world would reduce European tourism by -5% (€15 billion yr^{-1}), with losses up to -11% (€6 billion yr-1) for southern Europe and a potential gain of €0.5 billion yr^{-1} in the UK.

Growing evidence indicates that the magnitude of projected impacts is temperature-dependent and sector risks will be much greater with higher temperature increases and resultant environmental and socio-economic impacts (Markham et al., 2016; Scott et al., 2016a; Jones, 2017; Steiger et al., 2017). Studies from 27 countries consistently project substantially decreased reliability of ski areas that are dependent on natural snow, increased snowmaking requirements and investment in snowmaking systems, shortened and more variable ski seasons, a contraction in the number of operating ski areas, altered competitiveness among and within regional ski markets, and subsequent impacts on employment and the value of vacation properties (Steiger et al., 2017). Studies that continue to omit snowmaking do not reflect the operating realities of most ski areas and overestimate impacts at 1.5–2°C. In all regional markets, the extent and timing of these impacts depend on the magnitude of climate change and the types of adaptive responses by the ski industry, skiers and destination communities. The decline in number of former Olympic Winter Games host locations that could remain climatically reliable for future Olympic and Paralympic Winter Games was also projected to be much greater under scenarios warmer than 2°C (Scott et al., 2015; Jacob et al., 2018).

The tourism sector is also affected by climate-induced changes in environmental systems that are critical assets for tourism, including biodiversity, beaches, glaciers, and other environmental and cultural heritage. Limited analyses of projected risks associated with 1.5° versus 2°C are available (Section 3.4.4.12). A global analysis of SLR risk to 720 UNESCO Cultural World Heritage sites projected that about 47 sites could be affected under 1°C warming, increasing to 110 and 136 sites under 2°C and 3°C, respectively (Marzeion and Levermann, 2014). Similar risks to vast worldwide coastal tourism infrastructure and beach assets remain unquantified in most major tourism destinations and SIDS that economically depend on coastal tourism. One exception is the projection that an eventual 1 m SLR could partially or fully inundate 29% of 900 coastal resorts in 19 Caribbean countries, with a substantially higher proportion (49–60%) vulnerable to associated coastal erosion (Scott and Verkoeyen, 2017).

A major barrier to understanding the risks of climate change for tourism (from the destination community to global scales) has been the lack of integrated sectoral assessments that analyze the full range of potential compounding impacts and their interactions with other major drivers of tourism (Rosselló-Nadal, 2014; Scott et al., 2016b). A global vulnerability index (27 indicators) in 181 countries found that countries with the lowest risk are found in western and northern Europe, central Asia, Canada, and New Zealand, while the highest sector risks are projected in Africa, the Middle East, South Asia, and SIDS in the Caribbean, Indian and Pacific Oceans (Scott and Gössling, 2018). Countries with the highest risks and where tourism represents a significant proportion of the national economy (more than 15% GDP) include many SIDS and least developed countries. Sectoral climate change risk also aligned strongly with regions where tourism growth is projected to be the strongest over the coming decades, including sub-Saharan Africa and South Asia; representing an important potential barrier to tourism development. The transnational implications of these impacts on the highly interconnected global tourism sector and the contribution of tourism to achieving the 2030 Sustainable Development Goals (SDGs) remain important uncertainties.

In summary, climate is an important factor influencing the geography and seasonality of tourism demand and spending globally (*very high confidence*). Increasing temperatures will directly impact climate dependent tourism markets, including sun and beach, and snow sports tourism, with lesser risks for other tourism markets that are less climate sensitive (*high confidence*). The degradation or loss of beach and coral reef assets will increase risks for coastal tourism, particularly in sub-tropical and tropical regions (*high confidence*).

3.4.9.2 Energy systems

Climate change will likely increase the demand for air conditioning in most tropical and sub-tropical regions (Arent et al., 2014; Hong and Kim, 2015). Increasing temperatures will decrease the thermal efficiency of fossil, nuclear, biomass and solar power generation technologies, as well as buildings and other infrastructure (Arent et al., 2014). For example, in Ethiopia, capital expenditures through 2050 might either decrease by approximately 3% under extreme wet scenarios or increase by up to 4% under a severe dry scenario (Block and Strzepek, 2012). In the Zambezi River basin, hydropower may fall by 10% by 2030 (about 1.5°C) and by 35% by 2050 under the driest scenario (Strzepek et al., 2012).

Impacts on energy systems can affect Gross Domestic Product (GDP). The economic damage in the United States from climate change is estimated to be roughly 1.2% cost of GDP per 1°C increase on average under RCP8.5 (Hsiang et al., 2017). Projections of the GDP indicate that negative impacts of energy demand associated with space heating and cooling in 2100 are highest (median: –0.94%) under 4°C (RCP8.5) compared with a GDP change (median: –0.05%) under 1.5°C, depending on the socio-economic conditions (Park et al., 2018). Additionally, total energy demands for heating and cooling at the global scale do not change much with increases in Global Mean Temperature (GMT) up to 2°C. There is, however, a high degree of variability between regions (Arnell et al., 2018).

Evidence for the impact of climate change on energy systems since AR5 is limited. Globally, gross hydropower potential is projected to increase (+2.4% under RCP2.6; +6.3% under RCP8.5 for the 2080s) with the most growth in central Africa, Asia, India, and northern high latitudes (van Vliet et al., 2016). Byers et al. (2018) found energy impacts at 2ºC increase including increased cooling degree days, especially in tropical regions, as well as increased hydro-climatic risk to thermal and hydropower plants predominantly in Europe, North America, south and southeast Asia, and southeast Brazil. Donk et al. (2018) assessed future climate impacts on hydropower in Suriname, finding a decrease of approximately 40% power capacity is projected for global temperature increase in the range of 1.5°C. At minimum and maximum increases in global mean temperatures of 1.35° and 2°C, the overall stream flow in Florida, USA is projected to increase by an average of 21% with pronounced seasonal variations, resulting in increases in power generation in winter (72%) and autumn (15%) and decreases in summer (–14%; Chilkoti et al., 2017). Changes are greater at the higher projected temperature. In a reference scenario with global mean temperatures rising by 1.7°C from 2005 to 2050, U.S. electricity demand in 2050 was 1.6–6.5% higher than a control scenario with constant temperatures (McFarland et al., 2015). Decreased electricity generation of –15% is projected for Brazil starting in 2040, declining to –28% later in the century (de Queiroz et al., 2016). In large parts of Europe, electricity demand is projected to decrease mainly due to reduced heating demand (Jacob et al., 2018).

In Europe, no major differences in large-scale wind energy resources, inter-annual or intra-annual variability are projected for 2016–2035 under RCP8.5 and RCP4.5 (Carvalho et al., 2017). However, in 2046–2100, wind energy density is projected to decrease in Eastern Europe and increase in Baltic regions (–30% vs. +30%). Intra-annual variability is expected to increase in Northern Europe and decrease in Southern Europe. Under RCP4.5 and RCP8.5, the annual energy yield of European wind farms as a whole as projected to be installed by 2050 will remain stable (±5 for all climate models). However, wind farm yields will undergo changes up to 15% in magnitude at country and local scales and a 5% change in magnitude at regional scale (Tobin et al., 2015, 2016). Hosking et al. (2018) assessed wind power generation over Europe for 1.5°C warming, finding the potential for wind energy to be greater than previously assumed in Northern Europe. Additionally, Tobin et al. (2018) assessed impacts under 1.5°C and 2°C increases on wind, solar photovoltaic and thermoelectric power generation across Europe. Results found that photovoltaic and wind power might be reduced by up to 10%, and hydropower and thermoelectric generation might decrease by up to 20%, with limited impacts for 1.5°C warming, but increasing as temperature increases (Tobin et al., 2018).

3.4.9.3 Transportation

Road, air, rail, shipping and pipeline transportation can be impacted directly or indirectly by weather and climate, including increases in precipitation and temperature; extreme weather events (flooding and storms); SLR; and incidence of freeze-thaw cycles (Arent et al., 2014). Much of the published research on the risks of climate change for the transportation sector has been qualitative.

Limited new research since the AR5 supports that increases in global temperatures will impact the transportation sector. Warming is projected to result in increased numbers of days of ice-free navigation and a longer shipping season in cold regions, thus impacting shipping and reducing transportation cost (Arent et al., 2014). In the North Sea Route, large-scale commercial shipping might not be possible until 2030 for bulk shipping and until 2050 for container shipping under RCP8.5, but more shipping resulting in short-lived pollutants, as well as CO_2 and non-CO_2 emissions associated with additional economic growth enabled by the North Sea Route, is expected to contribute to a mean temperature rise of 0.05% (Yumashev et al., 2017). For a scenario with global mean temperature stabilization of open water vessel transits has the potential to double by mid-century with a season ranging from two to four months (Melia et al., 2016).

3.4.10 Livelihoods and poverty, and the changing structure of communities

Multiple drivers and embedded social processes influence the magnitude and pattern of livelihoods and poverty, and the changing structure of communities related to migration, displacement, and conflict (Adger et al., 2014). In AR5, evidence of a climate change signal was limited, with more evidence of impacts of climate change on the places where indigenous people live and on traditional ecological knowledge (Olsson et al., 2014).

3.4.10.1 Livelihoods and poverty

At approximately 1.5°C (2030), climate change will be a poverty-multiplier that makes poor people poorer, and increases the poverty head count (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). Poor people might be heavily affected by climate change even when impacts on the rest of population are limited. Climate change could force more than 100 million people into extreme poverty, with the numbers attributed to climate change alone between 3 million and 16 million, mostly through impacts on agriculture and food prices (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). Unmitigated warming could reshape the global economy later in the century by reducing average global incomes and widening global income inequality (Burke et al., 2015b). Most severe impacts are projected for urban areas and some rural regions in sub-Saharan Africa and Southeast Asia.

3.4.10.2 The changing structure of communities: Migration, displacement, and conflict

Migration: In AR5,the potential impacts of climate change on migration and displacement were identified as an emerging risk (Oppenheimer et al., 2014). The social, economic and environmental factors underlying migration are complex and varied; therefore, detecting the effect of observed climate change or assessing its possible magnitude is challenging with any degree of confidence (Cramer et al., 2014).

No studies specifically explored the difference in risks between 1.5ºC and 2ºC on human migration. The literature consistently highlights the complexity of migration decisions and the difficulties in attributing causation (e.g. (Nicholson, 2014; Baldwin and Fornalé, 2017; Bettini, 2017; Constable, 2017; Islam and Shamsuddoha, 2017; Suckall et al., 2017). The studies on migration that most closely explore the probable impacts of 1.5ºC and 2ºC typically focus on the effects of temperature and precipitation anomalies directly on migration or indirectly through examining migration due to changing agriculture yield and livelihood sources (Mueller et al., 2014; Piguet and Laczko, 2014; Mastrorillo et al., 2016; Sudmeier-Rieux et al., 2017).

Temperature had a positive and statistically significant effect on outmigration over recent decades in 163 countries, but only for agricultural-dependent countries (R. Cai et al., 2016). A 1°C increase in temperature in the International Migration Database of the Organisation for Economic Co-operation and Development (OECD) was associated with a 1.9% increase in bilateral migration flows from 142 sending countries and 19 receiving countries, and an additional millimeter of precipitation was associated with an increase in migration by 0.5% (Backhaus et al., 2015). An increase in precipitation anomalies, but over a different time period, was strongly associated with an increase in outmigration but no significant effects of temperature anomalies were reported (Coniglio and Pesce, 2015).

Internal and international migration have always been important for small islands (Farbotko and Lazrus, 2012; Weir et al., 2017). There is rarely a single cause for migration (Constable, 2017). Numerous factors are important, including work, education, quality of life, family ties, access to resources or development (Bedarff and Jakobeit, 2017; Speelman et al., 2017; Nicholls et al., 2018). Depending on the situation, changing weather, climatic, or environmental conditions might each be one factor in the choice to migrate (Campbell and Warrick, 2014).

Displacement: At 2°C warming, there is a potential for significant population displacement concentrated in the tropics (Hsiang and Sobel, 2016). Tropical populations may have to move at distances greater than 1000 km if global mean temperature rises by 2 °C from the period of 2011–2030 to the end of the century. A disproportionately rapid evacuation from the tropics could lead concentration of population in tropical margins and the subtropics, where population densities could increase by 300% or more (Hsiang and Sobel, 2016).

Conflict: A recent study has called for cautiousness in relating conflict to climate change due to sampling bias (Adams et al., 2018). Often taking limited consideration of the multiple drivers of conflict, inconsistent associations are reported between climate change and conflict (e.g., Hsiang et al., 2013; Hsiang and Burke, 2014; Buhaug, 2015, 2016; Carleton and Hsiang, 2016; Carleton et al., 2016). There also are inconsistent relationships between climate change, migration, and conflict (e.g., Theisen et al., 2013; Buhaug et al., 2014; Selby, 2014; Brzoska and Fröhlich, 2016; Burrows and Kinney, 2016; Christiansen, 2016; Reyer et al., 2017c; Waha et al., 2017). Across world regions and the international to micro level, the strength of the relationship between drought and conflict under most circumstances is limited (Buhaug, 2016; von Uexkull et al., 2016). However, drought significantly increases the likelihood of sustained conflict for particularly vulnerable nations or groups due to their livelihood dependance on agriculture. This is particularly relevant among groups in the least developed countries (von Uexkull et al., 2016), sub-Saharan Africa (Serdeczny et al., 2016; Almer et al., 2017) and in the Middle East (Waha et al., 2017). Hsiang et al. (2013) report causal evidence and convergence across studies that climate change is linked to human conflicts across all major regions of the world, and across a range of spatial and temporal scales. A 1°C increase in temperature or more extreme rainfall increases the frequency of intergroup conflicts by 14% (Hsiang et al., 2013). If the world warms by 2˚C–4˚C by 2050, then rates of human conflict could increase. Some causal associations between violent conflict and socio-political stability were reported from local to global scales and from hours to millennium (Hsiang and Burke, 2014). A temperature increase by one standard deviation in increased the risk of interpersonal conflict by 2.4% and intergroup conflict by 11.3% (Burke et al., 2015a). Armed-conflict risks and climate-related disasters are associated in ethnically fractionalized countries, indicating there is no clear signal that environmental disasters directly trigger armed conflicts (Schleussner et al., 2016a).

In summary, average global temperatures that extend beyond 1.5ºC are likely to increase poverty and disadvantage in many populations globally. By the mid to late 21st century, climate change is projected to be a poverty multiplier that makes poor people poorer and increases poverty head count, and the association of temperature and economic productivity is not linear (*high confidence*). Temperature has a positive and statistically significant effect on outmigration for agricultural-dependent communities (*medium confidence*).

3.4.11 Interacting and cascading risks

The literature on compound as well as interacting and cascading risks at warming of 1.5°C and 2°C is limited. Spatially compound risks, often referred to as hotspots, involve multiple hazards from different sectors overlapping in location (Piontek et al., 2014). Global exposures were assessed for 14 impact indicators covering water, energy and land sectors from changes including drought intensity and water stress index, cooling demand change and heatwave exposure, habitat degradation, and crop yields using an ensemble of climate and impact models (Byers et al., 2018). Exposures approximately double between 1.5°C and 2°C, and the land area affected by climate risks increases as warming progresses. For populations vulnerable to poverty, the exposure to climate risks in multiple sectors is an order of magnitude greater (8–32 fold) in the high poverty and inequality scenarios (SSP3; 765–1,220 million) compared to sustainable socioeconomic development (SSP1; 23–85 million). Asian and African regions are projected to experience 85–95% of global exposure with 91–98% of the exposed and vulnerable population (depending on SSP/GMT combination), approximately half of which are in South Asia. Figure 3.18 shows that moderate and high multi-sector impacts are prevalent where vulnerable people live, predominantly in South Asia (mostly Pakistan, India, and China), at 1.5°C, but spreading to sub-Saharan Africa, the Middle East, and East Asia at higher levels of warming. Beyond 2°C and at higher risk thresholds, the world’s poorest are expected to be disproportionately impacted, particularly in cases (SSP3) of high inequality in Africa and southern Asia. Table 3.4 shows the number of exposed and vulnerable people at 1.5°C and 2°C, with 3°C for context, for selected multi-sector risks.

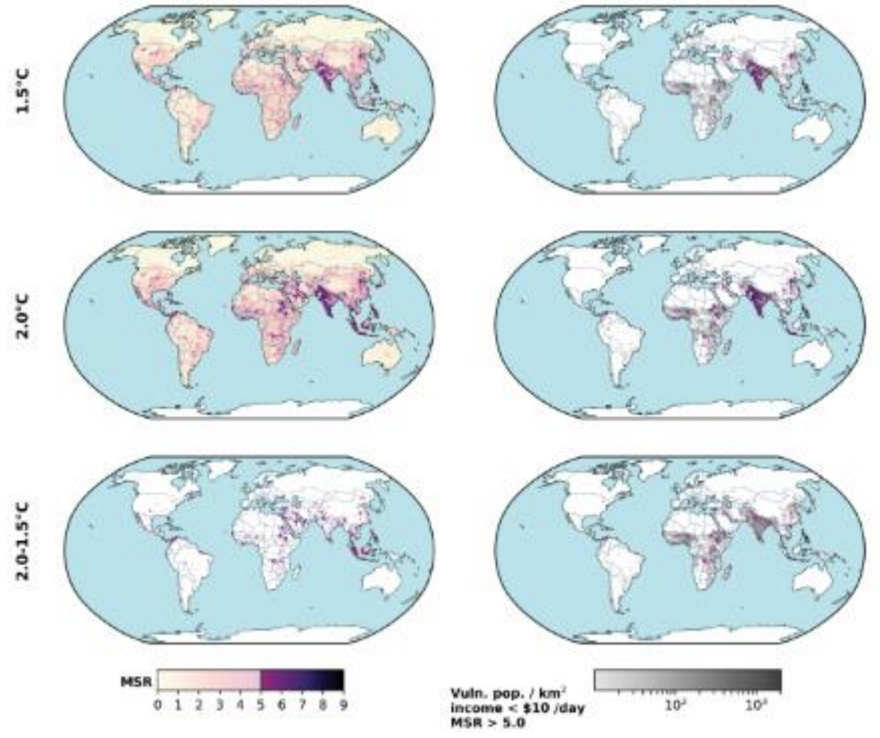


Figure 3.18: Multi-sector risk maps for 1.5, 2°C, and locations where 2°C brings impacts not experienced at 1.5°C (2–1.5°C). The left column shows the full range of the multi-sector risk score (range 0–9) with transparency and the scores >5.0 in full color. Score must be >4.0 to be considered “multi-sector”. The right column

greyscale overlays the 2050 vulnerable populations (low income) under Shared Socioeconomic Pathway (SSP)2 with the multi-sector risk score > 5.0 in full color, indicating the concentrations of exposed and vulnerable populations to risks in multiple sectors. Source: (Byers et al., 2018)

Table 3.4: Number of exposed and vulnerable people at 1.5°C, 2°C, and 3°C for selected multi-sector risks under Shared Socioeconomic Pathways (SSPs). Source: (Byers et al., 2018)

SSP2 (SSP1 to SSP3 range), millions	**1.5°C**		**2°C**		**3°C**	
Indicator	Exposed	Exposed & Vulnerable	Exposed	Exposed & Vulnerable	Exposed	Exposed & Vulnerable
Water stress index	3340 (3032-3584)	496 (103-1159)	3658 (3080-3969)	586 (115-1347)	3920 (3202-4271)	662 (146-1480)
Heatwave event exposure	3960 (3546-4508)	1187 (410-2372)	5986 (5417-6710)	1581 (506-3218)	7909 (7286-8640)	1707 (537-3575)
Hydroclimate risk to power production	334 (326-337)	30 (6-76)	385 (374-389)	38 (9-94)	742 (725-739)	72 (16-177)
Crop yield change	35 (32-36)	8 (2-20)	362 (330-396)	81 (24-178)	1817 (1666-1992)	406 (118-854)
Habitat degradation	91 (92-112)	10 (4-31)	680 (314-706)	102 (23-234)	1357 (809-1501)	248 (75-572)
Multi-sector exposure	Summarise					
2 indicators	1129 (1019 – 1250)	203 (42 – 487)	2726 (2132 – 2945)	562 (117 – 1220)	3500 (3212 – 3864)	707 (212 – 1545)
3 indicators	66 (66 – 68)	7 (0.9 – 19)	422 (297 – 447)	54 (8 – 138)	1472 (1177 – 1574)	237 (48 – 538)
4 indicators	5 (0.3 – 5.7)	0.3 (0 – 1.2)	11 (5 – 14)	0.5 (0 – 2)	258 (104 – 280)	33 (4 – 86)

3.4.12 Summary of projected risks at 1.5ºC and 2ºC of global warming

The following table summarises the information presented as part of Section 3.4, illustrating the growing of evidence of increasing risks across a broad range of natural and human systems at 1.5°C and 2°C of global warming.

Table 3.5: Summary of projected risks at 1.5°C and 2°C of global warming

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2°C global warming above pre-industrial**	**Global risks at 1.5°C global warming above pre-industrial**	**Change in risk when moving from 2°C to 1.5°C**	**Confidence in risk statements**	**Regions where risks are particularly high with 2°C global warming**	**Regions where change in risk when moving from 2°C to 1.5°C are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5°C**	**Adaptation potential at 2°C**	**Confidence in assigning adaptation**
Freshwater	Precipitation, temperature, snowmelt	Water Stress	Additional 8% of the world population in 2000 to new or aggravated water scarcity	Around half compared to the risks at 2.0°C	~100% increase	M		Europe, Australia and southern Africa		3	L	L	M
		Fluvial flood	170% increase in population affected as compared to the impact simulated over the baseline	100% increase in population affected as compared to the impact simulated over the	70% increase	M	U.S., Asia, and Europe		Africa and Oceania	2	L/M	L/M	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
			period 1976–2005	baseline period 1976–2005									
		Drought	410.7±213.5 million, changes in urban population exposure to severe drought at the globe	350.2±158.8 million, changes in urban population exposure to severe drought at the globe	60.5±84.1 million (±84.1 based on the SSP1 scenario)	M	Central Europe, Southern Europe, the Mediterranean, West Africa, East and West Asia and Southeast Asia			2	L/M	L/M	L
Terrestrial ecosystems	Temperature, precipitation	Species range loss	H (18% insects, 8% vertebrates, 16% plants lose >50% range)	M (6% insects, 4% vertebrates, 8% plants, lose >50% range)	Double or triple	H		Amazon, Europe, South Africa		1, 4	M	L	H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Loss of ecosystem functioning and services	H	M		M							
		Shifts of biomes (major ecosystem types)	13% (range 8–20%) transformed	Around 7% transformed	Around double	H		Arctic, Tibet, Himalayas, South Africa and Australia		4	-	-	-
	Heat and cold stress, warming, precipitation	Wildfire	H	H	L	M	Canada, USA, Mediterranean	Mediterranean	Central and South America, Australia, Russia, China, Africa	1, 2, 4, 5	L	L	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
Ocean	Warming and stratification of the surface ocean	Loss of framework species (coral reefs)	very H (*virtually certain*)	H	3	H/very H	Tropical/subtropical countries	Tropical/subtropical countries	Southern Red Sea, Somalia, Yemen; deep water coral reefs	1, 2	H	L	H
		Loss of framework species (seagrass)	H	M	5	H/very H	Tropical/subtropical countries	Tropical/subtropical countries	Southern Red Sea, Somalia, Yemen; Myanma	1, 2	M	L	M/H
		Loss of framework species (mangroves)	M/H	M	3	M/H	Tropical/subtropical countries	Tropical/subtropical countries	Southern Red Sea, Somalia, Yemen; Myanmar	1, 3	M	L	M/H
		Disruption of marine food webs	M	L	5	M	Global	Global	Deep Sea	4	M	L	M/H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Range migration of marine species and ecosystems	H	M	5	H	Global	Global	Deep Sea	1	M	L	H
		Loss of finfish and fisheries	M/H	M/H	5	H	Global	Global	Deep Sea	4	M	M/L	M/H
	Ocean acidification and elevated sea temperatures	Loss of coastal ecosystems and protection	M	L/M	5	M	Low latitude tropical/subtropical countries	Low latitude tropical/subtropical countries	Most regions - risks not well defined	1	M	M/L	M
		Loss of bivalves and bivalve fisheries	M	M	3	H	Temperate countries with up-welling	Temperate countries with up-welling	Most regions - risks not well defined	4	M/H	L/M	M/H

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Changes to physiology and ecology of marine species	M	L/M	3	H	Global	Global	Most regions - risks not well defined	4	L	L	M/H
	Reduced bulk ocean circulation and de-oxygenation	Increased hypoxic dead zones	L/M	L	5	L/M	Temperate countries with up-welling	Temperate countries with up-welling	Deep Sea	4	L	L	M
		Changes to up-welling productivity	M	L	5	L/M	Most upwelling regions	Most upwelling regions	Some up-welling systems	4	L	L	M
	Intensified storm	Loss of coastal ecosystems	H/very H	H	5	H	Tropical/subtropical countries	Tropical/subtropical countries		1, 4	M	L	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
		Inundation and destruction of human/coastal infrastructure and livelihoods.	H/very H	H	5	H	Global	Global		1, 5	M/H	M	M/L
	Loss of sea ice	Loss of habitat	very H	H	5	H	Polar regions	Polar regions		1	L	very L	H
		Increased productivity but changing fisheries	M/H	L/M	5	very H	Polar regions	Polar regions		1, 4	L	M/L	H

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5ºC global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
Coastal	Sea level rise, increased storminess	Area exposed (assuming no defences)	590-613 th km^2 when 2.0degC first reached	562-575 th km^2 when 1.5degC first reached	Increasing. 25 -38 th km^2 when temperatures are first reached, 10-17 th km^2 in 2100 increasing to 16-230 th km^2 in 2300	M/H (dependent on population datasets)	Asia. Small islands	Asia. Small islands	Small islands	2,3	M	M	M
		Population exposed (assuming no defences)	141-151 million when 2.0degC first reached	128-143 million when 1.5degC first reached	Increasing. 13 - 8 million when temperatures are first reached, 0-6 million people in	M/H (dependent on population datasets)	Asia. Small islands	Asia. Small islands	Small islands	2,3	M	M	M

Sector	Physical climate change drivers	Nature of risk	Global risks at 2ºC global warming above pre-industrial	Global risks at 1.5ºC global warming above pre-industrial	Change in risk when moving from 2ºC to 1.5ºC	Confidence in risk statements	Regions where risks are particularly high with 2ºC global warming	Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high	Regions with little or no information	RFC *	Adaptation potential at 1.5ºC	Adaptation potential at 2ºC	Confidence in assigning adaptation
					2100, increasing to 35-95 million people in 2300								
		People at risk taking account of defences (modelled in 1995)	Between 14.9-52.3 million people / yr if defences are not upgraded from the modelled 1995 baseline	Between 2.3-27.8 million people / yr as defences are not upgraded from the 1995 baseline	Increasing with time, but highly dependent on adaptation.	M/H (dependent on adaptation)	Asia. Small islands. Potentially African nations.	Asia. Small islands	Small islands	2,3, 4	M	M	M

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5°C global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
Food security and food production systems	Heat and cold stress, warming, precipitation	Changes in ecosystem production	H	M/H	M/H	M/H	Global	Noth America, Central and South America, Mediterranean basin, South Africa, Australia, Asia	- - -	2, 4,5	H	M/H	M/H
	Heat and cold stress, warming, precipitation	Shift and composition change of biomes (major ecosystem types)	H	M/H	M	L/M	Global	Global, Tropical areas, Mediterranean	Africa, Asia	1, 2, 3, 4	L/M	L	L/M
Human health	Temperature	Heat-related morbidity and mortality	M/H	M	Risk increased	VH	All regions at risk	All regions	Africa	2,3, 4	H	H	H
		Occupational heat stress	M/H	M	Risk increased	M	Tropical regions	Tropical regions	Africa	2,3, 4	H	M	M

Sector	**Physical climate change drivers**	**Nature of risk**	**Global risks at 2ºC global warming above pre-industrial**	**Global risks at 1.5ºC global warming above pre-industrial**	**Change in risk when moving from 2ºC to 1.5ºC**	**Confidence in risk statements**	**Regions where risks are particularly high with 2ºC global warming**	**Regions where change in risk when moving from 2ºC to 1.5ºC are particularly high**	**Regions with little or no information**	**RFC ***	**Adaptation potential at 1.5ºC**	**Adaptation potential at 2ºC**	**Confidence in assigning adaptation**
	Air quality	Ozone-related mortality	M/H (if precursor emissions remain the same)	M (if precursor emissions remain the same)	Risk increased	H	High income and emerging economies	High income and emerging economies	Africa, parts of Asia	2,3, 4	L	L	M
	Temperature, precipitati	Undernutrition	M/H	M	Risk increased	H	Low-income countries in Africa and Asia	Low-income countries in Africa and Asia	Small islands	2,3, 4	M	L	M
Key economic	Temperature	Tourism (sun and beach, and snow sports)	H	M/H	Risk increased	VH	Coastal tourism, particularly in sub-tropical and tropical regions	Coastal tourism, particularly in sub-tropical and tropical regions	Africa	1,2, 3	M	L	H

*RFC: 1 = unique and threatened systems, 2 = extreme events, 3 = unequal distribution of impacts, 4 = global aggregate impacts (economic + biodiversity), 5 = large scale singular events

3.4.13 Synthesis of key elements of risk

Some elements of the assessment in Section 3.4 are synthesised in a single diagram (Figure 3.19) that indicates the overall risk in five broad categories for natural and human systems as a result of anthropogenic climate change and increases in Global Mean Surface Temperature (GMST). The elements included are supported by a substantive enough body of literature providing at least *medium confidence* in the assessment. The format for figure 3.19 matches that of Figure 19.4 of WGII AR5 Chapter 19 (Oppenheimer et al., 2014) and Figure 3.19) by indicating the levels of the transition of risk from undetectable to moderate (detected and attributed), from moderate to high (severe and widespread) and from high to very high, the latter indicating significant irreversibility or persistence of climate-related hazards combined with a much reduced capacity to adapt. Regarding the transition from undetectable to moderate, the impact literature assessed in the AR5 focused on describing and quantifying linkages between weather and climate patterns and impact outcomes, with limited detection and attribution to anthropogenic climate change (Cramer et al., 2014). A more recent analysis of attribution to greenhouse gas forcing at the global scale (Hansen and Stone, 2016) confirmed that the impacts related to changes in regional atmospheric and ocean temperature can be confidently attributed to anthropogenic forcing, while attribution to anthropogenic forcing of those related to precipitation is only weakly evident or absent. Moreover, there is no strong direct relationship between the robustness of climate attribution and that of impact attribution (Hansen and Stone, 2016).

The current synthesis is complementary to the synthesis in Section 3.5.2 that categorizes risks into ‘Reasons for Concern’ (RFCs), as described in Oppenheimer et al. (2014). Each element presented here maps to one or more RFCs, and the figure indicates this relationship. It should be emphasized that risks to the issues assessed here are only a subset of the full range of risks that contribute to the RFCs. This figure is not intended to replace the RFCs but rather to indicate how risks to particular elements of the earth system accrue with global warming, with a focus on levels of warming of 1.5°C and 2°C. Key evidence assessed in earlier parts of this chapter are summarized to indicate the transition points between the levels of risk. A fuller account is in the Annex 3.1 S3-4-12.

In terrestrial ecosystems (related to RFC1 and RFC4), detection and attribution studies show that impacts of climate change on terrestrial ecosystems began to take place over the few decades, indicating a transition from no risk (white) to moderate risk (yellow) below recent temperatures (*high confidence*, Section 3.4.3). Risks to unique and threatened terrestrial ecosystems are generally higher under warming of 2°C as compared to 1.5°C (Section 3.5.2.1), while at the global scale, severe and widespread risks (red) are projected to occur by 2°C of warming. These risks are associated with biome shifts and species range loss (Sections 3.4.3 and 3.5.2.4); however, because many systems and species are unable to adapt to levels of warming below 2°C, the transition to high risk (red) is located below 2°C (*high confidence*). At 3°C of warming, however, biome shifts and species range losses escalate to very high levels and the systems have very little capacity to adapt (purple; Section 3.4.3; *high confidence*).

In the Arctic (related to RFC1), the increased rate of summer sea ice melt was detected and attributed to climate change by the year 2000 (corresponding to warming of 0.7°C), indicating moderate risk (yellow). At 1.5°C warming, an ice-free Arctic ocean is considered *unlikely* whilst by 2°C warming it is considered *likely* and this unique ecosystem is considered unable to adapt, hence a transition from high (red) to very high (purple) risk is expected between 1.5°C and 2°C warming.

For coral reefs, there is *high confidence* in the transitions between colour assignments, especially in the growing impacts in the transition of warming from 0.4˚C to 0.6˚C, and in projections of change from 0.6ºC to

1.3ºC (Section 3.4.4; Box 3.4). This assessment took into account the heat wave related loss of 50% of shallow water corals across hundreds of kilometres of the world's largest continuous coral reef system, the Great Barrier Reef, as well as other sites globally. Together with sequential mass coral bleaching and mortality events on the Great Barrier Reef (Hoegh-Guldberg, 1999; Hughes et al., 2017b, 2018), suggest that climate risks are very high for coral reefs. General assessment of climate risks for mangroves prior to this special report concluded that they face greater risks from deforestation and unsustainable coastal development than climate change (Alongi, 2008; Gattuso et al., 2015)(Hoegh-Guldberg et al., 2014). Recent climate related die-offs (Duke et al., 2017; Lovelock et al., 2017), however, suggest that climate change risks may have been underestimated for mangroves as well, leading to risks considered to be undetectable to moderate, with the transition now starting at 1.3°C as opposed to 1.8ºC as assessed in 2015 (Gattuso et al., 2015). Risks of climate change related impacts on small-scale fisheries at low latitudes (many of which are dependent on ecosystems such as coral reefs and mangroves) *are moderate today but are expected to reach high levels of* risk by 1.1ºC (*high confidence*) (Section 3.4.4.10).

The transition from white to yellow (related to RFC3, 4) is based on AR5 WGII Chapter 7 which indicated with *high confidence* that climate change impacts on crop yields have been detected and attributed to climate change, with the current assessment providing further evidence to confirm this (Section 3.4.6). Impacts were detected in the tropics (AR5 WGII Chapter 7, AR5 WGII Chapter 18) and with increasing warming regional risks become high in some regions by 1.5°C warming, and in many regions by 2.5ºC warming, indicating a transition from moderate to high risk between 1.5ºC and 2.5°C warming (*medium confidence*). Impacts from fluvial flooding (related to RFCs 2, 3 and 4) depend on the frequency and intensity of the events as well as the extent of exposure and vulnerability of society (i.e., socioeconomic conditions; the effect of non-climate stressors). Risks posed by 1.5°C warming continue to increase with warming (Sections 3.4.2, 3.3.5), with projected increases threefold relative to current risk in economic damages due to flooding in 19 countries for a warming of 2°C, indicating a transition to high risk at this level (*medium confidence*). Because few studies assess the potential to adapt to these risks, there was insufficient evidence to locate a transition to very high risk (purple).

Climate-change induced SLR and associated coastal flooding (related to RFCs 2, 3 and 4) were detectable and attributable since approximately 1970 (Slangen et al., 2016), where temperatures have risen by 0.3°C (Section 3.3.9) (*medium confidence*). Analysis suggests that impacts could be more widespread in sensitive systems such as small islands (Section 3.4.5.3) (*high confidence*) and increasingly widespread by the 2070s (Brown et al., 2018a), even when considering adaptation measures, suggesting a transition to high risk (red) (Section 3.4.5). With 2.5°C warming, adaptation limits would be exceeded in sensitive areas, and hence a transition to purple (very high risk) can be located here (*medium confidence*). Sea level rise could have adverse effects for centuries, posing significant risk to low lying areas (Sections 3.4.5.7 and 3.5.2.5) (*high confidence*).

For heat-related morbidity and mortality (related to RFCs 2, 3 and 4), detection and attribution studies show heat-related mortality in some locations increased due to climate change (*high confidence*, Section 3.4.7, Ebi et al., 2017). The projected risks of heat-related morbidity and mortality are generally higher under warming of 2°C than 1.5°C (*high confidence*), with projections of greater exposure to high ambient temperatures and increased morbidity and mortality (Section 3.4.7). Risk levels will depend on the rate of warming and the (related) level of adaptation, so a transition in risk from moderate (yellow) to high (red) is located between 1ºC and 3°C with *medium confidence*.

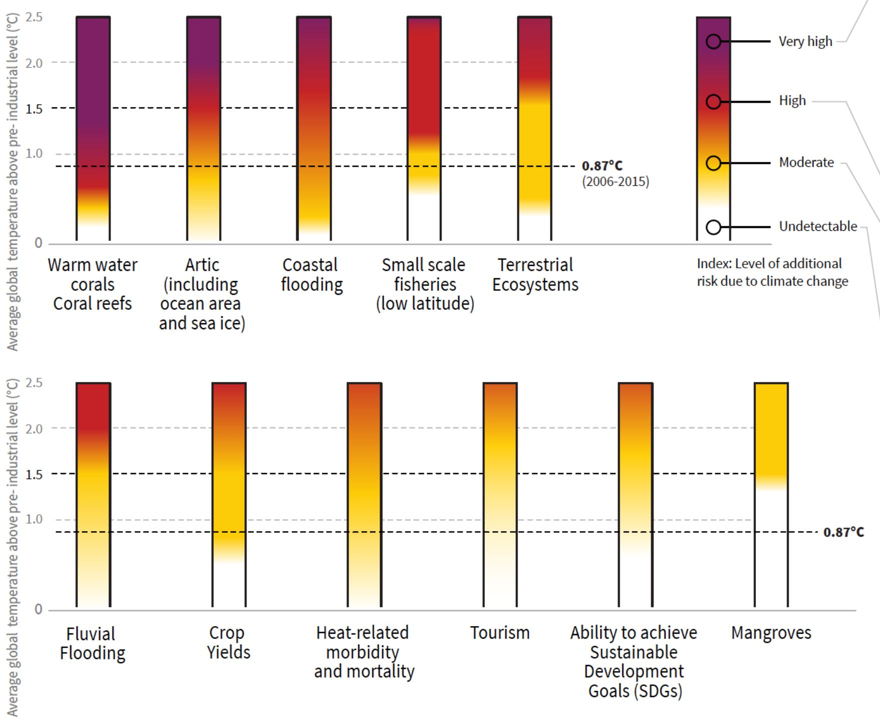
For tourism (related to RFCs 3 and 4), changing weather patterns, extreme weather and climate events, and sea level rise are affecting many (but not all) global tourism investments and environmental and cultural destination assets (Section 3.4.4.12), with ‘last chance’ tourism markets developing based on observed impacts on environmental and cultural heritage (Section 3.4.9.1), indicating a transition from undetected to moderate risk between 0°C and 1.5°C (*high confidence*). Based on limited analyses, risks to the tourism sector are higher at 2°C than at 1.5°C, with greater impacts on climate-sensitive sun, beach, and snow sports tourism markets. The degradation or loss of coral reef systems will increase the risks to coastal tourism, particularly in sub-tropical and tropical regions. A transition in risk from moderate (yellow) to high (red) is located between 1.5 and 3°C (*medium confidence*).

Owing to the existing effects that climate change is already having upon ecosystems, human health and agriculture, climate change is already beginning to make it more difficult to reach goals to eradicate poverty and hunger and protect health and life on land (Sections 5.1 and 5.2.1), suggesting a transition from undetected to moderate risk below recent temperatures at 0.5°C warming *(medium confidence).* Based on limited analyses there is evidence and agreement that the risks to sustainable development are considerably less at 1.5°C than 2°C (Section 5.2.2) including avoided impacts on poverty and food security. It is easier to achieve many of the Sustainable Development Goals (SDGs) at 1.5°C, suggesting that a transition to higher risk has not yet begin at this level. At 2°C and higher (e.g., RCP8.5) however, there are high risks of failure to meet SDGs such as eradicating poverty and hunger, providing safe water, reducing inequality, and protecting ecosystems and which are likely to become severe and widespread if warming were increase further to about 3°C *(medium confidence)* (Section 5.2.3).

Disclosure statement: The selection of elements is not intended to be fully comprehensive and does not necessarily include all elements for which there is a substantive body of literature, nor does it necessarily include all elements which are of particular interest to decision makers.

Risks for specific natural, managed and human systems

The key elements are presented here as a function of the risk level assessed between 1.5 and 2°C.



Purple indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impact.

Red indicates severe and widespread impacts.

Yellow indicates that associated impacts are both detectable and attributable to climate change with at least medium confidence.

White indicates that no associated impacts are detectable and attributable to climate change.

Assessment of risks at 2°C or higher are beyond the scope of the present assessment

The average global sea surface temperature was converted to GMST for marine related embers (warm water corals, mangroves and small scale fisheries, low latitude) by adjusting for the small difference between GMST and SST across a range of CMIP5 climate models.

Figure 3.19 The dependence of risk associated with selected elements of human and natural systems on the level of climate change, adapted from Figure 3.18 and from AR5 WGII Chapter 19, and highlighting the nature of this dependence between 0 and 2ºC warming above pre-industrial levels. The color scheme indicates the additional risks due to climate change. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual ‘element’. At one end, undetectable risk (white) indicates no detection and attribution of climate change with at least medium confidence. At the other end of the risk spectrum, the transition from red to purple, introduced for the first time in AR4, is defined by very high risk and the presence of significant irreversibility or persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across elements indicates the relative sensitivity of elements to increases in Global Mean Surface Temperature (GMST). As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation independently of development pathway. The levels of risk illustrated reflect the judgements of the authors of Chapter 3 and Gattuso et al. (2015; for three marine elements).

3.5 Avoided impacts and reduced risks at 1.5ºC compared with 2ºC

3.5.1 Introduction

Oppenheimer et al. (2014, AR5 Chapter 19) provide a framework that aggregates projected risks from global mean temperature change into five categories known as 'Reasons for Concern'. Risks are classified as moderate, high, or very high and coloured yellow, red and purple respectively in Figure 19.4 (see AR5 Chapter 19 for details and findings). The framework's conceptual basis and the risk judgments made in Oppenheimer et al. (2014) were recently reviewed, confirming most judgements made in the light of more recent literature (O'Neill et al., 2017). We adopt the approach of Oppenheimer et al. (2014), with updates in terms of the aggregation of risk as informed by the most recent literature, for the analysis of avoided impacts at 1.5°C compared to 2°C of global warming presented in this section.

The economic benefits to be obtained by achieving the global temperature goal of 1.5°C, as compared to 2°C (or higher) are discussed in Section 3.5.3 in the light of the five reasons for concern explored in Section 3.5.2. Climate change hot spots that can be avoided or reduced by achieving the 1.5°C target are summarised in Section 3.5.4. The section concludes with a discussion of regional tipping points that can be avoided at 1.5ºC compared to higher degrees of global warming (Section 3.5.5).

3.5.2 Aggregated avoided impacts and reduced risks at 1.5°C versus 2°C of global warming

A brief summary of the accrual of RFC with global warming as assessed in WGII AR5 is provided in the following sections, which leads into an update of relevant literature published since AR5. The new literature is used to confirm the levels of global warming at which risks are considered to increase to moderate, and from moderate to high, and from high to very high. Figure 3.20 modifies Figure 19.4 from AR5 WGII with the ensuing text in this subsection providing the justification for the modifications. O'Neill et al. (2017) presents a very similar assessment to WGII AR%, but with further discussion of the future potential to create socioeconomic-scenario specific embers. At present, there is insufficient literature to do this so the original simple approach has been used here. Since the focus in the present assessment is on the consequences of warming of 1.5ºC to 2°C, no assessment for global warming of 3°C or more are included, and the embers developed here are discontinued at 2.5˚C.

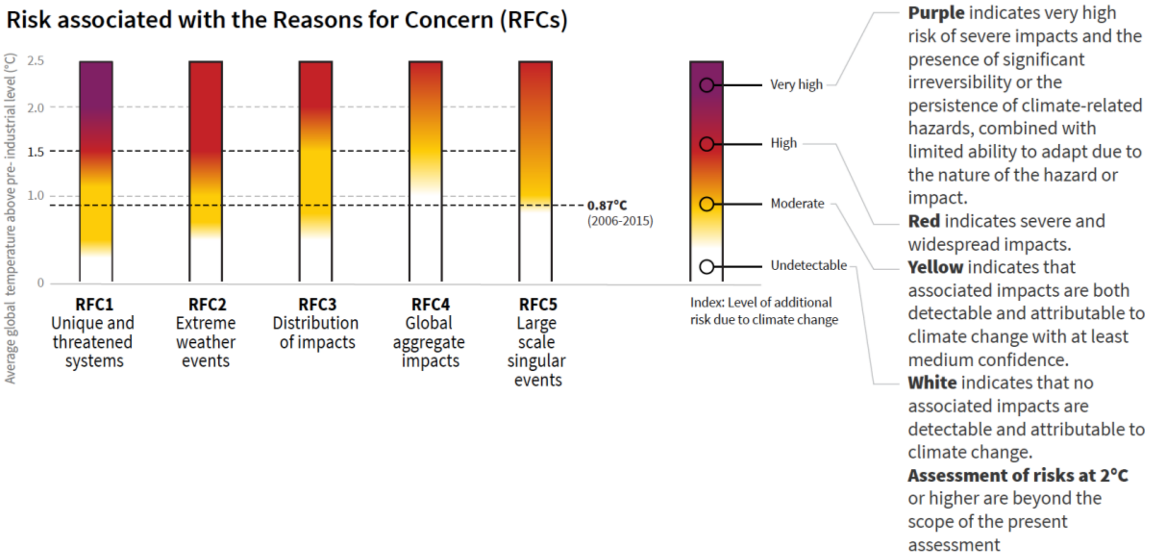


Figure 3.20: The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated and adapted from WGII AR5 Ch 19, Figure 19.4 and highlighting the nature of this dependence between 0ºC and 2ºC warming above pre-industrial levels. The color scheme indicates the additional risks due to climate change. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual 'reason'. The transition from red to purple, introduced for the first time in AR4, is defined by very high risk and the presence of significant irreversibility or persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMST. As was done previously, this assessment takes autonomous adaptation into account, as well as limits to adaptation (RFC 1, 3, 5) independently of development pathway. The rate and timing of impacts were taken into account in assessing RFC 1 and 5. The levels of risk illustrated reflect the judgements of the Ch 3 authors. [Note to reviewers: In WGII AR5 Ch 19 and more recently in O'Neill et al. 2017 the need to detail how these kinds of figures vary with socioeconomic pathway is noted and suggestions are made therein as to how this might be done. That is seen as a task for IPCC AR6, and beyond the scope of what is feasible to do for SR1.5]

3.5.2.1 RFC 1- Unique and threatened systems

WGII AR5 Chapter 19 found that some unique and threatened systems are at risk from climate change at current temperatures, with increasing numbers of systems at risk of severe consequences at global warming of 1.6ºC above pre-industrial levels. It was also observed that many species and ecosystems have limited ability to adapt to the very large risks associated with warming of 2.6ºC or more, particularly Arctic sea ice and coral reef systems (*high confidence*). A transition from white to yellow indicating the onset of moderate risk was therefore located below present day global temperatures (*medium confidence*); a transition from yellow to red indicating the onset of high risk was located at 1.6ºC, and a transition to purple indicating the onset of very high risk at about 2.6ºC. This WGII AR5 analysis already implies a significant reduction in risks to unique and threatened systems if warming is limited to 1.5ºC as compared with 2ºC. Since AR5, evidence of present day impacts in these systems has continued to grow (Sections 3.4.2.2, 3.4.2.3, and 3.4.2.5), whilst new evidence has also accumulated about increased risks at 1.5ºC vs 2˚C warming in Arctic ecosystems (Section 3.3.9), coral reefs (Section 3.4.3), some other unique ecosystems (Section 3.4.2) and biodiversity.

New literature since AR5 provides a closer focus on the comparative levels of risk to coral reefs at 1.5ºC versus 2ºC global warming. As assessed in Section 3.4.4 and Box 3.4, reaching 2ºC will increase the frequency of mass coral bleaching and mortality to a point at which it will result in the total loss of coral reefs from the world's tropical and subtropical regions. Restricting overall warming to 1.5ºC will still see a downward trend in average coral cover (70–90% decline by mid-century) but will prevent the total loss of coral reefs projected with warming of 2˚C. The remaining reefs at 1.5˚C will also benefit from increasingly stable ocean conditions by the mid-to-late 21st century. Limiting global warming to 1.5°C during the course of the century may, therefore, open the window for many ecosystems to adapt or reassort geographically past climate change. This indicates a transition in risk in this system from high to very high (red to purple) (*high confidence*) at 1.5ºC warming and contributes to a lowering of the transition from high to very high (red to purple) in this RFC1 compared to AR5. Further details of risk transitions for ocean systems are described in Figure 3.20.

Substantial losses of Arctic Ocean summer ice were projected in AR5 WGI for global warming of 1.6ºC, with a nearly ice-free Arctic Ocean being projected for global warming of greater than 2.6ºC. Since AR5, the importance of a threshold between 1ºC and 2ºC has been further emphasized in the literature, with sea ice projected to persist throughout the year for a global warming less than 1.5ºC, yet chances of an ice-free Arctic during summer being high at 2°C warming (Section 3.3.8). Less of the permafrost in the Arctic is projected to thaw (21–37% under 1.5˚C warming as compared with 35–47% for 2˚C warming) (Section 3.3.5.2), which would be expected to reduce risks to both social and ecological systems in the Arctic. This indicates a transition in risk in this system from high to very high (red to purple) between 1.5ºC and 2˚C warming and contributes to a lowering of the transition from high to very high (red to purple) in this RFC1 compared to AR5.

AR5 identifies a large number of threatened systems including mountain ecosystems, highly biodiverse tropical wet and dry forests, deserts, freshwater systems and dune systems. These include the Mediterranean areas in Europe, Siberian, tropical and desert ecosystems in Asia, Australian rainforests, the Fynbos and succuluent Karoo areas of S. Africa, and wetlands in Ethiopia, Malawi, Zambia and Zimbabwe. In all these systems, impacts accrue with greater warming and impacts at 2ºC being expected to be greater than those at 1.5ºC (*medium confidence*). One study since the AR5 has shown that constraining global warming to 1.5ºC would maintain the functioning of the prairie pothole ecosystem (north America) in terms of its productivity and biodiversity, whilst a warming of 2ºC would not do so (Carter Johnson et al., 2016). The large proportion of insects projected to lose over half their range at 2ºC warming (25%) as compared to 1.5°C warming (9%) also suggests a significant loss of functionality in these systems at 2ºC warming owing to the key role of insects in nutrient cycling, pollination, detritivory, and other key ecosystem processes (Section 3.4.2).

Unique and threatened systems in small island states and in systems fed by glacier meltwater were also considered in AR5 in making a contribution to this RFC, but there is little new information about these systems that pertains to 1.5ºor 2ºC global warming.

Taken together, the evidence suggests that the transition from high to very high risk (red to purple) in unique and threatened systems occurs at a lower level of warming, between 1.5ºC and 2ºC *(high confidence*), than in AR5 where this transition was located at 2.6ºC. The transition from moderate to high risk (yellow to red) would relocate very slightly from 1.6ºC to 1.5ºC.

3.5.2.2 RFC 2- Extreme weather events

In this sub-subsection reduced risks in terms of the likelihood of occurrence of extreme weather events are discussed for 1.5ºC as compared to 2ºC of global warming – for those extreme events where current evidence is available. AR5 assigned a moderate (yellow) level of risk due to extreme weather events at recent temperatures (1986-2005) due to the attribution of heat and precipitation extremes to climate change, and a transition to high (red) beginning below 1.6ºC global warming based on the magnitude, likelihood and timing of projected changes in risk associated with extreme events, indicating more severe and widespread impacts. The AR5 analysis already suggests a significant benefit of limiting warming to 1.5ºC, since this might keep risks closer to the moderate level. New literature since AR5 provides greater confidence in a reduced level of risks due to extreme weather events at 1.5ºC versus 2ºC for some types of extremes (see Section 3.3 and below).

Temperature: It is very likely that further increases in number of warm days/nights and decrease in number of cold days/nights and in overall temperature of hot and cold extremes will occur under 1.5ºC of global warming compared to present-day climate (1°C warming), with further increases towards 2ºC of warming (section 3.3). As assessed in Sections 3.3.1 and 3.3.2, impacts of a 0.5°C global warming can be identified for temperature extremes at global scales, based on observations and the analysis of climate models. At 2ºC of global warming, it is likely that temperature increases of more than 2°C will occur over most land regions in terms of extreme temperatures (on average between 3 and 8°C depending on region and considered extreme index) (Section 3.3.2). Regional increases in temperature extremes under 1.5°C of global warming, can be reduced to 2–6°C (Section 3.3.2). Benefits to be obtained from this general reduction in extremes depends to a large extent on whether the lower range of increases in extremes at 1.5ºC is sufficient for critical thresholds to be exceeded, within the context of wide-ranging aspects such as crop yields, human health and the sustainability of ecosystems.

Heavy precipitation: AR5 assessed trends in heavy precipitation for land regions where observational coverage was sufficient for assessment. It concluded with medium confidence that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century. A recent observations-based study also shows that a 0.5°C increase in global mean temperature has a detectable effect on changes in precipitation extremes at global scale (Schleussner et al., 2017), thus suggesting that there would be detectable differences in heavy precipitation at 1.5°C and 2°C of global warming. These results are consistent with analyses of climate projections, although they also highlight a large amount of regional variation in the sensitivity of changes in heavy precipitation (Section 3.3.3).

Droughts: When considering the difference between precipitation minus evaporation as a function of global temperature changes, the subtropics generally display an overall trend towards drying, whilst the northern high latitudes display a robust response towards increased wetting (Section 3.3.4, Figure 3.12). Limiting global mean temperature increase to 1.5°C as opposed to 2°C could substantially reduce the risk of reduced regional water availability (Section 3.3.4). Regions that are to benefit most include the Mediterranean region and southern Africa (Section 3.3.4). There are also some possible effects in parts of South America and on subregional scale in the Western Sahel (Section 3.3.4). Some possible effects are found in some other regions, mostly for the tails of multi-model projections (Fig. 3.12).

Fire: The increased amount of evidence that anthropogenic climate change has already caused significant increases in fire area globally (Section 3.4.3) is in line with projected fire risks. These risks are projected to increase further under 1.5ºC of global warming relative to the present day (Section 3.4.3). Under 1.2°C of global warming, fire frequency was estimated to increase by over 37.8% of global land areas, compared to 61.9% of global land areas under 3.5°C of warming. For in-depth discussion and uncertainty estimates, see (Meehl et al., 2007; Moritz et al., 2012; Romero-Lankao et al., 2014).

In “Extreme Weather Events” (RFC2) the transition from moderate to high risk is located between 1ºC and 1.5ºC global warming, which is very similar to the AR5 assessment but there is greater confidence in the assessment (*medium confidence*). The impact literature contains little information about the potential for human society to adapt to extreme weather events and hence it has not been possible to locate the transition from 'high' (red) to 'very high' risk within the context of assessing impacts at 1.5°C vs 2°C global warming.

There is thus *low confidence* in the level at which global warming could lead to very high risks associated with extreme weather events in the context of this report.

3.5.2.3 RFC 3 - Distribution of impacts

Risks due to climatic change are unevenly distributed and are generally greater at lower latitudes and for disadvantaged people and communities in countries at all levels of development. AR5 located the transition to moderate risk below recent temperatures owing to the detection and attribution of regionally differentiated changes in crop yields (*medium to high confidence*) and new literature continues to confirm this finding. Based on assessment of risks to regional crop production and water resources, AR5 located the transition from moderate to high risk between 1.6°C and 2.6°C above pre-industrial levels. Cross-Chapter Box 6 highlights that at 2°C warming, new literature shows that risks of food shortage are projected to emerge in the African Sahel, the Mediterranean, central Europe, the Amazon, western and southern Africa, and that these are much larger than the corresponding risks at 1.5°C. This suggests a transition from moderate to high risk of regionally differentiated impacts between 1.5°C and 2°C above pre-industrial levels for food security (medium confidence). Reduction in the availability of water resources for less than 2ºC is projected to be greater than 1.5ºC of global warming, although changes in socioeconomics could have a greater influence (Section 3.4.2), with larger risks in the Mediterranean (Box 3.2) but estimates of the magnitude of the risks remain similar to those cited in AR5. Globally, millions of people may be at risk from sea level rise during the 21st century (Hinkel et al., 2014; Hauer et al., 2016), particularly if adaptation is limited. At 2°C of warming, more than 70% of global coastlines will experience sea-level rise greater than 0.2 m, suggesting regional differences in the risks of coastal flooding. Regionally differentiated multi-sector risks are already apparent at 1.5°C warming, being more prevalent vulnerable people live, predominantly in South Asia (mostly Pakistan, India, and China), but these spread to sub-Saharan Africa, the Middle East and East Asia as temperature rises, with the world's poorest disproportionately impacted by 2°C (Byers et al., 2018). The hydrological impacts of climate change in Europe in a 1.5ºC, 2ºC and 3°C warmer world are intense and spatially more extensive (Donnelly et al., 2017). Taken together, a transition from moderate to high risk is now located between 1.5°C and 2°C above pre-industrial levels based on an assessment of risks to food security, water resources, drought, heat exposure and coastal submergence *(high confidence)*.

3.5.2.4 RFC 4 - Global aggregate impacts

Oppenheimer et al. (2014) explain the inclusion of non-economic metrics related to impacts on ecosystems and species at the global level, in addition to economic metrics in global aggregate impacts. The degradation of ecosystem services by climate change and ocean acifidification were in general excluded from previous global aggregate economic analyses.

Global economic impacts: WGII AR5 found that overall global aggregate impacts become moderate between 1–2ºC of warming and the transition to moderate risk levels was therefore located at 1.6ºC above pre-industrial levels. This was based on the assessment of literature using model simulations which indicate that the global aggregate economic impact will become significantly negative between 1ºC and 2ºC of warming (*medium confidence*), whilst there will be a further increase in the magnitude and likelihood of aggregate economic risks at 3ºC warming (*low confidence*).

Since AR5, three studies have emerged using two entirely different approaches which indicate that economic damages are projected to be higher by 2100 if warming reaches 2ºC than if it is constrained to 1.5ºC. The study of Warren et al. (2018c) uses the integrated assessment model PAGE09 to estimate that avoided global economic damages of 22% (10–26%) accrue from constraining warming to 1.5°C rather than 2°C, 90% (77–93%) from 1.5°C rather than 3.66°C, and 87% (74–91%) from 2°C rather than 3.66°C; while Petris et al. (2018) identify several regions in which economic damages are greater at 2°C warming compared to 1.5°C, further estimating that projected damages at 1.5ºC remain similar to today's levels of economic damage. Another study (Burke et al., 2018) uses an empirical, statistical approach and finds that limiting warming to 1.5ºC instead of 2ºC would save 1.5–2.0% of Gross World Product (GWP) by mid-century and 3.5% of GWP by end-of-century (see figure 2A in Burke et al 2018), which under a 3% discount rate corresponds to $8.1-11.6 trillion and $38.5 trillion in avoided damages by mid- and end-of-century, respectively, agreeing closely with the Warren et al. (2018c) estimate of $15 trillion. In the no policy baseline temperature rises by 3.66°C by 2100, resulting in global GDP loss of 2.6% (5-95% percentile range 0.5–8.2%), as compared with 0.3% (0.1–0.5%) by 2100 in the 1.5°C scenario and 0.5% (0.1–1.0%) in the 2°C scenario. Limiting warming to 1.5°C rather than 2°C by 2060 has also been estimated to result in co-benefits of 0.5–0.6% of world GDP due to reductions in air pollution (Shindell et al., 2018) which is similar to the avoided damages identified for the USA (see below).

Two studies focusing only on the USA (Hsiang et al., 2017; Yohe, 2017) also found that economic damages are projected to be higher by 2100 if warming reaches 2ºC than if it is constrained to 1.5ºC (one study finds a mean difference 0.35% GDP, range 0.2–0.65%, the other identifies a GDP loss of 1.2% per degree of warming, hence approximately 0.6% for half a degree). Further, the avoided risks compared to a 'no policy' baseline are greater in the 1.5ºC case (4%, range 2–7%) compared to the 2ºC case (3.5%, range 1.8–6.5%).

These analyses suggest that the point at which global aggregates of economic impacts become negative is below 2ºC (*medium confidence*), and that there is a possibility that this is below 1.5ºC warming.

Oppenheimer et al. (2014) note that the global aggregated damages associated with large scale singular events has not been explored, and reviews of integrated modelling exercises have indicated a potential underestimation of global aggregate damages due to the lack of consideration of the potential for these events in many studies. Since AR5, a further analysis of the potential economic consequences of triggering these large scale singular events (Y. Cai et al., 2016; Lemoine and Traeger, 2016), also indicates a two to eightfold larger economic impact associated with a warming of 3ºC than most previous analyses, depending on the number of events incorporated: Lemoine includes only three known singular events whereas (Y. Cai et al., 2016) include five.

Biome shifts, risks of species extinction and ecosystem functioning and services: 13% (range 8–20%) of the earth's land area is projected to undergo biome shifts under 2ºC warming compared to approximately 7% at 1.5°C warming (Section 3.4.3, Warszawski et al., 2013), hence implying a halving of biome transformations. Overall levels of species loss at 2ºC warming are similar to previous studies for plants and vertebrates (Warren et al., 2011; Warren et al., 2018b)but insects have been found to be more sensitive to climate change, with 18% (6–35%) projected to lose over half their range at 2°C warming compared to 6% (1–18%) under 1.5°C warming, which is 66% (Section 3.4.3). The critical role of insects in ecosystem functioning therefore suggests impacts already on global ecosystem functioning at 2ºC warming. Since AR5 new literature indicates that impacts on marine fish stocks and fisheries are lower in 1.5–2°C global warming relative to pre-industrial level when compared to higher warming scenarios (Section 3.4.6) especially in tropical and polar systems.

In AR5, the transition from no impacts detected (white) to moderate impacts (yellow) was considered to occur between 1ºC and 2°C global warming, reflecting the impacts on the economy and on biodiversity globally; whereas high risks (red) were associated with 3°C warming to reflect the high risks to biodiversity and accelerated effects on the global economy. The new evidence suggests moderate impacts on the global aggregate economy and global biodiversity by 1.5°C, suggesting a lowering of the transition to moderate risk (yellow) already by 1.5°C; and higher risks than previously thought on the global aggregate economy and global biodiversity by 2°C global warming warming; suggesting that risks transition to high between 2°C and 3°C warming, as opposed to at 3°C as previously thought (*medium confidence)*.

3.5.2.5 RFC 5 - Large scale singular events

Large scale singular events are components of the global earth system that are thought to hold the risk of reaching critical tipping points under climate change, and that can result in or be associated with major shifts in the climate system. These components include:

- The cryosphere: West-Antarctic ice sheet, Greenland ice sheet
- The thermohaline circulation (slowdown of the Atlantic Meridional Overturning Current, AMOC).
- The El Niño-Southern Oscillation (ENSO) as a global mode of climate variability
- Role of the Southern Ocean in global carbon cycle

AR5 assessed that the risks associated with these events become moderate between 0.6ºC and 1.6ºC above pre-industrial levels due to early warning signs and that risk becomes high between 1.6°C and 4.6ºC due to the potential for commitment to large irreversible sea level rise from the melting of land based ice sheets (*low to medium confidence*). The increase in risk between 1.6ºC and 2.6ºC above pre-industrial levels was assessed to be disproprortionately large. New findings since AR5 are detailed below.

Greenland and West-Antarctic ice sheets and Marine Ice Sheet Instability: Various feedbacks between the Greenland ice sheet and the wider climate system (most notably those related to the dependence of ice melt on albedo and surface elevation) make irreversible loss of the ice sheet a possibility. Church et al. (2013) assess this threshold to be 2°C or higher (relative to pre-industrial temperature).

Robinson et al. (2012) find a range for this threshold of 0.8–3.2°C (95% confidence). The threshold of global temperature increase that may initiate irreversible loss of the West-Antarctic ice sheet and Marine Ice Sheet Instability (MISI) is estimated to range between 1.5ºC and 2°C. The timescale for eventual loss of the ice sheets varies between millennia and tens of millennia and assumes constant surface temperature forcing during this period. Were temperature to cool subsequently, the ice sheets might regrow although the amount of cooling required is likely to be highly dependent on the duration and rate of the previous retreat. The magnitude of global sea level rise plausible to occur over the next two centuries under 1.5–2°C of global warming is estimated to be in the order of several tenths of a meter by most studies (*low confidence*) (Schewe et al., 2011; Church et al., 2013; Levermann et al., 2014; Marzeion and Levermann, 2014; Fuerst et al., 2015; Golledge et al., 2015), although a smaller number of investigations (Joughin et al., 2014; Golledge et al., 2015; DeConto and Pollard, 2016) project increases of 1–2 m. This body of evidence suggest that the temperature range of 1.5–2ºC may be regarded as representing moderate risk (it may trigger MISI in Antarctica or irreversible loss of the Greenland ice sheet and it may be associated with sea-level rise as high as 1–2 m over a period of two centuries).

Thermohaline circulation (slowdown of AMOC): It is more likely than not that the AMOC has been weakening in recent decades, given the detection of the cooling of surface waters in the North Atlantic and evidence that the Gulf Stream has slowed by 30% since the late 1950s (Srokosz and Bryden, 2015; Caesar et al., 2018). There is limited evidence linking the recent weakening of the AMOC to anthropogenic warming (Caesar et al., 2018). It is very likely that the AMOC will weaken over the 21st century. Best estimates and range for the reduction from CMIP5 are 11% (1–24%) in RCP2.6 and 34% (12–54%) in RCP8.5 (AR5). There is no evidence indicating significantly different amplitudes of AMOC weakening for 1.5°C vs 2°C of global warming, or of a shutdown of the AMOC at these global temperature thresholds. Associated risks are classified as low to medium.

El Niño-Southern Oscillation (ENSO)*:* Extreme El Niño events are associated with significant warming of the usually cold eastern Pacific Ocean, and occur about once every 20 years (Cai et al., 2015). Such events reorganize the distribution of regions of organized convection, and affect weather patterns across the globe. Recent research (G. Wang et al., 2017) indicate that the frequency of extreme El Niño events increases linearly with the global mean temperature, and that the number of such events might double (one event every ten years) under 1.5°C of global warming. This pattern is projected to persist for a century after stabilization at 1.5°C, thereby challenging the limits to adaptation, and thus indicating high risk even at the 1.5°C threshold. La Niña event frequencies are projected to remain similar to that of the present-day under 1.5–2°C of global warming.

Role of the Southern Ocean in the global carbon cycle*:* The critical role of the Southern Ocean as a net sink of carbon might decline under global warming, and assessing this effect under 1.5ºC compared to 2ºC of global warming is a priority. Changes in ocean chemistry (e.g., oxygen content, ocean acidification), especially those associated with the deep sea, are associated concerns (Section 3.3.10).

Large scale singular events (RFC5) moderate risk is now located at 1ºC and high risks are located 2ºC, as opposed to 1.9ºC (moderate) and 4ºC (high) risk in AR5 because of new observations and models of the West Antarctic ice sheet (medium confidence), which suggests the ice sheet may be in the early stages of Marine Ice Sheet Instability (MISI). Very-high risk is assessed as lying above 5ºC because the growing literature on process-based projections of the West Antarctic ice sheet predominantly supports the AR5 assessment of a MISI contribution of an additional several tenths of a metre by 2100.

3.5.3 Regional economic benefit analysis for the 1.5°C vs 2°C global temperature goals

This section reviews recent literature that estimates the economic benefits for constraining global warming to 1.5°C as compared to 2°C. The focus here is on evidence pertaining to specific regions, rather than on global aggregated benefits (Section 3.5.2.4). At 2°C of global warming, lower economic growth is projected for many countries, with low-income countries projected to experience the greatest losses (*limited evidence, medium confidence*) (Burke et al., 2018; Petris et al., 2018). A critical issue for developing countries in particular is that advantages in some sectors are projected to be offset by the increasing mitigation costs (Rogelj et al., 2013; Burke et al., 2018)– with food production being a key factor. That is, although restraining the global temperature increase to 2°C is projected to reduce crop losses under climate change, relative to higher levels of warming, the associated mitigation costs may increase the risk of hunger in low-income countries (*low confidence*) (Hasegawa et al., 2016). It is *likely* that the even more stringent mitigation measures required to restrict global warming to 1.5°C (Rogelj et al., 2013) will further increase these mitigation costs and impacts. International trade in food might be a key response measure for alleviating hunger in developing countries under 1.5°C and 2°C stabilization scenarios (Hasegawa et al., 2016).

Although warming is projected to be the highest in the Northern Hemisphere under 1.5ºC or 2°C of global warming, regions in the tropics and Southern Hemisphere subtropics that are projected to experience the largest impacts on economic growth (*limited evidence, medium confidence*) (Gallup et al., 1999; Burke et al., 2018; Petris et al., 2018). Despite the uncertainties associated with climate change projections and econometrics (e.g., Burke et al., 2016), it is *more likely than not* that there will be large differences in economic growth under 1.5°C and 2°C of global warming for developing versus developed countries (Burke et al., 2018; Petris et al., 2018). Statistically significant reductions in Gross Domestic Product (GDP) per capita growth are projected across much of the African continent, southeast Asia, India, Brazil and Mexico (*limited evidence, medium confidence*). Countries in the western parts of tropical Africa are projected to benefit most from restricting global warming to 1.5°C as opposed to 2°C, in terms of future economic growth (Petris et al., 2018). An important reason why developed countries in the tropics and subtropicas are to benefit substantially from restricting global warming to 1.5°C, relates to present-day temperatures in these regions being above the threshold thought to be optimal for econonomic production (Burke et al., 2015b, 2018).

The world's largest economies are also projected to benefit from restricting warming to 1.5°C, as opposed to 2°C (*medium confidence*), with the likelihood of such benefits to be realized estimated to be 76%, 85% and 81% for the USA, China and Japan, respectively (Burke et al., 2018). Two studies focusing only on the USA (Hsiang et al., 2017; Yohe, 2017) also found that economic damages are projected to be higher by 2100 if warming reaches 2°C than if it is constrained to 1.5ºC (one study finds a mean difference 0.35% GDP, range 0.2–0.65%, the other identifies a GDP loss of 1.2% per degree of warming, hence approximately 0.6% for half a degree). Indeed, no statistically significant changes in GDP are projected to occur over most of the developed world (*limited evidence, low confidence*) (Petris et al., 2018).

A caveat of the analysis of Petris et al. (2018) and Burke et al. (2018) is that the effects of sea-level rise are not included in the estimations of damages or future economic growth, implying a potentiall underestimate of the benefits of limiting warming to 1.5°C, for the case where significant sea level rise is avoided at 1.5°C but exceeded at 2°C.

3.5.4 Reducing hot spots of change for 1.5°C and 2°C global warming

This sub-section integrates Sections 3.3 and 3.4 in terms of climate change induced hot-spots that occur through interactions across the physical climate system, ecosystems and socio-economic human systems, with a focus on the extent to which risks can be avoided or reduced by achieving the 1.5°C global temperature goal (as opposed to the 2°C goal). Findings are summarised in Table 3.6.

3.5.4.1 Arctic sea ice

Ice-free Arctic Ocean summers are *very likely* at levels of global warming higher than 2°C (Notz and Stroeve, 2016; Rosenblum and Eisenman, 2016; Screen and Williamson, 2017; Niederdrenk and Notz, 2018). Some studies are even indicative of the entire Arctic Ocean summer period becoming ice-free under 2°C of global warming whilst other more conservatively estimate this probability to be in the order of 50% (Sanderson et al., 2017; Section 3.3.8). The probability for an ice-free Arctic in September at 1.5°C of global warming is low and substantially lower than for the case of 2°C of global warming *(high confidence)* (Screen and Williamson, 2017; Jahn, 2018; Niederdrenk and Notz, 2018; Section 3.3.8). There is, however, a single study that questions the validity of the 1.5°C threshold in terms of maintaining summer Arctic Ocean sea-ice (Niederdrenk and Notz, 2018). Finally, during winter, only little ice is projected to be lost for either 1.5°C or 2°C global warming (*medium confidence*) (Niederdrenk and Notz, 2018). The losses in sea ice at 1.5ºC and 2°C of warming will result in habitat losses for organisms such as seals, polar bears, whales and sea-birds (e.g., Larsen et al., 2014). There is *high agreement* and *robust evidence* that photosynthetic species will change due to sea-ice retreat and related changes in temperature and radiation (Section 3.4.4.7), and this is *very likely* to benefit fisheries productivity in the Northern Hemisphere spring bloom system (Section 3.4.4.7).

3.5.4.2 Arctic land regions

In some Actic land regions, the warming of cold extremes and annual minimum temperature at 1.5°C is stronger than the global mean temperature increase by a factor of 2–3, i.e. 3°C -4.5°C regional warming at 1.5°C global warming (e.g., northern Europe, Annex 3.1 Figure S3.6 – also see Section 3.3.2.2 and Seneviratne et al., 2016). Moreover, over much of the Arctic, a further increase of 0.5°C in the global surface temperature, from 1.5 to 2°C may lead to further temperature increases of 2–2.5°C (Figure 3.3). As a consequence, biome (major ecosystem types) shifts are *likely* in the Arctic, with increases in fire frequencies, degradation in permafrost and increases in tree cover *likely* to occur under at 1.5ºC warming, with further amplification of these changes under 2ºC of global warming (e.g., Gerten et al., 2013; Bring et al., 2016). Rising temperatures, thawing permafrost and changing weather patterns will increasingly impact on people, infrastructure and industries in the Arctic (W.N. Meier et al., 2014), with these impacts larger at 2°C vs 1.5°C of warming (*medium confidence*).

3.5.4.3 Alpine regions

Alpine regions are generally regarded as climate change hotspots given their generally cold and harsh climates in which a rich biodiversity has evolved, but which are vulnerable to increases in temperature. Under regional warming, alpine species have been found to migrate upwards on mountain slopes (Reasoner and Tinner, 2009), an adaptation response with obvious limited by mountain height and habitability. Moroever, many of the world's Alpine regions are important from a water security perspective through associated glacier melt, snow melt and river flow (Section 3.3.5.2 for a discussion of these aspects). Projected biome shifts are already *likely* to be severe in alpine regions at 1.5ºC warming and increase further for 2ºC warming (Chen et al., 2014a; Gerten et al., 2013; Figure 1b).

3.5.4.4 Southeast Asia

Southeast Asia is a region highly vulnerable to increased flooding in the context of sea-level rise (Arnell et al., 2016; Brown et al., 2016, 2018a). Risks from increased flooding rise from 1.5°C to 2°C of warming (*medium confidence*), with substantial increases beyond 2°C (Arnell et al., 2016). Southeast Asia displays statistically significant differences in projected changes in heavy precipitation, run-off and high flows at 1.5°C versus 2°C warming (with stronger increase at 2°C; (Wartenburger et al., 2017; Döll et al., 2018; Seneviratne et al., 2018a); Section 3.3.3), and thus is thought to be a hotspot in terms of increases in heavy precipitation between these two global temperature levels (Schleussner et al., 2016b; Seneviratne et al., 2016) (*medium confidence*). For Southeast Asia, a 2°C warming by 2040 indicated a one-third decline in per capita crop production (Nelson et al., 2010) associated with general decreases in crop yields. However, under

1.5°C of warming, significant risks for crop yield reduction in the region are avoided (Schleussner et al., 2016b). These changes pose significant risks for poor people in both rural regions and urban areas of Southeast Asia (Section 3.4.10.1), with these risks being larger at 2°C of global warming compared to 1.5°C of warming (*medium confidence*).

3.5.4.5 Southern Europe and the Mediterranean

The Mediterranean is regarded as a climate change hot spot both in terms of projected stronger warming of the regional land-based hot extremes compared to the mean global temperature warming (e.g., Seneviratne et al., 2016) and projected substantial decreases in mean precipitation with associated substantial increases in dry spells. The latter is projected to increase from 7% to 11% when comparing regional impacts at 1.5°C versus 2°C of global warming, respectively (Schleussner et al., 2016b). Low river flows are projected to decrease in the Mediterranean under 1.5°C of global warming (Marx et al., 2018) with associated significant decreases in high flows and floods (Thober et al., 2018), largely in response to reduced precipitation. The median reduction in annual runoff almost double from about 9% (likely range: 4.5–15.5%) at 1.5°C to 17% (likely range: 8–25%) at 2°C (Schleussner et al., 2016b). Similar results are found by (Döll et al., 2018). Overall, there is *high confidence* of strong increases in dryness and decreases in water availability in the Mediterranean and southern Europe from 1.5ºC to 2°C of global warming. Sea-level rise is expected to be lower for 1.5ºC versus 2°C, lowering risks for coastal metropolitan agglomerations. The risks (with current adaptation) related to water deficit in the Mediterranean are high for a global warming of 2°C, but can be substantially reduced if global warming is limited to 1.5°C (Guiot and Cramer, 2016; Schleussner et al., 2016b; Donnelly et al., 2017; Section 3.3.4).

3.5.4.6 West Africa and the Sahel

West Africa and the Sahel are *likely* to experience increases in the number of hot nights and longer and more frequent heat waves even if the global temperature increase is constrained to 1.5°C, with further increase at 2°C of global warming and beyond (e.g., Weber et al., 2018). Moreover, the daily rainfall intensity and run-off is expected to increase (*low confidence*) towards 2°C and higher global warming scenarios (Weber et al., 2018; Schleussner et al., 2016b), with these changes also being relatively large compared to the projected changes at 1.5°C of warming. Moreover, increased risks are projected in terms of drought, particularly for the pre-monsoon season (Sylla et al., 2015), with both rural and urban populations affected, and increasingly so at 2°C of global warming as opposed to 1.5°C (Liu et al., 2018). Based on a World Bank (2013) study for sub-Saharan Africa, a 1.5°C warming by 2030 might reduce the present maize cropping areas by 40%, rendering these no longer suitable for current cultivars. Substantial negative impacts are also projected for sorghum suitability in the western Sahel (Läderach et al., 2013; Sultan and Gaetani, 2016). Increase in warming (2°C) by 2040 would result in further yield losses and damages to crops (i.e., maize, sorghum, wheat, millet, groundnut, cassava). Schleussner et al. (2016b) consistently indicate reduced impacts on crop yield for West Africa under 2°C vs 1.5°C of global warming. There *is medium confidence* that vulnerabilities to water and food security in the African Sahel will be higher at 2°C compared to 1.5°C of global warming (Cheung et al., 2016b; Betts et al., 2018), and at 2°C these vulnerabilities are expected to be worse (Sultan and Gaetani, 2016; Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018) (*high evidence).* For global warming greater than 2°C, the western Sahel might experience the strongest drying and experience serious food security issues (Ahmed et al., 2015; Parkes et al., 2018).

3.5.4.7 Southern Africa

The southern African region is projected to be a climate change hot spot in terms of both hot extremes (Figures 3.5 and 3.6) and drying (Figure 3.12). Indeed, temperatures have been rising in the subtropical regions of southern Africa at approximately twice the global rate over the last five decades (Engelbrecht et al., 2015). Associated elevated warming of the regional land-based hot extremes has occurred (Section 3.3; Seneviratne et al., 2016). Increases in the numer of hot nights as well as longer and more frequent heat waves are projected even if the global temperature increase is constrained to 1.5°C *(high confidence)*, with further increase at 2°C of global warming and beyond *(high confidence)* (Weber et al., 2018).

Moreover, the region is *likely* to become generally drier with reduced water availability under low mitigation (Niang et al., 2014; Engelbrecht et al., 2015; Karl et al., 2015; James et al., 2017), with this particular risk also prominent under 2°C of global warming and even 1.5ºC of warming (Gerten et al., 2013). Risks are significantly reduced, however, under 1.5°C of global warming (Schleussner et al., 2016b). There are consistent and statistically significant projected increases in risks of increased meteorological drought in southern Africa at 2°C vs 1.5°C of warming (*medium confidence*). Despite the general rainfall reductions projected for southern Africa, daily rainfall intensities are expected to increase over much of the region (*medium confidence)*, and increasingly so with further amounts of global warming. There is medium confidence that livestock in southern Africa will experience increased water stress under both 1.5ºC and 2°C of global warming, with negative economic consequences (e.g., Boone et al., 2017). The region is also projected to experience reduced maize, sorghum and cocoa cropping area suitability as well as yield losses under 1.5°C of warming, with further decreases towards 2°C of warming (World Bank, 2013). Generally, there is *high confidence* that vulnerability to decreases in water and food availability is reduced at 1.5°C versus 2°C for southern Africa (Betts et al., 2018), whilst at 2°C these are expected to be higher (Lehner et al., 2017; Betts et al., 2018; Byers et al., 2018; Rosenzweig et al., 2018) (*high confidence*).

3.5.4.8 Tropics

Worldwide, the largest increases in the number of hot days are projected to occur in the tropics (Figure 3.7). Moreover, the largest differences in the number of hot days for 1.5°C of global warming versus 2°C of global warming are found in the tropics (Mahlstein et al., 2011). In tropical Africa, increases in the number of hot nights, as well as longer and more frequent heat waves, are projected under 1.5°C of global warming, with further increases under 2°C of global warming (Weber et al., 2018). Impact studies for major tropical cereals reveal that yields of maize and wheat begin to decline with 1°C to 2°C of local warming in the tropics. Schleussner et al. (2016b) project that constraining warming to 1.5ºC rather than 2ºC would avoid significant risks of tropical crop yield declines in West Africa, South East Asia, and Central and South America. There is *limited evidence* and thus *low confidence* that these changes may result in significant population displacement from the tropics to the subtropics (e.g., Hsiang and Sobel, 2016).

3.5.4.9 Small islands

Small islands are well recognized to be very sensitive to climate change impact such as sea-level rise, oceanic warming, precipitation, cyclones and coral bleaching (high agreement, robust evidence) (Nurse et al., 2014; Ourbak and Magnan, 2017). Even at 1.5°C of global warming, the compounding impacts of changes in rainfall, temperature, tropical cyclones and sea levels are likely to be significant across multiple natural and human systems. There are potential benefits to Small Island Developing States (SIDS) from avoided risks at 1.5˚C versus 2˚C, especially when coupled with adaptation efforts. In terms of sea-level rise, by 2150, roughly 40,000 less people living in SIDS will be inundated in a 1.5°C world than in a 2˚C world

(Rasmussen et al., 2018). Constraining global warming to 1.5ºC would significantly reduce water stress (about 25%) as compared to the projected water stress at 2ºC (e.g., Caribbean region, Karnauskas et al., 2018), and may enhance the ability of SIDS to adapt (Benjamin and Thomas, 2016). Up to 50% of the year is projected to be very warm in the Caribbean for 1.5°C, with a further increase by up to 70 days for 2˚C versus 1.5˚C (Taylor et al., 2018). By limiting warming to 1.5°C instead of 2°C in 2050, risks of coastal flooding (measured as the flood amplification factors for 100-year flood events) are reduced between 20 and 80% for SIDS (Rasmussen et al., 2018). A case study of Jamaica with lessons for other Caribbean SIDS demonstrates that the difference between 1.5ºC and 2ºC is likely to challenge livestock thermoregulation, resulting in persistent heat stress for livestock (Lallo et al., 2018).

3.5.4.10 Fynbos and shrub biomes

The Fynbos and succulent Karoo biomes of South Africa are threatened systems that have been assessed in AR5. Similar shrublands exists in the semi-arid regions of other continents, the Sonora-Mojave Creosotebush-White Bursage Desert Scrub ecosystem in the USA being a prime example. Impacts accrue across these systems with greater warming, with impacts at 2°C likely to be greater than those at 1.5°C (*medium confidence*). Under 2°C of global warming, regional warming in drylands will be 3.2–4°C and under 1.5°C of global warming, mean warming in drylands will still be about 3°C. The Fynbos biome in southwestern South Africa is vulnerable to the increasing impact of fires under increasing temperatures and drier winters (*high confidence*). The Fynbos biome is projected to lose about 20%, 45% and 80% of its current suitable climate area under 1°C, 2°C and 3°C of warming with respect to present-day climate (Engelbrecht and Engelbrecht, 2016), demonstrating the value of climate change mitigation in protecting this rich centre of biodiversity.

Table 3.6: Emergence and intensity of climate change hot-spots under different degrees of global warming

Region and/or Phenomena	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of 2°C - 3°C
Arctic sea-ice	Arctic summer sea-ice is *likely* to be maintained. Habitat losses for organisms such as polar bears, whales, seals and sea-birds Benefits for arctic fisheries	The risk of an ice free Arctic in summer is ~ 50% or higher. Habitat losses for organisms such as polar bears, whales, seals and sea-birds may be critical if summers are ice-free Benefits for arctic fisheries	Arctic is *very likely* to be ice-free in summer. Critical habitat losses for organsims such as polar bears, whales, seals and sea-birds Benefits for arctic fisheries
Arctic land regions	Cold extremes warm by a factor of 2.5-3, reaching up to 5.5 °C *(high confidence)* Biome shifts in the tundra and	Cold extremes warm by as much as 8 °C *(high confidence)* Larger intrusions of trees and shrubs in the tundra than under 1.5 °C of warming	Drastic regional warming is *very likely* A collapse in permafrost may

Region and/or Phenomena	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of 2°C - 3°C
	permafrost deterioration is *likely*	is *likely*; larger but constrained losses in permafrost are *likely*	plausibly occur (*low confidence*); a drastic biome shift from tundra to boreal forest is possible *(low confidence*).
Alpine regions	Severe shifts in biomes are *likely* Reduced grassland net primary productivity	Even more severe shifts are *likely* Increased risks for reduced grassland net primary productivity	Critical losses in alpine habitats are *likely* Increased risks for significantly reduced grassland net primary productivity
Southeast Asia	Risks for increased flooding related to sea-level rise Increases in heavy precipitation events Significant risks of crop yield reductions are avoided	Higher risks for increased flooding related to sea-level rise *(medium confidence)* Stronger increases in heavy precipitation events *(medium confidence)* One third decline in per capita crop production *(medium confidence)*	Substantial increases in risks related to flooding from sea-level rise Substantial increased in heavy precipitation and high flow events Substantial reductions in crop yield
Small Islands	Land of 40,000 less people inundated by 2150 on SIDS Risks for coastal flooding reduced by 20-80% for SIDS Fresh water stress reduced by 25% Increase in the	Tens of thousands displaced due to inundation of SIDS High risks for coastal flooding Fresh water stress from projected aridity Further increase of about 70 warm days per year	Substantial and wide-spread impacts through indundation of SIDS, coastal flooding, fresh water stress, persistent heat stress and loss of most coral reefs very likely

Region and/or Phenomena	**Warming of 1.5ºC or less**	**Warming of 1.5ºC-2°C**	**Warming of 2°C - 3°C**
	number of warm days for SIDS in the tropics Persistent heat stress in cattle avoided Loss of 70-90% of coral reefs	Persistent heat stress in cattle in SIDS Loss of most coral reefs – remaining structures weaker due to ocean acidification	
Mediterranean	Increase (about 7%) in dry-spells Reduction in runoff of about 9% (likely range: 4.5–15.5%) Risk of water deficit	*High confidence* of further increases (11%) in dry spells *High confidence* of further reductions (about 17%) in runoff (likely range 8–28%) Higher risks for water deficit	Substantial reductions in precipitation and reductions in runoff *very likely* Very high risks for water deficit
West African and the Sahel	Reduced maize and sorghum production is *likely,* with suitable for maize production reduced by as much as 40% Increased risks for under-nutrition	Negative impacts on maize and sorghum production *likely* larger than at 1.5 °C Higher risks for undernutrition;	Negative impacts on crop yield may result in major regional food insecurities (*medium confidence*) High risks for undernutrition
Southern African savannahs and drought	*Likely* reductions in water availability High risks for increased mortality from heat-waves; High risk for undernutrition in communities dependent on dryland agriculture and livestock	Even larger reductions in rainfall and water availability *likely*; Higher risks for increased mortality from heat-waves (*high confidence*); Higher risks for undernutrition in communities dependent on dryland agriculture and livestock	Large reductions in rainfall and water availability are *likely* Very high risks for undernutrition in communities dependent on dryland agriculture and livestock

Region and/or Phenomena	**Warming of 1.5ºC or less**	**Warming of 1.5ºC-2°C**	**Warming of 2°C - 3°C**
Tropics	Accumulated heat-wave duration up to two months *(high confidence)*; 3% reduction in maize crop yield.	Accumulated heat-wave duration up to three months *(high confidence)*; 7% reduction in maize crop yield.	Oppressive temperatures and accumulated heat-wave duration *very likely* to directly impact on human health, mortality and productivity Substantial reductions in crop yield *very likely*
Fynbos biome	About 30% of suitable climate area lost *(medium confidence)*	Increased losses (about 45%) of suitable climate area *(medium confidence)*	Up to 80%of suitable climate area lost*(medium confidence)*

3.5.5 Avoiding regional tipping points by achieving more ambitious global temperature goals

Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as ecosystems and human systems, is essential for understanding the risks and opportunities from mitigation. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C versus 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems is also analysed. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5ºC and 2ºC of global warming – note that tipping points in the global climate system, referred to as large scale singular events, have already been discussed in Section 3.5.2. A summary of regional tipping points is provided in Table 3.7.

3.5.5.1 Arctic sea-ice

Collins et al. (2013) discuss the loss of Artic sea ice in the context of potential tipping points. Climate models have been used to assess whether a bifurcation exists that would lead to the irreversible loss of Arctic sea ice (Armour et al., 2011; Boucher et al., 2012; Ridley et al., 2012) and to test whether summer sea ice extent can recover after it has been lost (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011). These studies do not find evidence of bifurcation and find that sea ice returns within a few years of its loss, leading Collins et al. (2013) to conclude that there is little evidence for a tipping point in the transition from perennial to seasonal ice cover. Studies do not find evidence of irreversibility or tipping points, and suggest that year-round sea ice could return with years given a suitable climate (*medium confidence*) (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011).

3.5.5.2 Tundra

Tree-growth in tundra-dominated landscapes is strongly constrained by the number of days above 0°C. A potential tipping points exists, where the number of days below 0°C decrease to the extent that tree fraction increases significantly. Tundra-dominated landscapes have warmed more than the global average over the last century (Settele et al., 2014), with associated increases in fires and permafrost degradation (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Yang et al., 2016). Both of these processes facilitate conditions for woody species establishment in tundra areas, and the eventual transition of the tundra to boreal forest. The number of investigations into how the tree-fraction may respond in the Arctic to different degrees of global warming is limited, and generally indicative that substantial increases will likely occur gradually (e.g., Lenton et al., 2008). Abrupt changes only plausible at levels of warming significantly larger than 2°C (*low confidence*) and are to occur in conjunction with a collapse in permafrost (Drijfhout et al., 2015).

3.5.5.3 Permafrost

Widespread thawing of permafrost potentially makes a large carbon store (estimated to be twice the size of the atmospheric store, Dolman et al., 2010) vulnerable to decomposition, which would lead to further increases in atmospheric carbon dioxide and methane and hence further global warming. This feedback loop between warming and the release of greenhouse gas from thawing tundra represents a potential tipping point. However, the carbon released from thawing permafrost is projected to be restricted to 0.12-0.25 Gt C a^{-1} to the atmosphere in a 2ºC world, and to 0.08-0.16 Gt C $a^{-1}$for 1.5ºC (Burke et al., 2006), and thus do not represent a tipping point *(medium confidence*). At higher degrees of global warming, in the order of 3°C, a different type of tipping point in permafrost may be reached. A single model projection (Drijfhout et al., 2015) suggests that higher temperatures may induce a smaller ice fraction in soils in the tundra, leading to more rapidly warming soils and a positive feedback mechanism that results in permafrost collapse (*low confidence*). The disparity between the multi-millennial timescales of soil carbon accumulation and potentially rapid decomposition in a warming climate implies that the loss of this carbon to the atmosphere is essentially irreversible (Collins et al., 2013).

3.5.5.4 Asian monsoon

It is the pressure gradient between the Indian Ocean and Asian continent that at a fundamental level determines the strength of the Asian monsoon. As land masses warm faster than the oceans, a general strengthening of this gradient, and hence monsoons, may be expected under global warming (e.g., Lenton et al., 2008). Additional factors such as changes in albedo induced by aerosols and snow-cover change may also affect temperature gradients and consequently pressure gradients and the strength of the monsoon. In fact, it has been estimated that an increase of the landmass albedo to 0.5 would represent a tipping point resulting in the collapse of the monsoon system (Lenton et al., 2008). The overall impacts of the various types of radiative forcing under different emission scenarions are more subtle, with a weakening of the monsoon north of about 25°N in East Asia and a strengthening south of this latitude projected by (Jiang and Tian, 2013) under high and modest emission scenarios. Increases in the intensity of monsoon precipitation is likely under low mitigation (AR5). Given that scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than those assessed in the studies of Jiang and Tian (2013) there is *low confidence* regarding changes in monsoons at these low global warming levels, as well as regarding the differences between responses at 1.5°C versus 2°C levels of global warming.

3.5.5.5 *West African monsoon and the Sahel*

Earlier work has identified 3°C of global warming as a tipping point leading to a significant strengthening of the West African monsoon and subsequent wettening (and greening) of the Sahel and Saharah (Lenton et al., 2008). AR5 (Niang et al., 2014) as well as more recent research through the Coordinated Regional Downscaling Experiment for Africa (CORDEX-AFRICA) provide a more uncertain view, however, in terms of the rainfall futures of the Sahel under low mitigation futures. Even if a wetter Sahel should materialize under 3°C of global warming (*low confidence)*, it should be noted that there will be significant offsets in the form of strong regional warming and related adverse impacts on crop yield, livestock mortality and human health under such low mitigation futures (Engelbrecht et al., 2015; Sylla et al., 2016; Weber et al., 2018b)

3.5.5.6 *Rain forests*

A large portion of rainfall over the world’s largest rainforests are recirculated (e.g., Lenton et al., 2008), which raises the concern that deforestation may trigger a threshold in reduced forest cover leading to pronounced forest dieback. For the Amazon, this deforestation threshold has been estimated to be 40% (Nobre et al., 2016). Global warming of 3°C–4°C may also, independent of deforestation, represent a tipping point that results in a significant dieback of the Amazon forest, with a key forcing mechanism being stronger El Niño envents bringing more frequent droughts to the region (Nobre et al., 2016). Increased fire frequencies under global warming may interact with and accelerate deforestation, particularly during periods of El Niño induced droughts (Lenton et al., 2008; Nobre et al., 2016). Global warming of 3°C is projected to reduce the extent of tropical rainforest in Central America, with biomass productivity being reduced by more than 50%, and a large replacement of rainforest by savanna and grassland (Lyra et al., 2017). Overall, modelling studies (Huntingford et al., 2013; Nobre et al., 2016) and observational constraints (Cox et al., 2013) suggest that pronounced rainforest dieback may only be triggered at 3°C–4 °C (*medium confidence*), although pronounced biomass losses may occur at 1.5°C and 2°C of global warming.

3.5.5.7 *Boreal forests*

Boreal forests are likely to experience higher local warming than the global average (WGII AR5: Collins et al., 2013). Increased disturbance from fire, pests and heat related mortality may affect in particular the southern boundary of boreal forests (Gauthier et al., 2015) (*medium confidence*), with these impacts accruing with greater warming and thus impacts at 2°C would be expected to be greater than those at 1.5°C (*medium confidence*). A tipping point for significant dieback of the boreal forests is thought to exist, where increased tree mortality will result in the creation of large regions of open woodlands and grasslands, which would favour further regional warming and increased fire frequencies, thus inducing a powerful positive feedback mechanism (Lenton et al., 2008; Lenton, 2012). This tipping point has been estimated to exist between 3 and 4°C of global warming (Lucht et al., 2006; Kriegler et al., 2009) (*low confidence*), but given the complexities of the various forcing mechanisms and feedback processes this is thought to be an uncertain estimate.

3.5.5.8 *Heat-waves, unprecedented heat and human health*

Increases in ambient temperature are linearly related with hospitalizations and deaths (so there isn’t a tipping point per se) once specific thresholds are exceeded. It is plausible that coping strategies will not be in place for many regions, with potentially significant impacts on communities with low adaptive capacity, effectively representing the occurrence of a local/regional tipping point. In fact, even if global warming is restricted to below 2°C, taking into consideration urban heat island effects, there could be a substantial increase in the occurrence of deadly heatwaves in cities, with the impacts similar at 1.5°C and 2°C, but substantially larger than under the present climate (Matthews et al., 2017). At +1.5°C, twice as many megacities as present (such as Lagos, Nigeria, and Shanghai, China) are *likely* to become heat stressed, potentially exposing more than 350 million more people to deadly heat stress by 2050. At +2°C warming, Karachi (Pakistan) and Kolkata (India) could expect annual conditions equivalent to their deadly 2015 heatwaves (*medium confidence*). These statistics imply a tipping point in the extent and scale of heat-wave impacts. However, these projections do not integrate adaptation to projected warming, for instance, cooling that could be achieved with more reflective roofs and urban surfaces overall (Akbari et al., 2009; Oleson et al., 2010).

3.5.5.9 Agricultural systems: key staple crops

A large number of studies consistently indicate that maize crop yield will be negatively affected under increased global warming, with negative impacts being higher under 2°C of warming than at 1.5°C of warming (e.g., Niang et al., 2014; Schleussner et al., 2016b; J. Huang et al., 2017; Iizumi et al., 2017). Under 2°C of global warming, losses of 8-14% are projected in global maize production (Bassu et al., 2014). Under more than 2°C of global warming, regional losses are projected to be about 20% if they co-occur with reductions in rainfall (Lana et al., 2017). These changes may be classified as incremental rather than representing a tipping point. Large-scale reductions in maize crop yield including the potential for the collapse of this crop in some regions may exist under 3°C or more of global warming (*low confidence*) (e.g., Thornton et al., 2011).

3.5.5.10 Agricultural systems: livestock in the tropics and subtropics

The potential impacts of climate change on livestock (Section 3.4.6) and in particular direct impacts through inceased heat-stress has been less well studied than impacts on crop yield, in particular from the perspective of critical thresholds being exceeded. A case study of Jamaica reveals that the difference in heat stress for livestock between 1.5°C and 2°C is likely to exceed the limits for normal thermoregulation and result in persistent heat stress for livestock animals (Lallo et al., 2018). It is plausible that this finding holds for livestock production in both tropical and subtropical regions more generally (*medium confidence*) (see Section 3.4.6). It is plausible that under 3°C of global warming, significant reductions in the areas suitable for livestock production occur (*low confidence*) due to strong increases in regional temperatures in the tropics and subtropics (*high confidence).* Thus, regional tipping points in the viability of livestock production may well exist, but little evidence quantifying such changes exist.

Table 3.7: Summary of enhanced risks in the exceedance of regional tipping points under different global temperature goals.

Tipping point	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of up to 3°C
Arctic sea-ice	Arctic summer sea-ice is *likely* to be maintained. Sea-ice changes reversible under suitable climate restoration	The risk of an ice free Arctic in summer is ~ 50% or higher. Sea-ice changes reversible under suitable climate restoration	Arctic is *very likely* to be ice-free in summer. Sea-ice changes reversible under suitable climate restoration
Tundra	Decrease in number of growing degree days	Further decreases in number of growing	Potential for an abrupt increase in tree-

Tipping point	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of up to 3°C
	below 0°C Abrupt increases in tree-cover are *unlikely*	degree days below 0°C Abrupt increased in tree cover are unlikely	fraction (*low confidence*)
Permafrost	21-37% reduction in permafrost 2 million km^2 more permafrost maintained than under 2°C of global warming (*medium confidence*) 0.08-0.16 Gt C a^{-1} released Irreversible loss of stored carbon	35-47% reduction in permafrost 0.12-0.25 Gt C a^{-1} released Irreversible loss of stored carbon	Potential for permafrost collapse (*low confidence*)
Asian Monsoon	*Low confidence* in projected changes	*Low confidence* in projected changes	Increases in the intensity of monsoon precipitation *likely*.
West African monsoon and the Sahel	Uncertain changes, *unlikely* that a tipping point is reached	Uncertain changes, *unlikely* that tipping point is reached	Strengthening of monsoon and wettening and greening of Sahel and Saharah *(low confidence)* Negative associated impacts through increase in extreme temperature events
Rainforests	Reduced biomass, deforestation and fire increases pose uncertain risks to forest dieback	Larger biomass reductions than under 1.5 °C warming, deforestation and fire increases pose uncertain risk to forest dieback	Potential tipping point leading to pronounced forest dieback *(medium confidence)*
Boreal forests	Increased tree mortality at southern boundary of boreal forest *(medium confidence*)	Further increases in tree mortality at southern boundary of boreal forest (*medium confidence)*	Potential tipping point for significant dieback of boreal forest (*low confidence*)
Heat-waves, unprecedented heat	Substantial increase in occurrence of potentially	Substantial increase in potentially deadly	Substantial increase in potentially deadly

Tipping point	Warming of 1.5ºC or less	Warming of 1.5ºC-2°C	Warming of up to 3°C
and human health	deadly heat-waves *likely* More than 350 million more people exposed to deadly heat by 2050 under a midrange population growth scenario	heat-waves *likely* Annual occurrence of heat-waves similar to deadly 2015 heat-waves in India and Pakistan	heat-waves *very likely*
Key staple crops	Global maize crop reductions of about 10%	Larger reductions in maize crop production that under 1.5°C of about 15%	Drastic reductions in maize crop globally and in Africa *(high confidence),* of 20% or more; potential tipping point for collapse of maize crop in some regions *(low confidence)*
Livestock in the tropics and subtropics	Increased heat-stress	Onset of persistent heat-stress *(medium confidence)*	Persistent heat-stress *likely.*

[START BOX 3.6 HERE]

Box 3.6: Economic Damages from Climate Change

Balancing of the costs and benefits of mitigation is challenging because estimating the value of climate change damages depends on multiple parameters whose appropriate values have been debated for decades (for example, the appropriate value of the discount rate) or that are very difficult to quantify (for example, the value of non-market impacts; the economic effects of losses in ecosystem services; and the potential for adaptation, which is dependent on the rate and timing of climate change and on the socioeconomic content) (see Cross-Chapter Box 5 in Chapter 2 for the definition of the social cost of carbon, and discussion of the economics of 1.5°C-consistent pathways and the social cost of carbon, including the impacts of inequality on the social cost of carbon).

Global economic damages of climate change are smaller under warming of 1.5°C than 2°C in 2100 (Warren et al., 2018c). The mean net present value of the costs of damages from warming in 2100 for 1.5°C and. 2°C (including costs associated with climate change-induced market and non-market impacts, impacts due to sea level rise, and impacts associated with large scale discontinuities) are $54 and $69 trillion, respectively, relative to 1961-1990.

Values of the social cost of carbon vary when tipping points are included. The social cost of carbon in the default setting of the Dynamic Integrated Climate-Economy (DICE) model increases from \$15/tCO_2 to \$116 (range 50-166)/tCO_2 when large-scale singularities or 'tipping elements'are incorporated (Y. Cai et al., 2016; Lemoine and Traeger, 2016). Lemoine and Traeger (2016) included optimization calculations that minimize welfare impacts resulting from the combination of climate change risks and climate change mitigation costs, showing that welfare is minimized if warming is limited to 1.5ºC. These calculations excluded the large health co-benefits that accrue when greenhouse gas emissions are reduced (Shindell 2018; Section 3.4.7.1)

The economic damages of climate change in the USA are projected to be large (Hsiang et al., 2017; Yohe, 2017). Although not specifically related to 1.5˚C warming, Hsiang et al. (2017) concluded that the USA could lose 2.3% Gross Domestic Product (GDP) per degree of global warming. Yohe (2017) calculated transient temperature trajectories from a linear relationship with contemporaneous cumulative emissions under a median no-policy baseline trajectory that brings global emissions to roughly 93 GtCO_2 per year by the end of the century (Fawcett et al., 2015), with 1.75˚C per 1000 GtCO_2 as the median estimate (Yohe, 2017). Associated aggregate economic damages in decadal increments through the year 2100 are estimated in terms of the percentage loss of GDP at the median, 5th percentile, and 95th percentile transient temperature (Hsiang et al., 2017). The results for the baseline no-policy case indicate that economic damages along median temperature change and median damages (median-median) reach 4.5% of GDP by 2100, with an uncertainty range of 2.5% and 8.5% resulting from different combinations of temperature change and damages. Avoided damages from achieving a 1.5ºC temperature limit along the median-median case is nearly 4% (range 2.0 – 7.0%) by 2100. Avoided damages from achieving a 2ºC temperature limit is lower: 3.5% (range 1.8% - 6.5%). Avoided damages from achieving 1.5ºC vs. 2ºC is modest; it is about 0.35% (range 0.20 – 0.65%) by 2100. The values of achieving either temperature limit do not diverge significantly until 2040, when their difference tracks between 0.05% and 0.13%; the differences between the two temperature targets begin to diverge substantially in the second half of the century.

[END BOX 3.6 HERE]

3.6 Implications of different 1.5ºC and 2ºC pathways

This section provides an overview on specific aspects of the mitigation pathways considered compatible with 1.5°C global warming. Some of these aspects are also addressed in more detail in the Cross-Chapter Boxes 7 and 8 in this Chapter.

3.6.1 Gradual vs overshoot in 1.5ºC scenarios

All 1.5°C scenarios from Chapter 2 include some overshoot above 1.5°C global warming during the 21st century (Chapter 2, Cross-Chapter Box 8 in this Chapter). The level of overshoot may also depend on natural climate variability. An overview of possible outcomes of a 1.5°C-consistent mitigation scenarios for changes in physical climate at the time of overshoot and by 2100 is provided in the Cross-Chapter Box 8 on "1.5°C warmer worlds". Cross-Chapter Box 8 also highlights the implications of overshoots.

3.6.2 Non-CO_2 implications and projected risks of mitigation pathways

3.6.2.1 Risks arising from Land use changes in mitigation pathways

In mitigation pathways, land use change is affected by many different mitigation options. First of all, mitigation of non-CO_2 emissions from agricultural production can shift agricultural production between regions via trade of agricultural commodities. Secondly, protection of carbon rich ecosystems such as tropical forests constrains area for agricultural expansion. Thirdly, also demand side mitigation measures such as les consumption of resource intensive commodities (animal products) or food waste reductions reduce pressure on land (Popp et al., 2017; Rogelj et al., 2018). Finally, Carbon Dioxide Removal (CDR) is a key component of most, but not all mitigation pathways presented in the literature to date which constrain warming to 1.5°C or 2°C. Typically, CDR measures that require land can include Bioenergy with Carbon Capture and Storage (BECCS), afforestation and reforestation (AR), soil carbon sequestration, direct air capture, biochar, and enhanced weathering (see Cross-Chapter Box 7 in this Chapter). These potential methods are assessed in Section 4.3.7.

In cost-effective Integrated Assessment Modelling (IAM) pathways recently developed to be consistent with limiting warming to 1.5°C, use of CDR in the form of BECCS and AR are also fundamental elements (Chapter 2; Popp et al., 2017; Hirsch et al., 2018; Rogelj et al., 2018; Seneviratne et al., 2018c). The land-use footprint of CDR deployment in 1.5°C-consistent pathways can be substantial (Section 2.3.4, Figure 2.11), even though IAMs predominantly rely on second generation biomass and assume future productivity increases in agriculture.

A body of literature has explored potential consequences of large scale use of CDR. In this case, the corresponding land footprint by the end of the century could be extremely large, with estimates including: up to 18% of the land surface being used (Wiltshire and Davies-Barnard, 2015); vast acceleration of the loss of primary forest and natural grassland (Williamson, 2016) leading to increased greenhouse gas emissions (P. Smith et al., 2013, Smith et al., 2015); potential loss of up to 10% of the current forested lands to biofuels (Yamagata et al., 2018). Other estimates reach 380-700 Mha/21-64% of current arable cropland (Section 4.3.7); while Boysen et al. (2017) find that in a scenario in which emission reductions were sufficient only to limit warming to 2.5ºC, use of CDR to limit warming further to 1.7ºC would result in conversion of 1.1-1.5

Gha of land – implying enormous losses of both cropland and natural ecosystems (Boysen et al., 2017). Newbold et al. (2015) find that biodiversity loss in the scenario Representative Concentation Pathway (RCP)2.6 could be greater than that in RCP4.5 and RCP6.0, in which there is more climate change but less land use change. Risks to biodiversity conservation and agricultural production are therefore projected to result from large-scale bioenergy deployment pathways (P. Smith et al., 2013; Tavoni and Socolow, 2013). One study explores an extreme mitigation strategy encouraging biofuel expansion sufficient to limit warming to 1.5ºC, which finds that this is more disruptive to land use and crop prices than the climate change impacts of +2.0 ºC world which has a larger climate signal and lower mitigation requirement (Ruane et al., 2018). However, it should again be emphasized that many of the pathways explored in Chapter 2 of this report follow strategies that explore how to reduce these issues. Chapter 4 provides an assessment of the land footprint of various CDR technologies (Section 4.3.7).

The degree to which BECCS would have these large land-use footprints depends on the source of the bioenergy used, and the scale at which BECCS is deployed. Whether there is competition with food production and biodiversity depends on the governance of land use, agricultural intensification, trade, demand for food (in particular meat), feed and timber, and the context of the whole supply chain (Section 4.3.7, Fajardy and Mac Dowell, 2017; Booth, 2018; Sterman et al., 2018).

The more recent literature reviewed in Chapter 2 explores pathways which limit warming to 2°C or below and achieve a balance between sources and sinks of CO_2, using BECCS that relies on second-generation (or even third generation) biofuels, or which relies on changes in diet or more generally, management of food demand, or CDR options such as forest restoration (see Chapter 2, Bajželj et al., 2014). Overall this literature explores how to reduce the issues of competition for land with food production and with natural ecosystems (in particular forests) (see Cross-Chapter Box 1 in Chapter 1, van Vuuren et al., 2009; Haberl et al., 2010, 2013; Bajželj et al., 2014; Daioglou et al., 2016; Fajardy and Mac Dowell, 2017).

Some IAMs manage this transition by effectively protecting carbon stored on land and focussing on the conversion of pasture area into both forest area and bioenergy cropland. Some IAMs explored 1.5°C consistent pathways with demand side measures (such as dietary changes) and efficiency gains such as agricultural changes (Sections 2.3.4, 2.4.4) which lead to a greatly reduced CDR deployment and consequently land use impacts (van Vuuren et al., 2018). However, in reality whether this CDR (and more broadly, bioenergy in general) has large adverse impacts on environmental and societal goals depends in large parts on the governance of land use (Obersteiner et al., 2016; Bertram et al., 201; Humpenöder et al. 2018; Section 2.3.4).

Rates of sequestration of 3.3 GtC/ha require 970 Mha of afforestation and reforestation (Smith et al., 2015). Humpenöder et al. (2014) estimates that in least cost pathways afforestation would cover 2800 Mha by the end of the century to constrain warming to 2°C. Hence, the amount of land considered if least-cost mitigation is implemented by afforestation and reforestation could be up to 3 to 5 times greater than that required by BECCS, depending on the forest management used. However, not all of the land footprint of CDR need be in competition with biodiversity protection. Where reforestation is the restoration of natural ecosystems, this benefits both carbon sequestration and conservation of biodiversity and ecosystem services (Section 4.3.7) and can contribute to the achievement of the Aichi targets under the Convention on Biological Diversity (CBD) (Leadley et al., 2016). However, reforestation is often not defined in this way (Stanturf et al., 2014, Section 4.3.8) and the ability to deliver biodiversity benefits is strongly dependent on the precise nature of the reforestation, which has many different interpretations in different contexts and can often include agroforestry rather than restoration of pristine ecosystems (Pistorious and Kiff, 2017).

However, 'natural climate solutions' defined as conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands is estimated to have the potential to provide 37% of cost-effective CO_2 mitigation needed through 2030 consistent with a >66% chance of holding warming to below 2°C (Griscom et al., 2017).

Any reductions in agricultural production driven by climate change and/or land management decisions related to CDR may (e.g., Nelson et al., 2014a; Dalin & Rodríguez-Iturbe, 2016) or may not (Muratori et al., 2016) affect food prices. However, these studies do not consider the deployment of second-generation bioenergy crops (instead of first-generation) for which the land footprint can be much smaller. Irrespective of any mitigation-related issues, in order for ecosystems to adapt to climate change, land use would also need to be carefully managed to allow biodiversity to disperse to areas that become newly climatically suitable for it Section 3.4.1) as well as protecting the areas where the climate still remains suitable in the future. This implies a need for a considerable expansion of the protected area network (Warren et al., 2018a), either to protect existing natural habitat or to restore it (perhaps through reforestation, see above). At the same time, adaptation to climate change in the agricultural sector (Rippke et al., 2016) can require transformational as well as new approaches to land use management; whilst in order to meet the rising future food demand of a growing human population, additional land is projected to be needed to be brought into production, unless there are large increases in agricultural productivity (Tilman et al., 2011) yet future rates of deforestation may be underestimated in the existing literature (Mahowald et al., 2017a). Hence, reforestation may be associated with significant co-benefits if implemented so as to restore natural ecosystems (*high confidence*).

3.6.2.2 Biophysical feedbacks on regional climate associated with land use changes

Changes in the biophysical characteristics of the land surface are known to have an impact on local and regional climates through changes in albedo, roughness, evapotranspiration and phenology that can lead to a change in temperature and precipitation. This includes changes in land use through agricultural expansion/intensification (e.g., Mueller et al., 2016) or reforestation/revegetation endeavours (e.g., Feng et al., 2016; Sonntag et al., 2016; Bright et al., 2017) and changes in land management (e.g., Luyssaert et al., 2014; Hirsch et al., 2017) that can involve double cropping (e.g., Jeong et al., 2014; Mueller et al., 2015; Seifert and Lobell, 2015), irrigation (e.g., Lobell et al, 2009; Sacks et al., 2009; Cook et al., 2011; Qian et al., 2013; de Vrese et al., 2016; Pryor et al., 2016; Thiery et al., 2017), no-till farming and conservation agriculture (e.g., Lobell et al., 2006; Davin et al., 2014) and wood harvest (e.g., Lawrence et al., 2012). Hence, the biophysical impacts of land use changes are an important topic to assess in the context of low-emissions scenarios (e.g., (van Vuuren et al., 2011b), in particular for 1.5°C warming levels (see also Cross-Chapter Box 7 in this Chapter).

The magnitude of the biophysical impacts is potentially large for temperature extremes. Indeed, both changes induced by modifications in moisture availability and irrigation, or by changes in surface albedo, tend to be larger (i.e., stronger cooling) for hot extremes than for mean temperatures (e.g., (Seneviratne et al., 2013; Davin et al., 2014; Wilhelm et al., 2015; Hirsch et al., 2017; Thiery et al., 2017). The reasons for reduced moisture availability are related to a strong contribution of moisture deficits to the occurrence of hot extremes in mid-latitude regions (Mueller and Seneviratne, 2012; Seneviratne et al., 2013). In the case of surface albedo, cooling associated with higher albedo (e.g., in the case of no-till farming) is more effective at cooling hot days because of the higher incoming solar radiation for these days (Davin et al., 2014). The overall effect of either irrigation or albedo has been found to be at the most of the order of ca. 1–2°C regionally for temperature extremes. This can be particularly important in the context of low-emissions scenarios because the overall effect is in this case of similar magnitude to the response to the greenhouse gas forcing (Hirsch et al., 2017, Figure 3.21; Seneviratne et al., 2018a).

In addition to the biophysical feedbacks from land use change and land management on climate, there are potential consequences for particular ecosystem services. This includes climate change induced changes in crop yield (e.g., (Schlenker and Roberts, 2009; van der Velde et al., 2012; Asseng et al., 2013, 2015; Butler and Huybers, 2013; Lobell et al., 2014) which may be further exacerbated by competing demands for arable land between reforestation mitigation activities, growing crops for BECCS (Chapter 2), increasing food production to support larger populations or urban expansion (e.g., see review by Smith et al., 2010). In particular, some land management practices may have further implications for food security where some regions may have increases or decreases in yield when ceasing tillage (Pittelkow et al., 2014).

We note that the biophysical impacts of land use in the context of mitigation pathways is an emerging research topic. This topic as well as the overall role of land use change for climate change projections and socio-economic pathways will be addressed in depth in the upcoming IPCC Special Report on Climate Change and Land due in 2019.

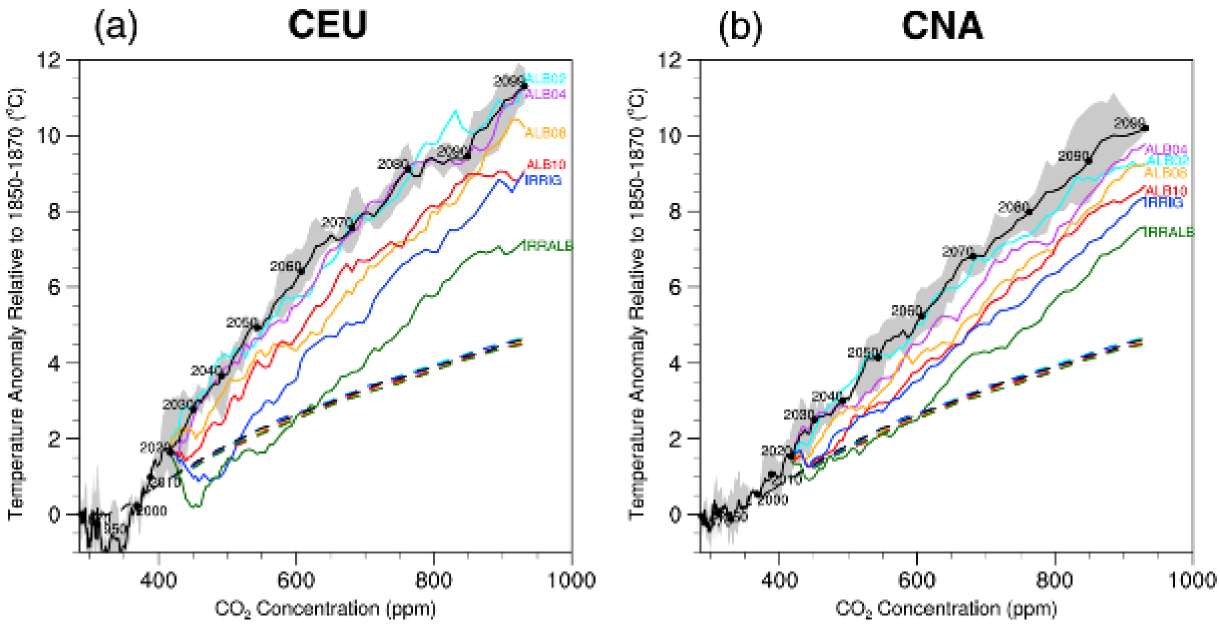


Figure 3.19: Regional temperature scaling with carbon dioxide (CO_2) concentration (ppm) over 1850 to 2099 for two different regions as defined in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX): Central Europe (CEU) (a) and Central North America (CNA) (b). Solid lines correspond to the regional average annual maximum daytime temperature (TXx) anomaly and dashed lines correspond to the global mean temperature anomaly, where all temperature anomalies are relative to 1850–1870 and units are degrees Celsius. The black line in all panels denotes the 3-member control ensemble mean with the grey shaded regions corresponding to the ensemble range. The colored lines correspond to the 3-member ensemble means of the experiments corresponding to albedo +0.02 (cyan), albedo +0.04 (purple), albedo + 0.08 (orange), albedo +0.10 (red), irrigation on (blue), and irrigation with albedo +0.10 (green). Adapted from Hirsch et al. (2017).

3.6.2.3 Atmospheric compounds (aerosols and methane)

There are multiple pathways that could be used to limit anthropogenic climate change, and the details of the pathways will change the climate impacts on humans and ecosystems. Anthropogenic driven changes in aerosols cause important modifications to global climate (Bindoff et al., 2013a; Boucher et al., 2013b; P. Wu et al., 2013; Sarojini et al., 2016; H. Wang et al., 2016). Enforcement of strict air quality policies may lead to a large decrease in cooling aerosols emissions in the next few decades. These aerosol emission reductions may cause a comparable warming to the increase in greenhouse gases by mid-21st century in the low CO_2 pathways (Kloster et al., 2009; Navarro et al., 2017), especially in the low CO_2 pathways (Cross Chapter Box 1; Sections 2.2.2 and 2.3.1). Because aerosol effects on the energy budget are regional, strong regional changes in precipitation changes from aerosols may occur if aerosols emissions are reduced for air quality or as a co-benefit from switches to sustainable energy sources (H. Wang et al., 2016). Thus regional impacts, especially on precipitation, are very sensitive to 1.5ºC-consistent pathways (Z. Wang et al., 2017).

Pathways which rely strong on reductions in methane (CH_4) versus CO_2 will reduce warming in the short-term because methane is such a stronger and shorter-lived greenhouse gas, but will be warmer in the long term because of the much longer residence time of CO_2 (Myhre et al., 2013; Pierrehumbert, 2014). In addition, the dominant loss mechanism for methane is atmospheric photooxidation. This conversion modifies ozone formation and destruction in the troposphere and stratosphere, and therefore modifies the contribution of ozone to radiative forcing, as well as feedbacks onto the oxidation rate of methane itself (Myhre et al., 2013). Focusing on pathways and policies which both improve air quality and reduce climate impacts can serve to provide multiple co-benefits (Shindell et al., 2017), and these pathways are discussed in detail in Sections 4.3.7 and 5.4.1; and Cross Chapter Box 12 in Chapter 5.

Atmospheric aerosols and gases can also modify the land and ocean uptake of anthropogenic carbon dioxide, but some compounds enhance uptake, while others reduce uptake (Ciais et al., 2013) (Section 2.6.2). While CO_2 emissions tend to encourage greater uptake of carbon by the land and the ocean (Ciais et al., 2013), methane emissions can enhance ozone pollution, depending on nitrogen oxides, volatile organic compounds, and other organic species concentrations, and ozone tends to reduce land productivity (Myhre et al., 2013; B. Wang et al., 2017). Aside from inhibiting land vegetation productivity, ozone may also alter the CO_2, CH_4 and nitrogen (N_2O) exchange at the land-atmosphere interface and transform the global soil system from a sink to a source of carbon (B. Wang et al., 2017). Aerosols and associated nitrogen-based compounds tend to enhance the uptake of carbon dioxide in land and ocean systems through the deposition of nutrients and modification of climate (Ciais et al., 2013; Mahowald et al., 2017b).

[START BOX Cross-Chapter Box 7]

Cross-Chapter Box 7: Land-Based Carbon Dioxide Removal, in Relation to 1.5°C Warming

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Climate and land form a complex system characterised by multiple feedback processes and the potential for non-linear responses to perturbation. Climate determines land cover and the distribution of vegetation affecting above and below ground carbon stocks. At the same time, land cover influences global climate through altered biogeochemical processes (e.g. atmospheric composition and nutrient flow into oceans), and regional climate through changing biogeophysical processes (including albedo, hydrology, transpiration and vegetation structure) (Forseth, 2010).

Greenhouse Gas (GHG) fluxes related to land use are reported in the Agriculture, Forestry and Other Land Use sector (AFOLU) and comprise about 25% (about 10–12 $GtCO_{2eq}yr^{-1}$) of anthropogenic GHG emissions (P. Smith et al., 2014). Reducing emissions from land use, and land use change are thus an important component of low-emissions mitigation pathways (Clarke et al., 2014), particularly as land-use emissions can be influenced by human actions such as deforestation, afforestation, fertilisation, irrigation, harvest, and other aspects of cropland, grazing land and livestock management (Paustian et al., 2006; Griscom et al., 2017; Houghton and Nassikas, 2018).

In the IPCC Fifth Assessment Report, the vast majority of scenarios assessed with a 66% or better chance of limiting global warming to 2°C by 2100 included Carbon Dioxide Removal (CDR) – typically about 10 $GtCO_2$ per year in 2100 or about 200–400 $GtCO_2$ over the course of the century (Smith et al., 2015; van Vuuren et al., 2016). These Integrated Assessment Model (IAM) results were predominately achieved by using bioenergy with carbon capture and storage (BECCS) and/or afforestation and reforestation (AR). Virtually all scenarios that either limit peak or end-of-century warming to 1.5°C also use land intensive CDR technologies (Rogelj et al., 2015; Holz et al., 2017; Kriegler et al., 2017; Fuss et al., 2018; van Vuuren et al., 2018). Again, afforestation and reforestation (AR) (Sections 2.3, 4.3.7); and BECCS (Sections 4.3.2., 4.3.7) predominate. Other CDR options such as the application of biochar to soil, soil carbon sequestration, and enhanced weathering (Section 4.3.7) are not yet widely incorporated in IAMs, but their deployment would also necessitate the use of land and/or changes in land management.

IAMs provide a simplified representation of land use and, with only a few exceptions, they do not include biophysical feedback processes (e.g. albedo and evapotranspiration effects) (Kreidenweis et al., 2016) despite the importance of these processes for regional climate, in particular hot extremes (Seneviratne et al., 2018c; section 3.6.2.2). The extent, location, and impacts of large-scale land-use change described by existing IAMs can also be widely divergent depending on model structure, scenario parameters, modelling objectives, and assumptions (including land availability and productivity) (Prestele et al., 2016; Alexander et al., 2017; Popp et al., 2017; Seneviratne et al., 2018d). Despite these limitations, IAM scenarios effectively highlight the extent and nature of potential land-use transitions implicit in limiting warming to 1.5^{o}C .

Cross-Chapter Box 7 Table 1, presents a comparison of the five CDR options assessed in this report. This illustrates that if deployed at a scale -e.g. 12 $GtCO_2yr^{-1}$ in 2100-, BECCS and AR would have a substantial land and water footprint. Wether this footprint results in adverse impacts, for example on biodiversity or food production, depends on the existence and effectiveness of measures to conserve land carbon stocks, limit the expansion of agriculture at the expense of natural ecosystems, and increase agriculture productivity (Bonsch et al., 2016; Obersteiner et al., 2016; Bertram et al., 2018; Humpenöder et al., 2018). In comparison, the land and water footprints of enhanced weathering, soil carbon sequestration and biochar application are expected to be far less per $GtCO_2$ sequestered. These options may offer potential co-benefits by providing an additional source of nutrients or reducing N_2O emissions, but they are also associated with potential side-effects. Enhanced weathering would require massive mining activity, and providing feedstock for biochar would require additional land, even though a proportion of the required biomass is expected to come from residues (Woolf et al., 2010; Smith, 2016). For the terrestrial CDR options permanence and saturation are important considerations, making their viability and long-term contributions to carbon reduction targets uncertain.

The technical, political, and social feasibility of scaling up and implementing land-intensive CDR technologies (Cross-Chapter Box 3 in Chapter 1) is recognised to present considerable potential barriers to future deployment (Boucher et al., 2013a; Fuss et al., 2014, 2018; Anderson and Peters, 2016; Williamson, 2016; Vaughan and Gough, 2016; Minx et al., 2017, 2018; Nemet et al., 2018; Strefler et al., 2018; Vaughan et al., 2018). To investigate the implications of restricting CDR options should these barriers prove difficult to overcome IAM studies (Section 2.3.4) have developed scenarios that limit (either implicity or explicity) the use of BECCS and bioenergy (Krey et al., 2014; Bauer et al., 2018; Rogelj et al., 2018), or BECCS and afforestation (Strefler et al., 2018). Alternative strategies to limit future reliance on CDR have also been examined including increased electrification, agricultural intensification, behavioral change and dramatic improvements in energy and material efficiency (Bauer et al., 2018; Grübler, 2018; van Vuuren et al., 2018). Somewhat counterintuitively, scenarios that seek to limit the deployment of BECCs may result in increased land use through greater deployment of bioenergy, and afforestation (Krey et al., 2014; Krause et al., 2017; Bauer et al., 2018; Rogelj et al., 2018) (Chapter 2, Box 2.1). Scenarios aiming to minimize the total human land footprint (including land for food, energy, and climate mitigation) also result in land use change, for example by postulating that increases in agricultural efficiency and changes in diet can enable land use, for example by postulating that increases in agricultural efficiency and changes in diet can enable land use switching from food crop production to energy crop production without altering the overall agricultural area (Grübler, 2018).

The impacts of changing land use are highly context, location and scale dependent (Robledo- Abad et al., 2017). The supply of biomass for CDR (e.g. energy crops) has received particular attention. The literature identifies regional examples of where the use of land to produce biofuels might be sustainably increased (Jaiswal et al., 2017), where biomass markets could contribute to the provision of ecosystem services (Dale et al., 2017), and where bioenergy could increase the resilience of production systems and contribute to rural development (Kline et al., 2017). Yet studies of global biomass potential provide only limited insight into the local feasibility of supplying large quantities of biomass on a global scale (Slade et al., 2014). Concerns about large scale use of biomass for CDR include a range of potential consequences including: greatly increased demand for freshwater use, increased competition for land, loss of biodiversity and/or impacts on food security (Heck et al., 2018; Section 3.6.2.1). The short versus long term carbon impacts of substituting biomass for fossil fuels (in large part determined by feedstock choice) also remain a source of contention (Schulze et al., 2012; Jonker et al., 2014; Booth, 2018; Sterman et al., 2018).

AR can also present trade-offs between biodiversity, carbon sequestration and water use, and has a higher land footprint per ton of CO_2 removed (Cunningham et al., 2015; Naudts et al., 2016; Smith et al., 2018). For example, changing forest management to strategies towards faster growing species, greater residue extraction, and shorter rotations may have a negative impact on biodiversity (de Jong et al., 2014). In contrast, reforestation of degraded land with native trees can have substantial benefits for biodiversity (Section 3.6). Despite these constraints the potential for increased carbon sequestration through improved land stewardship measures is considered to be substantial (Griscom et al., 2017).

Evaluating the synergies and trade-offs between mitigation and adaptation actions, resulting land and climate impacts, and the myriad issues related to land-use governance will be essential to better understand the future role of CDR technologies. This will be further addressed in the IPCC Special Report on Climate Change and Land (SRCCL) due to be published in 2019.

Key messages:

Cost-effective strategies to limit peak or end-of-century warming to 1.5°C all include enhanced GHG removals in the AFOLU sector as part of their portfolio of measures (*high agreement, robust evidence*).

Large-scale deployment of land-based CDR would have far reaching implications for land and water availability (*high agreement, robust evidence*). This may impact food production, biodiversity and the provision of other ecosystem services (*high agreement, medium evidence*)

The impacts of deploying land-based CDR at scale can be reduced if a wider portfolio of CDR options is deployed, and if increased mitigation effort focusses on strongly limiting demand for land, energy and material resources including lifestyle and dietary change (*high agreement, medium evidence*).

Afforestation and reforestation may be associated with significant co-benefits if implemented appropriately, but feature large land water footprints if deployed at scale (*medium agreement, medium evidence*).

Cross-Chapter Box 7, Table 1: Comparison of land-based carbon removal options

Sources: [a] assessed ranges by Fuss et al. (2018); see Figures in Section 4.3.7 for full literature range; [b] based on 2100 estimate for mean potentials by (Smith et al., 2015). Note that biophysical impacts of land-based CDR options besides albedo changes (e.g., through changes in evapotranspiration related to irrigation or land cover/use type) are not displayed.

Option	**Potentials [a]**	**Cost [a]**	**Required land [b]**	**Required water [b]**	**Impact on nutrients [b]**	**Impact on albedo [b]**	**Saturation & permanence [a]**
	$GtCO_2\ y^{-1}$	*\$ per* tCO_2	*Mha* $GtCO_2^{-1}$	km^3 $GtCO_2^{-1}$	*Mt N, P, K* y^{-1}	*No units*	*No units*
BECCS	0.5-5	100-200	31-58	60	Variable	Variable, depends on source of biofuel (higher albedo for crops than for forests) and on land management (e.g., no-till farming for crops)	Long-term governance of storage; limits on rates of bioenergy production and carbon sequestration
Afforestation & Reforestation	0.5-3.6	5-50	80	92	0.5	Negative; or reduced GHG benefit where not negative	Saturation of forests; vulnerable to disturbance; post-AR forest management essential
Enhanced Weathering	2-4	50-200	3	0.4	0	0	Saturation of soil; residence time from months to geological time scale

Biochar	0.3-2	30-120	16-100	0	N:8.2, P:2.7, K:19.1	0.08–0.12	Mean residence times between decades to centuries depending on soil type, management, and environmental conditions
Soil Carbon Sequestration	2.3-5	0-100	0	0	N:21.8, P:5.5, K:4.1	0[1]	Soil sinks saturate and can reverse if poor management practices were to resume

[END BOX Cross-Chapter Box 7]

3.6.3 *Implications beyond the end of the century*

3.6.3.1 Sea ice

Sea ice is often cited as a tipping point in the climate system (Lenton, 2012). Detailed modelling of sea ice (Schroeder and Connolley, 2007; Sedláček et al., 2011; Tietsche et al., 2011), however, suggests that summer sea ice can return within a few years after its artificial removal for climates in the late 20th and early 21st centuries. Further studies (Armour et al., 2011; Boucher et al., 2012; Ridley et al., 2012) remove sea ice by raising CO_2 concentrations and study subsequent regrowth by lowering CO_2. These studies also suggest changes in Arctic sea ice are neither irreversible nor exhibit bifurcation behavior. It is therefore plausible that the extent of Arctic sea ice may quickly re-equilibrate to end-of-century climate in the event of an overshoot scenario.

3.6.3.2 Sea level

The impacts of policy decisions related to anthropogenic climate change will have a profound impact on sea level not only for the remainder of this century but for many millennia to come (Clark et al., 2016). On these long timescales, 50 m of sea level rise are potentially possible (Clark et al., 2016). While it is *virtually certain* that sea level will continue to rise well beyond 2100, the amount of rise depends on future cumulative emissions (Church et al., 2013) as well as their profile over time (Bouttes et al., 2013; Mengel et al., 2018). Marzeion et al. (2018) find that 28–44% of present-day glacier volume is unsustainable in the present-day climate, so that it would eventually (over the course of a few centuries) melt, even if there were no further climate change. Some components of sea level rise, such as thermal expansion, are only reversible on centennial timescales (Bouttes et al., 2013; Zickfeld et al., 2013), while the contribution from ice sheets may not be reversible under any plausible future scenario (see below).

Based on the sensitivities summarized by Levermann et al. (2013), the contributions of thermal expansion (0.20–0.63 m $°C^{-1}$) and glaciers (0.21 m $°C^{-1}$ falling at higher degrees of warming mostly because of the depletion of glacier mass, with a possible total of ~0.6 m) amount to 0.5–1.2 m and 0.6–1.7 m in 1.5 and 2°C warmer worlds, respectively. The bulk of Sea Level Rise (SLR) on greater than centennial timescales will therefore be contributed by the two continental ice sheets of Greenland and Antarctica, whose existence is threatened on multi-millennial timescales.

For Greenland, where melting from the ice sheet's surface is important, a well-documented instability exists where the surface of a thinning ice sheet encounters progressively warmer air temperatures that further promote melt and thinning. A useful indicator associated with this instability is the threshold at which annual mass loss from the ice sheet by surface melt exceeds mass gain by snowfall. Previous estimates (Gregory and

Huybrechts, 2006) put this threshold about 1.9ºC to 5.1°C above preindustrial period. More recent analyses, however, suggest that this threshold sits between 0.8ºC and 3.2°C with a best estimate at 1.6°C (Robinson et al., 2012). The continued decline of the ice sheet after this threshold has been passed is highly dependent on future climate and varies between about 80% loss after 10,000 years to complete loss after as little as 2000 years (contributing ~6 m to SLR).

The Antarctic ice sheet, in contrast, loses the mass gained by snowfall as outflow and subsequent melt to the ocean (either directly from the underside of floating ice shelves or indirectly by the melt of calved icebergs). The long-term existence of this ice sheet is also affected by a potential instability (the Marine Ice Sheet Instability, MISI), which links outflow (or mass loss) from the ice sheet to water depth at the grounding line (the point at which grounded ice starts to float and becomes an ice shelf) so that retreat into deeper water (the bedrock underlying much of Antarctica slopes downwards towards the centre of the ice sheet) leads to further increases in outflow and promotes yet further retreat (Schoof, 2007). More recently, a variant on this mechanism has been postulated in which an ice cliff forms at the grounding line which retreats rapidly though fracture and iceberg calving (DeConto and Pollard, 2016). There is a growing body of evidence (Golledge et al., 2015; DeConto and Pollard, 2016) that large-scale retreat may be avoided in emission scenarios such as Representative Concentration Pathway (RCP)2.6 but that higher-emission RCP scenarios could lead to the loss of the West Antarctic ice sheet and sectors in East Antarctica, although the duration (centuries or millennia) and amount of mass loss during such as collapse is highly dependent on model details and no consensus yet exists. Current thinking (Schoof, 2007) suggests that retreat may be irreversible, although a rigorous test has yet to be made. In this context, overshoot scenarios, especially of higher magnitude or longer duration, could be anticipated to increase the risk of such irreversible retreat.

The assessment also noted that the collapse of marine sectors of the Antarctic ice sheet could lead to Global Mean Sea Level (GMSL) rise above the likely range, and that there was *medium confidence* that this additional contribution 'would not exceed several tenths of a metre during the 21st century' (Church et al., 2013).

The multi-centennial evolution of the Antarctic ice sheet is considered in papers by DeConto and Pollard (2016) and Golledge et al. (2015). Both suggest that RCP2.6 is the only RCP scenario leading to long-term contributions to GMSL of below 1.0 m. The long-term committed future of Antarctica (and GMSL contribution at 2100) are complex and require further detailed process-based modelling, however a threshold in this contribution may be present close to 1.5ºC.

3.6.3.3 Permafrost

The slow rate of permafrost thaw introduces a lag between the transient degradation of near-surface permafrost and contemporary climate, so that the equilibrium response is expected to be 25–38% greater than the transient response simulated in climate models (Slater and Lawrence, 2013). The long-term, equilibrium Arctic permafrost loss to global warming is analyzed by Chadburn et al. (2017). They use an empirical relation between recent mean annual air temperatures and the area underlain by permafrost coupled to CMIP5 stabilization projections to 2300 for RCP2.6 and RCP4.5. Their estimate of the sensitivity of permafrost to warming is 2.9–5.0 million km^2 $°C^{-1}$ (1 standard deviation confidence interval), which suggests that stabilizing climate at 1.5°C as opposed to 2°C would reduce the area of eventually permafrost loss by roughly 2 million km^2 (stabilizing at 56–83% as opposed to 43–72% of 1960–1990 levels). This work combined with the assessment of Collins et al. (2013) on the link of global warming and permafrost loss, leads to the assessment that permafrost extent would be appreciably greater in a 1.5°C world compared to a

2°C world (*medium confidence*, *limited evidence*).

3.7 Knowledge gaps

Most scientific literature specific to global warming of 1.5˚C is only just emerging. This has led to differences in the amount of information available and gaps across the various sections of this chapter. In general, the number of impact studies specifically focused on 1.5˚C lags behind climate change projections in general, due in part to the dependence of the former on the latter. There are also insufficient studies focusing on regional changes, impacts and consequences at +1.5°C and +2°C of global warming.

The following gaps have been identified with respect to tools, methodologies and understanding in the current scientific literature specific to Chapter 3. The gaps identified here are not comprehensive but highlight general areas for improved understanding, especially of global warming at 1.5°C as compared to 2°C and higher.

3.7.1 Gaps in Methods and Tools

- Regional and global climate model simulations for low-emission scenarios such as a 1.5°C world.
- Robust probabilistic models which separate the relatively small signal between 1.5°C versus 2°C from background noise, and which handle the many uncertainties associated with non-linearities, innovations, overshoot, local scales, latent or lagging responses in climate.
- Projections of risks under a range of climate and development pathways required to understand how development choices affect the magnitude and pattern of risks, and to provide better estimates of the range of uncertainties.
- More complex and integrated socio-ecological models for predicting the response of terrestrial ecosystems to climate and models which are increasingly capable of separating climate effects from those associated with human activities.
- Tools for informing local and regional decision-making especially when the signal is ambiguous at 1.5˚C and/or reverses sign at higher levels of global warming.

3.7.2 Gaps in Understanding

Earth systems and 1.5ºC:

- The cumulative effects of multiple stresses and risks (e.g., increased storm intensity interacting with sea level rise and the effect on coastal people; feedback on wetlands due to climate change and human activities).
- Feedbacks associated with changes in land use/cover for low-emissions scenarios, for example,

feedback from changes in forest cover, food production, and biofuel production, Bio-Energy with Carbon Capture and Storage (BECCS), and associated unquantified biophysical impacts.

- The distinct impacts of different overshoot scenarios depending on (a) the peak temperature of the overshoot, (b) the length of the overshoot period, and (c) the associated rate of change in global temperature over the time period of the overshoot.

Physical and chemical characteristics of a 1.5ºC world:

- Critical thresholds for extreme events (e.g., drought, inundation) between 1.5°C and 2°C, for different climate models and projections. All aspects of storm intensity and frequency as a function of climate change, especially for 1.5°C and 2°C worlds, and the impact of changing storminess on storm surge, damage and coastal flooding at regional and local scales.

- The timing and implications of the release of stored carbon in Arctic permafrost in a 1.5˚C world and for climate stabilization by the end of the century.

- Antarctic ice sheet dynamics, global sea level, and links between seasonal and year-long sea ice in both polar regions.

Terrestrial and freshwater systems

- The dynamics between climate change, freshwater resources, and socioeconomic impacts for lower levels of warming.

- How the health of vegetation is likely to change, carbon storage in plant communities and landscapes, and phenomena such as the fertilization effect.

- The risks associated with species' maladaptation in response to climatic changes (e.g., effect of late frosts), and questions associated with issues such as the consequences of species advancing their spring phenology in response to warming, and the interaction between climate change, range shifts and local adaptation in a 1.5°C world.

- The biophysical impacts of land use in the context of mitigation pathways.

Ocean Systems

- Deep sea processes and risks to deep sea habitats and ecosystems.

- Changes in ocean chemistry in a 1.5˚C world, including how decreasing ocean oxygen content, ocean acidification, and changes to activity of multiple ion species, will affect natural and human systems.

- How ocean circulation is changing towards a 1.5°C and 2°C world, for example, vertical mixing, deep ocean processes, currents, and their impacts on weather patterns at regional to local scales.

- The impacts of changing ocean conditions at 1.5˚C and 2˚C warming on food webs, disease, invading species, coastal protection, fisheries and human well-being, especially as organisms modify their biogeographical ranges within a changing ocean.

- Specific linkages between food security and changing coastal and ocean resources.

Human systems

- The impacts of global and regional climate change at 1.5°C on food distribution, nutrition, poverty, tourism, coastal infrastructure, and public health, particularly for developing nations.

- Health and well-being risks in the context of socio-economic and climate change at 1.5°C, especially in key areas such as occupational health, air quality and infectious disease.

- Micro-climates at urban/city scales and their associated risks for natural and human systems, within cities and interactions with surrounding areas. For example, current projections do not integrate adaptation to projected warming by taking into account cooling that could be achieved through a combination of revised building codes, zoning, and land use to build more reflective roofs and urban surfaces that reduce urban heat islands.

- Implications of climate change at 1.5°C on livelihoods and poverty, on rural communities, indigenous groups and marginalised people.

- The changing levels of risk in terms of extreme events (including storms and heat events), especially with respect to people being displaced or having to migrate away from sensitive and exposed systems such as small islands, low lying coasts and deltas.

Cross-Chapter Box 8: 1.5ºC Warmer Worlds

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Introduction

The Paris Agreement includes goals of stabilizing Global Mean Surface Temperature (GMST) well below 2˚C and 1.5°C above preindustrial period, in the longer term. There are several aspects, however, that remain open regarding what a '1.5°C warmer world' could be like, in terms of mitigation (Chapter 2) and adaptation (Chapter 4), as well as in terms of projected warming and associated regional climate change (Chapter 3), overlaid on anticipated and differential vulnerabilities (Chapter 5). **Alternative '1.5°C warmer worlds' resulting from mitigation and adaptation choices, as well as from climate variability (climate 'noise'), can be vastly different** as highlighted in this Cross-Chapter Box. In addition, the range of models underlying 1.5°C projections can be substantial and needs factoring in.

Key questions[3]:

- **What is a 1.5°C global mean warming, how is it measured, and what temperature increase does it imply for single locations and at specific times?** GMST corresponds to the globally averaged temperature of the Earth derived from point-scale ground observations or computed in climate models (Chapters 1 and 3). GMST is additionally defined over a given time frame, for example, averaged over a month, a year, or multiple decades. Because of climate variability, a climate-based global mean temperature typically needs to be defined over several decades (typically 20 or 30 years; Chapter 3, Section 3.2). Hence, whether or when global temperature reaches 1.5°C depends to some extent on the choice of preindustrial reference period, whether 1.5°C refers to total or human-induced warming, and which variables and coverage are used to define GMST change (Chapter 1). By definition, because GMST is an average in time and space, there will be locations and time periods in which 1.5°C warming is exceeded, even if the global mean temperature warming is at 1.5°C. In some locations, these differences can be particularly large (Cross-Chapter Box 8, Figure 1).

- **What is the impact of different climate models for projected changes in climate at 1.5°C global warming?** The range between single model simulations of projected regional changes at 1.5°C GMST warming can be substantial for regional responses (Chapter 3, Section 3.3). For instance, for the warming of cold temperature extremes in a 1.5°C warmer world, some model simulations project a 3°C warming and others more than 6°C warming in the Arctic land areas (Cross-Chapter Box 8, Figure 2). For warm temperature extremes in the contiguous United States, the range of model simulations includes colder temperatures than pre-industrial (-0.3°C) and a warming of 3.5°C (Cross-Chapter Box 8, Figure 2). Some regions display an even larger range (e.g., 1–5°C regional warming in hot extremes in Central Europe at 1.5°C warming, Chapter 3, Sections 3.3.1 and 3.3.2). This large spread is due both to modelling

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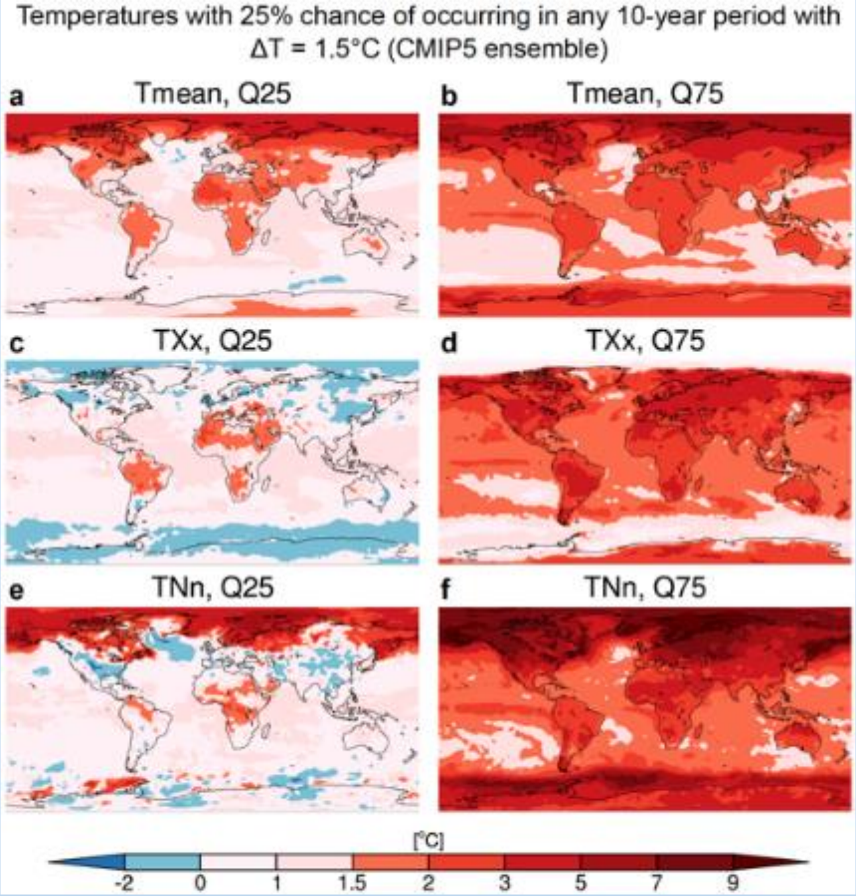
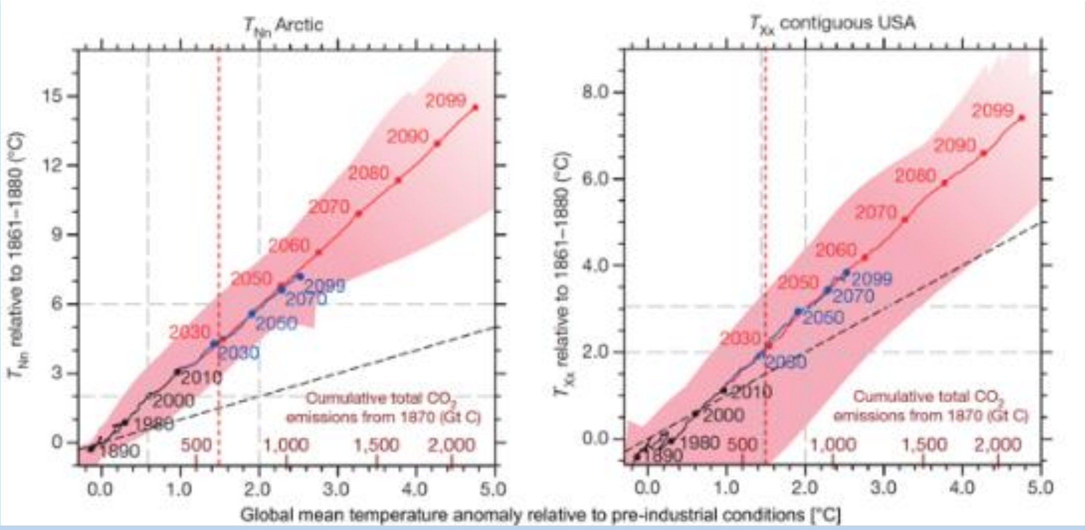
[3] FOOTNOTE: Part of this discussion is based on Seneviratne et al. (2018b)

uncertainty and internal climate variability. While the range is large, it also highlights risks that can be avoided with near certainty in a 1.5°C warmer world compared to worlds at higher levels of warming (e.g., an 8°C warming in cold extremes in the Arctic is not reached at 1.5°C global warming in the multi-model ensemble, but could happen at 2°C global warming, Cross-Chapter Box 8, Figure 2). Inferred projected ranges of regional responses (mean value, minimum and maximum) for different mitigation scenarios from Chapter 2 are displayed in Cross-Chapter Box 8, Table 1.



Cross-Chapter Box 8, Figure 1: Range of projected realized temperature at 1.5°C (due to stochastic noise and model-based spread). Temperature with a 25% chance of occurrence at any location within 10-year time frames corresponding to GMST anomalies of 1.5°C (Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble). The plots display at each location the 25th percentile (Q25, left) and 75th percentile (Q75, right) values of mean temperature (Tmean), yearly maximum day-time temperature (TXx), yearly minimum night-time temperature (TNn), sampled from all time frames with GMST anomalies of 1.5°C in Representative Concentration Pathway (RCP)8.5 model simulations of the CMIP5 ensemble. From (Seneviratne et al., 2018b).



Cross-Chapter Box 8, Figure 2: Spread of projected multi-model changes in minimum annual night-time temperature (TNn) in the Arctic land (left) and in maximum annual day-time temperature (TXx) in the contiguous United States as a function of mean global warming in climate simulations. The multi-model range (due to model spread and internal climate variability) is indicated in red shading (minimum and maximum value based on climate model simulations). The multi-model mean value is displayed with solid red and blue lines for two emissions pathways (blue : Representative Concentration Pathway (RCP)4.5; red : RCP8.5). The dashed red line indicates projections for a 1.5°C warmer world. The dashed black line displays the 1:1 line. [after Seneviratne et al., 2016].

- **What is the impact of emissions pathways with, versus without, an overshoot?** All mitigation pathways projecting less than 1.5°C global warming over or at the end of the 21st century, include some probability of overshooting 1.5°C. These pathways include some time periods with higher warming than 1.5°C in the course of the coming decades and/or some probability of not reaching 1.5°C (Chapter 2; Section 2.2). This is inherent to the difficulty of limiting global warming to 1.5°C given that we are already very close to this warming level. The implications of overshooting are large for risks to natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (Chapter 3, Box 3.4). The chronology of emission pathways and their implied warming is also important for the more slowly evolving parts of the Earth system, such as those associated with sea level rise. In addition, for several types of risks, the rate of change may be of most relevance (Loarie et al., 2009; LoPresti et al., 2015) with thus potentially large risks in case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later. On the other hand, if overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions has to be very small, which implies that large, immediate, and unprecedented global efforts to mitigate GHGs are required (Cross-Chapter Box 8, Table 1; Chapter 4).

- **What is the probability of reaching 1.5°C global warming if emissions compatible with 1.5°C pathway are followed?** Emissions pathways in a “prospective scenario” (see Chapter 1, Section 1.2.3, and Cross-Chapter Box 1 in Chapter 1 on “Scenarios and pathways”) compatible with a 1.5°C global warming, are determined based on their probability of reaching 1.5°C by 2100 (Chapter 2, Section 2.1) given current knowledge of the climate system response. These probabilities cannot be quantified precisely, but are typically 50–66% in 1.5°C-consistent pathways (Section 1.2.3). This implies a one-in-two to one-in-three probability that warming exceeds 1.5°C even under a 1.5°C-consistent pathway, including some possibility of being substantially over this value (generally about 5–10% probability, see Cross-Chapter Box 8, Table 1, and Seneviratne et al., 2018b). These alternative outcomes need to be factored into the decision-making process. To address this issue, "adaptive" mitigation scenarios are those in which emissions are continually adjusted to achieve a temperature goal (Millar et al., 2017). The set of dimensions involved in mitigation options (Chapter 4) is complex and need systemic approaches to be successful. Adaptive scenarios could be facilitated by the Global Stocktake mechanism established in the Paris Agreement, and thereby transfer the risk of higher-than-expected warming to a risk of faster-than-expected mitigation efforts. However, there are some limits to the feasibility of such approaches, because some investments (e.g. in infrastructure) are long-term and also because the actual departure from an aimed pathway will need to be detected against the backdrop of internal climate variability, typically over several decades (Haustein et al., 2017; Seneviratne et al., 2018b). Avoiding impacts that depend on atmospheric composition as well as GMST (Baker et al., 2018) would also require limits on atmospheric CO_2 concentrations in the event of a lower-than-expected GMST response.

- **How can the transformation towards a 1.5°C warmer world be implemented?** This can be achieved in a variety of ways such as decarbonizing the economy with an emphasis on demand reductions and sustainable lifestyles, or, alternatively, with an emphasis on large-scale technological solutions, amongst many other options (Chapter 2, Sections 2.3 and 2.4; Chapter 4, Sections 4.1 and 4.4.4). Different portfolios of mitigation measures come with distinct synergies and trade-offs for other societal objectives. Integrated solutions and approaches are required to achieve multiple societal objectives simultaneously (see Chapter 4, Section 4.5.4, for a set of synergies and trade-offs).

- **What determines risks and opportunities in 1.5°C warmer worlds?** The risks to natural, managed, and human systems in a 1.5°C warmer world will depend not only on uncertainties in the regional climate that results from this level of warming, but also very strongly upon the methods that humanity uses to limit warming to 1.5°C global warming. This is particularly the case for natural ecosystems and agriculture (see Cross-Chapter Box 7 in this Chapter and Chapter 4, Section 4.3.2). The risks to human systems will also depend on the magnitude and effectiveness of policies and measures implemented to increase resilience to the risks of climate change and will depend on development choices over coming decades that will influence underlying vulnerabilities and capacities of communities and institutions for responding and adapting.

- **Which aspects are not considered, or only partly considered, in the mitigation scenarios from Chapter 2?** These include biophysical impacts of land use, water constraints on energy infrastructure, and regional implications of choices of specific scenarios for tropospheric aerosol concentrations or the modulation of concentrations of short-lived climate forcers (Greenhouse Gases, Chapter 3, Section 3.6.3). Such aspects of development pathways need to be factored into comprehensive assessments of the regional implications of mitigation and adaptation measures. On the other hand, some of these aspects are assessed in Chapter 4 as possible options for mitigation and adaptation to a 1.5°C warmer world.

- **Are there commonalities to all 1.5°C warmer worlds?** Human-driven warming linked to CO_2 emissions is near irreversible over time frames of 1000 years or more (Matthews and Caldeira, 2008; Solomon et al., 2009). The global mean temperature of the Earth responds to the cumulative amount of CO_2 emissions. Hence all **1.5°C stabilization scenarios require both net CO_2 emissions and multi-gas CO_2-forcing-equivalent emissions to be zero** at some point (Chapter 2, Section 2.2). This is also the case for stabilization scenarios at higher levels of warming (e.g., at 2°C), the only difference would be the time at which the net CO_2 budget is zero.

- **Hence, a transition to decarbonisation of energy use is necessary in all scenarios**. It should be noted that **all scenarios of Chapter 2 include approaches for Carbon Dioxide Removal (CDR)** in order to achieve the net-zero CO_2 emission budget. **Most of these use Carbon Capture and Storage (CCS)** in addition to reforestation, to varying degrees (Chapter 4, Section 4.3.7). Some potential pathways to 1.5°C warming in 2100 would minimize the need for CDR (Obersteiner et al., 2018; van Vuuren et al., 2018). Taking into account the implementation of CDR, the CO_2-induced warming by 2100 is determined by the difference between the total amount of CO_2 generated (that can be reduced by early decarbonisation) and the total amount permanently stored out of the atmosphere, for example by geological sequestration (Chapter 4, Section 4.3.7).

- **What are possible storylines of 'warmer worlds' at 1.5°C vs higher levels of warming? Cross-Chapter Box 8, Table 2,** displays possible storylines based on the scenarios of Chapter 2, the impacts of Chapters 3 and 5, and the options of Chapter 4. These storylines are not intended to be comprehensive of all possible future outcomes. Rather, they are intended as plausible scenarios of alternative warmer worlds, with two storylines that either include stabilization at 1.5°C (Scenario 1) or close to 1.5°C (Scenario 2), and one missing this goal and consequently only including reductions of CO_2 emissions and efforts towards stabilization at higher temperatures (Scenario 3).

Summary:

There is no single '1.5°C warmer world'. Important aspects to consider (beside that of global temperature) are the possible occurrence of an overshoot and its associated peak warming and duration, how stabilization of global surface temperature at 1.5°C is achieved, how policies might be able to influence the resilience of human and natural systems, and the nature of the regional and sub-regional risks.

The implications of overshooting are large for risks to natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems. In addition, for several types of risks, the rate of change may be of most relevance with thus potentially large risks in case of a rapid rise to overshooting temperatures, even if a decrease to 1.5°C may be achieved at the end of the 21st century or later. If overshoot is to be minimized, the remaining equivalent CO_2 budget available for emissions has to be very small, which implies that large, immediate, and unprecedented global efforts to mitigate GHGs are required.

The time frame to initiate major mitigation measures is essential in order to reach a 1.5°C (or even a 2°C) global stabilization of climate warming (see consistent cumulative CO_2 emissions up to peak warming, Cross-Chapter Box 8, Table 1). If mitigation pathways are not rapidly activated, much more expensive and complex adaptation measures would have to be taken to avoid the impacts of higher global warming on the Earth system.

Cross-Chapter Box 8, Table 1: Different worlds resulting from 1.5°C and 2°C mitigation (prospective) pathways, including 66% (probable) best-case outcome, and 5% worst-case outcome, based on Chapter 2 scenarios and Chapter 3 assessments of changes in regional climate. Note that the pathway characteristics estimates are based on computations with the MAGICC model (Meinshausen et al., 2011) consistent with its set-up used in AR5 WGIII (Clarke et al., 2014), but are uncertain and will be subject to updates and adjustments (see Chapter 2 for details).

		B1.5_LOS (below 1.5°C with low overshoot) with 2/3 "probable best-case outcome"[a]	B1.5_LOS (below 1.5°C with low overshoot) with 1/20 "worst-case outcome"[b]	L20 (lower than 2°C) with 2/3 "probable best-case outcome"[a]	L20 (lower than 2°C) with 1/20 "worst-case outcome"[b]
General characteristics of pathway	**Overshoot > 1.5°C in 21st century[c]**	**Yes (51/51)**	**Yes (51/51)**	**Yes (72/72)**	**Yes (72/72)**
	Overshoot > 2°C in 21st century	**No (0/51)**	**Yes (37/51)**	**No (72/72)**	**Yes (72/72)**
	Cumulative CO_2 emissions up to peak warming (relative to 2016)[d]	610–760	590–750	1150–1460	1130–1470
	Cumulative CO_2 emissions up to 2100 (relative to 2016)[d] [$GtCO_2$]	170–560		1030–1440	
	Global GHG emissions in 2030[d] [$GtCO_2$ y-1]	19–23		31–38	
	Years of global net zero CO_2 emissions[d]	2055–2066		2082–2090	
Possible climate range at peak warming (regional+global)	**Global mean temperature anomaly at peak warming**	**1.7°C (1.66–1.72°C)**	**2.05°C (2.00–2.09°C)**	**2.11°C (2.05–2.17°C)**	**2.67°C (2.59–2.76°C)**
	Warming in the Arctic[e] (TNn[f])	4.93°C (4.36, 5.52)	6.02°C (5.12, 6.89)	6.24°C (5.39, 7.21)	7.69°C (6.69, 8.93)
	Warming in the Central North America[e] (TXx[g])	2.65°C (1.92, 3.15)	3.11°C (2.37, 3.63)	3.18°C (2.50, 3.71)	4.06°C (3.35, 4.63)
	Warming in Amazon region[e] (TXx)	2.55°C (2.23, 2.83)	3.07°C (2.74, 3.46)	3.16°C (2.84, 3.57)	4.05°C (3.62, 4.46)
	Drying in the Mediterranean region[e]	-1.11 (-2.24, -0.41)	-1.28 (-2.44, -0.51)	-1.38 (-2.58, -0.53)	-1.56 (-3.19, -0.67)
	Increase in heavy precipitation events[e] in Southern Asia[e]	9.94% (6.76, 14.00)	11.94% (7.52, 18.86)	12.68% (7.71, 22.39)	19.67% (11.56, 27.24)
Possible climate range in 2100 (regional+global)	**Global mean temperature warming in 2100**	**1.46°C (1.41—1.51°C)**	**1.87°C (1.81—1.94°C)**	**2.06°C (1.99—2.15°C)**	**2.66°C (2.56—2.76°C)**
	Warming in the Arctic[i] (TNn)	4.28°C (3.71, 4.77)	5.50°C (4.74, 6.21)	6.08°C (5.20, 6.94)	7.63°C (6.66, 8.90)
	Warming in Central North America[i] (TXx)	2.31°C (1.56, 2.66)	2.83°C (2.03, 3.49)	3.12°C (2.38, 3.67)	4.06°C (3.33, 4.59)
	Warming in Amazon region[i] (TXx)	2.22°C (2.00, 2.45)	2.76°C (2.50, 3.07)	3.10°C (2.75, 3.49)	4.03°C (3.62, 4.45)
	Drying in the Mediterranean region[i]	-0.95 (-1.98, -0.30)	-1.10 (-2.17, -0.51)	-1.26 (-2.43, -0.52)	-1.55 (-3.17, -0.67)
	Increase in heavy precipitation events in Southern Asia[i]	8.38% (4.63, 12.68)	10.34% (6.64, 16.07)	12.02% (7.41, 19.62)	19.72% (11.34, 26.95)

Cross-Chapter Box 8, Table 2: Storylines of possible worlds resulting from different mitigation options. The storylines build upon Cross-Chapter Box 8, Table 1, and the assessments of Chapters 1-5. These are only a few of possible storylines; their choice is for illustrative purposes.

Scenario 1 [one possible storyline among best-case scenarios]: **Mitigation: Early move to**	**In 2020, strong participation and support for the Paris Agreement and its ambitious goals for reducing CO_2 emissions by an almost unanimous international community led to a time frame for net-zero emissions that is compatible with halting of global temperature warming to 1.5°C by 2100.** There is strong participation in all major world regions at national, state and/or city levels. Transport is strongly decarbonized through a shift to electric vehicles, with

decarbonisation, decarbonisation designed to minimise land footprint, coordination and rapid action of world's nations towards 1.5°C goal by 2100	more cars with electric than combustion engines being sold by 2025 **(Chapter 2, Section 2.4.3; Chapter 4, Section 4.3.3)**. Several industry-sized plants for carbon capture and storage are installed and tested in the 2020s **(Chapter 2, Section 2.4.2; Chapter 4, Sections 4.3.4 and 4.3.7)**. Competition for land between bioenergy cropping, food production, and biodiversity conservation is minimised by sourcing bioenergy for carbon capture and storage from agricultural wastes, algae, and kelp farms (**Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2)**. Agriculture is intensified in countries with coordinated planning associated with a drastic decrease in food wastage **(Chapter 2, Section 2.4.4; Chapter 4, Section 4.3.2)**. This leaves many natural ecosystems relatively intact, supporting continued provision of most ecosystem services, although relocation of species toward higher latitudes and altitudes resulted in changes in local biodiversity in many regions, particularly in mountain, tropical coastal, and Arctic ecosystems **(Chapter 3, Section 3.4.3)**. Adaptive measures such as the establishment of corridors for the movement of species and parts of ecosystems become a central practice within conservation management **(Chapter 3, Section 3.4.3; Chapter 4, Section 4.3.2)**. The movement of species presents new challenges for resource management as novel ecosystems, and pests and disease, increase **(Cross-chapter Box 6 in Chapter 3)**. Crops are grown on marginal land and no-till agriculture deployed, and large areas are reforested with native trees **(Chapter 2, Section 2.4.4; Chapter 3, Section 3.6.2; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2)**. Societal preference for healthy diets reduces meat consumption and associated GHG emissions **(Chapter 2, Section 2.4.4; Chapter 4, Section 4.3.2; Cross-Chapter Box 6 in Chapter 3).**
Internal climate variability: Probable (66%) best-case outcome for global and regional climate responses.	By 2100, global mean temperature is on average 0.5°C warmer than it was in 2018 **(Chapter 1, Section 1.2.1)**. Only a minor temperature overshoot occurs during the century **(Chapter 2, Section 2.2)**. In mid-latitudes, there are frequent hot summers and precipitation events tend to be more intense **(Chapter 3, Section 3.3)**. Coastal communities struggle with increased inundation associated with rising sea levels and more frequent and intense heavy rainfall **(Chapter 3, Sections 3.3.2 and 3.3.9; Chapter 5, Box 5.3 and Section 5.3.2; Cross-Chapter Box 12 in Chapter 5; Chapter 4, Section 4.3.2)**, and some respond by moving, in many cases, with consequences for urban areas. In the Tropics, in particular in mega-cities, there are frequent deadly heatwaves whose risks are reduced by proactive adaptation **(Chapter 3, Sections 3.3.1 and 3.4.8; Chapter 4, Section 4.3.8)**, overlaid on a suite of development challenges and limits in disaster risk management **(Chapter 4, Section 4.3.3; Chapter 5, Sections 5.2.1 and 5.2.2; Cross-Chapter Box 12 in Chapter 5)**. Glaciers extent decreases in most mountainous areas **(Chapter 3, Sections 3.3.5 and 3.5.4)**. Reduced Arctic sea ice opens up new shipping lanes and commercial corridors **(Chapter 3, Section 3.3.8; Chapter 4, Box 4.3)**. Small Island Developing States (SIDS), Coastal and low-lying areas have faced significant changes but have largely persisted in most regions **(Chapter 3; Sections 3.3.9 and 3.5.4; Box 3.5)**. The Mediterranean area becomes drier **(Chapter 3, Section 3.3.4 and Box 3.2)** and irrigation of crops expands, drawing the water table down in many areas **(Chapter 3, Section 3.4.6)**. The Amazon is reasonably well preserved (through avoided risk of possible large changes in regional temperature means and hot extremes and the probability of most extreme droughts **(Chapter 3, Sections 3.3.3, 3.3.4 and 3.4.3; Chapter 4, Box 4.3)** as well as through reduced deforestation **(Chapter 2, Section 2.4.4; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Section 4.3.2))** and the forest services are working with the pattern observed at the beginning of the 21st century **(Chapter 4, Box 4.3).** While some climate hazards become more frequent **(Chapter**

	3, Section 3.3), timely adaptation measures help reduce the associated risks for most, although poor and disadvantaged groups continue to experience high climate risks to their livelihoods and wellbeing **(Chapter 5, Section 5.3.1; Cross-Chapter Box 12 in chapter 5; Chapter 3, Boxes 3.4 and 3.5; Cross-Chapter Box 6 in Chapter 3)**. Summer sea ice has not completely disappeared from the Arctic (**3.4.4.7**) and coral reefs having been driven to a low level (10-30% of levels in 2018) have partially recovered after extensive dieback by 2100 **(Chapter 3, Section 3.4.4.10 and Box 3.4)**. The Earth system, while warmer, is still recognizable compared to the 2000s and no major tipping points are reached **(Chapter 3, Section 3.5.2.5)**. Crop yields remain relatively stable **(Chapter 3, Section 3.4)**. Aggregate economic damage of climate change impacts is relatively small, although there are some local losses associated with extreme weather events **(Chapter 3, Section 3.5; Chapter 4)**. Human well-being remains overall similar to that in 2020 (**Chapter 5, Section 5.2.2**).
Scenario 2 [one possible storyline among mid-case scenarios]: **Mitigation: Delayed action (ambitious targets reached only after warmer decade in the 2020s due to internal climate variability), overshoot at 2°C, decrease towards 1.5°C afterward, with no efforts to minimize the land and water footprints of bioenergy.** **Internal climate variability: First, 10% worst-case outcome (2020s), then normal internal climate variability**	**The international community continues to largely support the Paris Agreement and agrees in 2020 on reduction targets for CO_2 emissions and time frames for net-zero emissions. However, these targets are not ambitious enough to reach stabilization at 2°C warming, let alone 1.5°C.** **In the 2020s, internal climate variability leads to higher warming than projected, in a reverse development to what happened in the so-called “hiatus” period of the 2000s.** Temperatures are regularly above 1.5°C warming although radiative forcing is consistent with a warming of 1.2°C or 1.3°C. Deadly heatwaves in major cities (Chicago, Kolkata, Beijing, Karachi, São Paulo), droughts in Southern Europe, South Africa and the Western Sahel, and major flooding in Asia, all intensified by the global and regional warming **(Chapter 3, Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.4.8; Chapter 4, Cross-Chapter Box 11 in Chapter 4)**, lead to increasing levels of public unrest and political destabilization (**Chapter 5, Section 5.2.1**). An emergency global summit in 2025 moves to much more ambitious climate targets. Costs for rapidly phasing out fossil fuel use and infrastructure, while rapidly expanding renewables to reduce emissions, are much higher than in Scenario 1 due to a failure to support economic measures to drive the transition **(Chapter 4)**. Disruptive technologies become crucial to face up to the adaptation measures needed **(Chapter 4, Section 4.4.4)**. Temperature peaks at 2°C by the middle of the century before decreasing again due to intensive implementation of bioenergy plants with carbon capture and storage **(Chapter 2)**, without efforts to minimize the land and water footprint of the bioenergy production **(Cross-Chapter Box 7 in Chapter 3)**. Reaching 2˚C for several decades eliminates or severely damages key ecosystems such as coral reefs and tropical forests **(Chapter 3, Section 3.4)**. The elimination of coral reef ecosystems and the deterioration of their calcified frameworks, as well as serious losses of coastal ecosystems such as mangrove forests and seagrass beds **(Chapter 3, Box 3.4, Box 3.5, 3.4.4.10, 3.4.5)**, leads to much reduced levels of coastal defence from storms, winds and waves increases the vulnerability and risks facing communities in tropical and sub-tropical regions with consequences for many coastal communities **(Chapter 5, Cross-Chapter Box 12 in Chapter 5)** These impacts are being amplified by steadily rising sea levels **(Chapter 3, Section 3.3.9)** and intensifying storms **(Section 3.4.4.3)**. The intensive area required for the production of bioenergy combined with increasing water stress sets pressures on food prices

	(Cross-Chapter Box 6 in Chapter 3), driving elevated rates of food insecurity, hunger, and poverty **(Chapter 4, Section 4.3.2; Cross-Chaper Box 6 in Chapter 3; Cross-Chapter Box 11 in Chapter 4)**. Crop yields decline significantly in the tropics, leading to prolonged famines in some African countries **(Chapter 3, Section 3.4; Chapter 4 Section 4.3.2)**. Food trumps environment in terms of importance in most countries with the result that natural ecosystems decrease in abundance due to climate change as well as of land-use change **(Cross-Chapter Box 7 in Chapter 3)**. The ability to implement adaptive action to prevent the loss of ecosystems is frustrated under the circumstances and is consequently minimal **(Chapter 3, Section 3.4.4.10)**. Many natural ecosystems, in particular in the Mediterranean, are lost due to the combined effects of climate change and land use change, and extinction rates increase greatly **(Chapter 3, Section 3.4 and Box 3.2)**. By 2100, temperature has decreased but is still higher than 1.5°C, and the yields of some tropical crops are recovering **(Chapter 3, Section 3.4.3)**. Several of the remaining natural ecosystems experience irreversible climate-change related damages whilst others have been lost to land use change, with very rapid increases in the rate of species extinctions **(Chapter 3, Section 3.4; Cross-Chapter Box 7 in Chapter 3; Chapter 4, Cross-Chapter Box 11 in Chapter 4)**. Migration, forced displacement, and loss of identity are extensive in some countries, reversing some achievements in sustainable development and human security **(Chapter 5, Section 5.3.2)**. Aggregate economic impacts of climate change damage are small, but the loss in ecosystem services creates large economic losses **(Chapter 4, Sections 4.3.2 and 4.3.3)**. The health and well-being of people generally decrease from 2020, while the levels of poverty and disadvantage increase very significantly **(Chapter 5, Section 5.2.1)**.
Scenario 3 [one possible storyline among worst-case scenarios]: **Mitigation: Uncoordinated action, major actions late in the 21st century, 3°C warming in 2100.** **Internal climate variability: First unusual (ca. 10%) best-case scenario for one decade, then normal internal climate variability**	**In 2020, despite past pledges, the international support for the Paris Agreement starts to wane. In the years that follow, CO_2 emissions are reduced at local and national level but efforts are limited and not always successful.** **Radiative forcing increases and, due to chance, the most extreme events tend to happen in less populated regions thus not increasing global concerns.** Nonetheless, there are more frequent heatwaves in several cities and less snow in mountain resorts in the Alps, Rockies, and Andes **(Chapter 3, Section 3.3)**. 1.5°C warming is reached by 2030, but no major changes in policies occur. Starting with an intense El Niño-La Niña phase in the 2030s, several catastrophic years occur while global temperature warming starts to approach 2°C. There are major heatwaves on all continents, with deadly consequences in tropical regions and Asian megacities, especially for those ill-equipped for protecting themselves and their communities from the effects of extreme temperatures **(Chapter 3, Sections 3.3.1, 3.3.2 and 3.4.8)**. Droughts occur in regions bordering the Mediterranean Sea, Central North America, the Amazon region and southern Australia, some of which are due to natural variability and others to enhanced greenhouse forcing **(Chapter 3, Section 3.3.4; Chapter 4, Section 4.3.2; Cross-Chapter Box 11 in Chapter 4)**. Intense floodings occur in high-latitude and tropical regions, in particular in Asia, following increases in heavy precipitation events **(Chapter 3, Section 3.3.3)**. Major ecosystems (coral reefs, wetlands, forests) are destroyed over that period **(Chapter 3, Section 3.4)** with massive disruption to local livelihoods **(Chapter 5, Section 5.2.2 and Box 5.3; Cross-Chapter Box 12 in Chapter 5)**. An unprecedented drought leads to large impacts on the Amazon rain forest **(Chapter 3, Sections 3.3.4 and 3.4)**, which is also affected by deforestation **(Chapter 2)**. A hurricane with intense rainfall and

associated with high storm surges **(Chapter 3, Section 3.3.6)** destroys a large part of Miami. A 2-year drought in the Great Plains and a concomitant drought in Eastern Europe and Russia decrease global crop production **(Chapter 3, Section 3.3.4)**, resulting in major increases in food prices and eroding food security. Poverty levels increase to a very large scale and risk and incidence of starvation increase very significantly as food stores dwindle in most countries; human health suffers (**Chapter 3, Section 3.4.6.1; Chapter 4, Sections 4.3.2 and 4.4.3; Chapter 5, Section 5.2.1**).

There are high levels of public unrest and political destabilization due to the increasing climatic pressures, resulting in some countries becoming dysfunctional (**Chapter 4, Sections 4.4.1 and 4.4.2**). The main countries responsible for the CO_2 emissions design rapidly conceived mitigation plans and try to install plants for carbon capture and storage, in some cases without sufficient prior testing (**Chapter 4, Section 4.3.6**). Massive investments in renewable energy often happen too late and are uncoordinated; energy prices soar as a result of the high demand and lack of infrastructure. In some cases, demand cannot be met, leading to further delays. Some countries propose to consider sulphate-aerosol based SRM (**Chapter 4, Section 4.3.8**), however intensive international negotiations on the topic take substantial time and are inconclusive, because of overwhelming concerns about potential impacts to monsoon rainfall and risks in case of termination **(Cross-Chapter Box 10 in Chapter 5)**. Global and regional temperatures continue to strongly increase while mitigation solutions are being developed and implemented.

Global mean warming reaches 3°C by 2100 but is not yet stabilized despite major decreases in yearly CO_2 emissions, as a net-zero CO_2 emissions budget could not yet be achieved and because of the long life-time of CO_2 concentrations **(Chapters 1, 2 and 3)**. The world as it was in 2020 is no longer recognizable, with decreasing life expectancy, reduced outdoor labour productivity, and lower quality of life in many regions because of too frequent heatwaves and other climate extremes (**Chapter 4, Section 4.3.3**). Droughts and water resources stress renders agriculture economically un-viable in some regions **(Chapter 3, Section 3.4; Chapter 4, Section 4.3.2)** and contributes to increases in poverty **(Chapter 5, Section 5.2.1; Cross-Chapter Box 12 in Chapter 5)**. Progress on the sustainable development goals is largely undone and poverty rates reach new highs **(Chapter 5, Section 5.2.3)**. Major conflicts take place **(Chapter 3, Section 3.4.9.6; Chapter 5, Section 5.2.1)**. Almost all ecosystems experience irreversible impacts, species extinction rates are high in all regions, forest fires escalate, and biodiversity strongly decreases, resulting in extensive losses to ecosystem services. These losses exacerbate poverty and reduce quality of life **(Chapter 3, Section 3.4; Chapter 4, Section 4.3.2)**. Life, for many indigenous and rural groups, becomes untenable in their ancestral lands **(Chapter 4, Box 4.3; Chapter 5, Cross-Chapter Box 12 in Chapter 5)**. The retreat of the West Antarctic ice sheet accelerates **(Chapter 3, Sections 3.3 and 3.6)**, leading to more rapid SLR **(Chapter 3, Section 3.3.9; Chapter 4, Section 4.3.2)**. Several small island states give up hope to survive in their place and look to an increasingly fragmented global community for refuge **(Chapter 3, Box 3.5; Chapter 5, Cross-Chapter Box 12 in Chapter 5)**. Aggregate economic damages are substantial owing to the combined effects of climate changes, political instability, and losses of ecosystem services **(Chapter 4, Sections 4.4.1 and 4.4.2; Chapter 3, Box 3.6 and Section 3.5.2.4)**. The general health and well-being of people substantially decreased compared to the conditions in 2020 and continues to worsen over the following decades (**Chapter 5, Section 5.2.3**).

Frequently Asked Questions

FAQ 3.1: What are the impacts of 1.5°C and 2°C of warming?

***Summary**: The impacts of climate change are being felt in every inhabited continent and in the oceans. But they are not spread uniformly across the globe, and different parts of the world experience impacts differently. An average warming of 1.5°C across the whole globe raises the risk of heatwaves and heavy rainfall events, amongst many other potential impacts. Limiting warming to 1.5°C rather than 2°C can help reduce these risks. But the impacts the world experiences will depend on the specific greenhouse gas emission 'pathway' taken. The consequences of temporarily overshooting 1.5°C and returning later in the century, for example, could be larger than if temperature stabilizes below 1.5°C. The size and duration of an overshoot will also affect future impacts.*

Human activity has warmed the world by ~1°C since pre-industrial times, and the impacts of this warming are already been felt in many parts of the world. This warming in global temperature is the average of many thousands of temperature measurements taken over the world's land and oceans. But temperatures aren't changing at the same speed everywhere. Warming is greatest on continents and is particularly strong in the Arctic in the cold season and mid-latitude regions in the warm season. This is due to self-amplifying mechanisms which increase resulting warming, for instance due to snow and ice melt reducing the reflectivity of solar radiation at the surface, or soil moisture drying leading to less evaporative cooling in the interior of continents. This means that some parts of the world have already experienced temperatures above 1.5°C above pre-industrial levels.

Extra warming on top of the ~1°C we have seen so far would amplify the risks and associated impacts, with implications for the world and its inhabitants. This would be the case even if the total warming is held at 1.5°C, just half a degree above where we are now, and would be further amplified at 2°C global warming. Reaching 2°C instead of 1.5°C global warming would lead to substantial warming of extreme hot days in all land regions. It would also lead to an increase in heavy rainfall events in some regions, particularly in the high latitudes of the Northern Hemisphere, potentially raising the risk of flooding. In addition, some regions are projected to become drier at 2°C vs 1.5°C global warming, for example the Mediterranean region. The impacts of any additional warming would also include stronger melting of ice sheets and glaciers, as well as increased sea level rise, which would continue long after the stabilization of atmospheric CO_2 concentrations.

Change in climate means and extremes have knock on effects for the societies and ecosystems living on the planet. Climate change is projected to be a poverty multiplier, which means that its impacts make the poor poorer and increase the total number of people living in poverty. The 0.5°C rise in global temperatures that we have experienced in the past 50 years has contributed to shifts in the distribution of plant and animal species, decreasing crop yields and leading to more frequent wildfires. Similar changes can be expected for further rises in global temperature.

Essentially, the lower the rise in global temperature above preindustrial levels, the lower the risks to human societies and natural ecosystems. Put another way, limiting warming to 1.5°C can be understood in terms of 'avoided impacts' compared to higher levels of warming. Many of the impacts of climate change assessed in this report have lower associated risks at 1.5°C compared to 2°C.

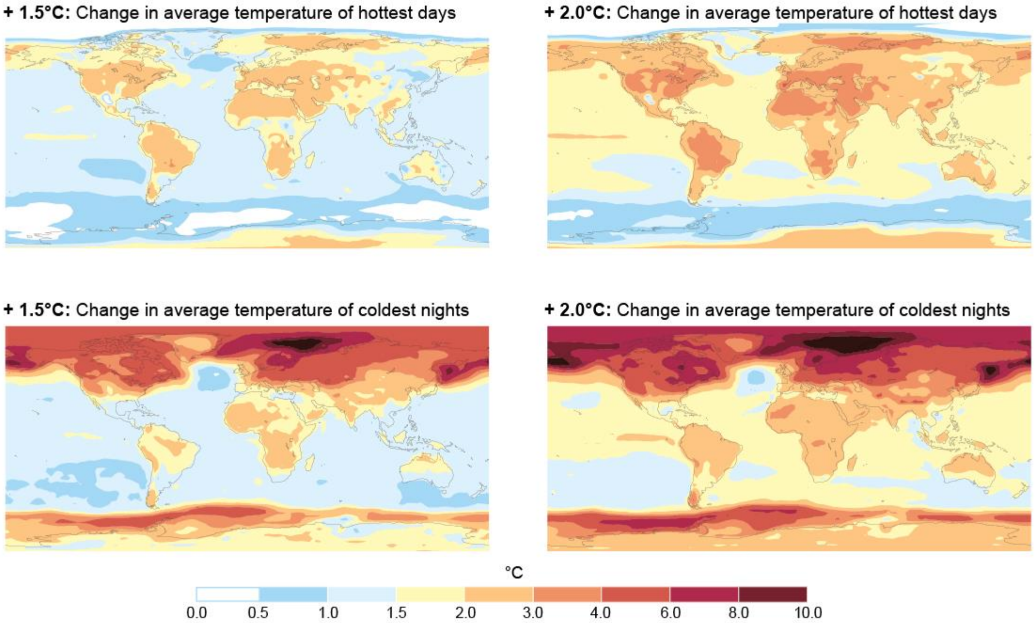
Thermal expansion of the oceans, resulting from the delayed ocean mixing, means sea level will continue to rise even if global temperature is limited to 1.5°C, but this would be lower than in a 2°C world. Ocean acidification, the process by which excess CO_2 is dissolving into oceans and making them more acidic, is expected to be less damaging in a world where CO_2 emissions are reduced and warming is stabilised at 1.5°C compared to 2°C. The prospect for coral reefs in a 1.5°C world of less damaging than that of a 2ºC world, too.

The impacts of climate change that we experience in future will also be affected by factors other than the change in temperature. The consequences of 1.5°C warming will additionally depend on the specific greenhouse gas emissions 'pathway' that is followed and the extent to which adaptation can reduce vulnerability. This IPCC Special Report uses a number of 'pathways' to explore different possibilities for limiting global warming to 1.5°C above preindustrial levels. One type of pathway sees global temperature stabilize at, or just below, 1.5°C. Another sees global temperature temporarily exceed 1.5°C before coming back down later in the century (known as an 'overshoot' pathway).

Such pathways would have different associated impacts, so it is important to distinguish between them for planning adaptation and mitigation strategies. For example, impacts from an overshoot pathway could be larger than impacts from a stabilization pathway. The size and duration of an overshoot would also have consequences for the impacts the world experiences. For example, pathways that overshoot 1.5°C run a greater risk of passing through 'tipping points'. These are thresholds beyond which certain impacts can no longer be avoided, even if temperatures are brought back down later on. An example is the collapse of the Greenland and Antarctic ice sheets on the time scale of centuries and millennia.

FAQ3.1: **Impact of 1.5°C and 2.0°C global warming**

Temperature rise is not uniform across the world. Some regions will experience greater increases in hot days and decreases in cold nights than others



FAQ 3.1, Figure 1: Temperature change is not uniform across the globe. Projected change in average temperature of the annual hottest day (top) and the annual coldest night (bottom) with 1.5°C global warming (left) and 2°C global warming (right) compared to pre-industrial levels.

References

Aalto, J., S. Harrison, and M. Luoto, 2017: Statistical modelling predicts almost complete loss of major periglacial processes in Northern Europe by 2100. *Nature Communications*, 1-8, doi:10.1038/s41467-017-00669-3.

Abatzoglou, J.T. and A.P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America***, 113(42)**, 11770-11775, doi:10.1073/pnas.1607171113.

Abebe, A. et al., 2016: Growth, yield and quality of maize with elevated atmospheric carbon dioxide and temperature in north-west India. *Agriculture, Ecosystems & Environment***, 218**, 66-72, doi:10.1016/j.agee.2015.11.014.

Acharya, S.S. and M.K. Panigrahi, 2016: Eastward shift and maintenance of Arabian Sea oxygen minimum zone: Understanding the paradox. *Deep-Sea Research Part I: Oceanographic Research Papers***, 115**, 240-252, doi:10.1016/j.dsr.2016.07.004.

Adams, C., T. Ide, J. Barnett, and A. Detges, 2018: Sampling bias in climate-conflict research. *Nature Climate Change***, 8(3)**, 200-203, doi:10.1038/s41558-018-0068-2.

Adger, W.N. et al., 2014: Human Security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755-791.

AghaKouchak, A., D. Feldman, M. Hoerling, T. Huxman, and J. Lund, 2015: Water and climate: Recognize anthropogenic drought. *Nature***, 524(7566)**, 409-411, doi:10.1038/524409a.

Aguilera, R., R. Marcé, and S. Sabater, 2015: Detection and attribution of global change effects on river nutrient dynamics in a large Mediterranean basin. *Biogeosciences***, 12**, 4085-4098, doi:10.5194/bg-12-4085-2015.

Ahlström, A., G. Schurgers, A. Arneth, and B. Smith, 2012: Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections. *Environmental Research Letters***, 7(4)**, 44008.

Ahmed, K.F., G. Wang, M. Yu, J. Koo, and L. You, 2015: Potential impact of climate change on cereal crop yield in West Africa. *Climatic Change***, 133(2)**, 321-334, doi:10.1007/s10584-015-1462-7.

Ainsworth, C.H. et al., 2011: Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. *ICES Journal of Marine Science***, 68(6)**, 1217-1229.

Akbari, H., S. Menon, and A. Rosenfeld, 2009: Global cooling: Increasing world-wide urban albedos to offset CO 2. *Climatic Change***, 94(3-4)**, 275-286, doi:10.1007/s10584-008-9515-9.

Albert, S. et al., 2017: Heading for the hills: climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5 °C future. *Regional Environmental Change*, 1-12, doi:10.1007/s10113-017-1256-8.

Albright, R. et al., 2016: Ocean acidification: Linking science to management solutions using the Great Barrier Reef as a case study. *Journal of Environmental Management***, 182**, 641-650.

Alexander, P. et al., 2017: Assessing uncertainties in land cover projections. *Global Change Biology***, 23(2)**, 767-781, doi:10.1111/gcb.13447.

Alfieri, L., F. Dottori, R. Betts, P. Salamon, and L. Feyen, 2018: Multi-Model Projections of River Flood Risk in Europe under Global Warming. *Climate***, 6(1)(6)**.

Alfieri, L. et al., 2017: Global projections of river flood risk in a warmer world. *Earth's Future***, 5(2)**, 171-

182, doi:10.1002/2016EF000485.

Allen, R., A. Foggo, K. Fabricius, A. Balistreri, and J.M. Hall-Spencer, 2017: Tropical CO 2 seeps reveal the impact of ocean acidification on coral reef invertebrate recruitment. *Marine Pollution Bulletin***, 124(2)**, 607-613, doi:10.1016/j.marpolbul.2016.12.031.

Alongi, D.M., 2008: Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science***, 76(1)**, 1-13, doi:10.1016/j.ecss.2007.08.024.

Alongi, D.M., 2015: The Impact of Climate Change on Mangrove Forests. *Current Climate Change Reports***, 1(1)**, 30-39, doi:10.1007/s40641-015-0002-x.

Altieri, A.H. and K.B. Gedan, 2015: Climate change and dead zones. *Global Change Biology***, 21(4)**, 1395-1406, doi:10.1111/gcb.12754.

Altieri, A.H. et al., 2017: Tropical dead zones and mass mortalities on coral reefs. *Proceedings of the National Academy of Sciences***, 114(14)**, 3660-3665, doi:10.1073/pnas.1621517114.

Alvarez-Filip, L., N.K. Dulvy, J.A. Gill, I.M. Cote, and A.R. Watkinson, 2009: Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. *Proceedings of the Royal Society B: Biological Sciences***, 276(1669)**, 3019-3025, doi:10.1098/rspb.2009.0339.

Amir, A.K., C. Linyin, M. Omid, and F. Alireza, 2014: Global warming and changes in risk of concurrent climate extremes: Insights from the 2014 California drought. *Geophysical Research Letters***, 41(24)**, 8847-8852, doi:10.1002/2014GL062308.

Anderegg, W.R.L. et al., 2015: Tropical nighttime warming as a dominant driver of variability in the terrestrial carbon sink. *Proceedings of the National Academy of Sciences of the United States of America***, 112(51)**, 15591-15596, doi:10.1073/pnas.1521479112.

Anderson, K. and G. Peters, 2016: The trouble with negative emissions. *Science***, 354(6309)**, 182-183, doi:10.1126/science.aah4567.

André, C., D. Boulet, H. Rey-Valette, and B. Rulleau, 2016: Protection by hard defence structures or relocation of assets exposed to coastal risks: Contributions and drawbacks of cost-benefit analysis for long-term adaptation choices to climate change. *Ocean and Coastal Management***, 134**, 173-182, doi:10.1016/j.ocecoaman.2016.10.003.

André, G., B. Engel, P.B.M. Berentsen, T.V. Vellinga, and A.G.J.M. Oude Lansink, 2011: Quantifying the effect of heat stress on daily milk yield and monitoring dynamic changes using an adaptive dynamic model. *Journal of Dairy Science***, 94(9)**, 4502-4513, doi:10.3168/jds.2010-4139.

Anthony, K., 2016: Coral reefs under climate change and ocean acidification: challenges and opportunities for management and policy. *Annu. Rev. Environ. Resour.***, 41**, 41:59-81.

Anthony, K.R.N. et al., 2015: Operationalizing resilience for adaptive coral reef management under global environmental change. *Global Change Biology***, 21(1)**, 48-61, doi:10.1111/gcb.12700.

Araos, M. et al., 2016: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science and Policy***, 66**, 375-382, doi:10.1016/j.envsci.2016.06.009.

Arent, D.J. et al., 2014: Key economic sectors and services. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-708.

Argüeso, D., J.P. Evans, L. Fita, and K.J. Bormann, 2014: Temperature response to future urbanization and climate change. *Climate Dynamics***, 42(7-8)**, 2183-2199, doi:10.1007/s00382-013-1789-6.

Argüeso, D., J.P. Evans, A.J. Pitman, A. Di Luca, and A. Luca, 2015: Effects of city expansion on heat stress under climate change conditions. *PLOS ONE***, 10(2)**, e0117066, doi:10.1371/journal.pone.0117066.

Arheimer, B., C. Donnelly, and G. Lindström, 2017: Regulation of snow-fed rivers affects flow regimes more than climate change. *Nature Communications*, **8(1)**, 62, doi:10.1038/s41467-017-00092-8.

Arias-Ortiz, A. et al., 2018: A marine heatwave drives massive losses from the world's largest seagrass carbon stocks. *Nature Climate Change*, **8(4)**, 338-344, doi:10.1038/s41558-018-0096-y.

Arkema, K.K. et al., 2013: Coastal habitats shield people and property from sea-level rise and storms. *Nature Climate Change*, **3(10)**, 913-918, doi:10.1038/nclimate1944.

Armour, K.C., I. Eisenman, E. Blanchard-Wrigglesworth, K.E. McCusker, and C.M. Bitz, 2011: The reversibility of sea ice loss in a state-of-the-art climate model. *Geophysical Research Letters*, **38(16)**, doi:10.1029/2011GL048739.

Arnell, N.W. and B. Lloyd-Hughes, 2014: The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Climatic Change*, **122(1-2)**, 127-140, doi:10.1007/s10584-013-0948-4.

Arnell, N.W., J.A. Lowe, B. Lloyd-Hughes, and T.J. Osborn, 2018: The impacts avoided with a 1.5°C climate target: a global and regional assessment. *Climatic Change*, **147(1-2)**, 61-76, doi:10.1007/s10584-017-2115-9.

Arnell, N.W. et al., 2016: Global-scale climate impact functions: the relationship between climate forcing and impact. *Climatic Change*, **134(3)**, 475-487, doi:10.1007/s10584-013-1034-7.

Asiedu, B., J.–O. Adetola, and I. Odame Kissi, 2017a: Aquaculture in troubled climate: Farmers' perception of climate change and their adaptation. *Cogent Food & Agriculture*, **3(1)**, 1296400, doi:10.1080/23311932.2017.1296400.

Asiedu, B., F.K.E. Nunoo, and S. Iddrisu, 2017b: Prospects and sustainability of aquaculture development in Ghana, West Africa. *Cogent Food & Agriculture*, **3(1)**, doi:10.1080/23311932.2017.1349531.

Asplund, M.E. et al., 2014: Ocean acidification and host-pathogen interactions: Blue mussels, Mytilus edulis, encountering Vibrio tubiashii. *Environmental Microbiology*, **16(4)**, 1029-1039, doi:10.1111/1462-2920.12307.

Asseng, S. et al., 2013: Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*, **3(9)**, 827-832, doi:10.1038/nclimate1916.

Asseng, S. et al., 2015: Rising temperatures reduce global wheat production. *Nature Climate Change*, **5(2)**, 143-147, doi:10.1038/nclimate2470.

Atkinson, A., V. Siegel, E.A. Pakhomov, M.J. Jessopp, and V. Loeb, 2009: A re-appraisal of the total biomass and annual production of Antarctic krill. *Deep-Sea Research Part I: Oceanographic Research Papers*, **56(5)**, 727-740, doi:10.1016/j.dsr.2008.12.007.

Auerbach, L.W. et al., 2015: Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nature Climate Change*, **5**, 153-157.

Backhaus, A., I. Martinez-Zarzoso, and C. Muris, 2015: Do climate variations explain bilateral migration? A gravity model analysis. *IZA Journal of Migration*, **4(1)**, 3, doi:10.1186/s40176-014-0026-3.

Bader, D.A. et al., 2018: Urban Climate Science. *Climate Change and Cities: Second Assessment Report of the Urban Cliamte Change Research Network*, 27-60.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924-929, doi:10.1038/nclimate2353.

Baker, A.C., P.W. Glynn, and B. Riegl, 2008: Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. *Estuarine, Coastal and Shelf Science*, **80(4)**, 435-471, doi:10.1016/j.ecss.2008.09.003.

Baker, H.S. et al., 2018: World, Higher CO2 concentrations increase extreme event risk in a 1.5ºC. *Nature Climate Change* (in press).

Bakun, A., 1990: Global climate change and intensification of coastal ocean upwelling. *Science*, **247(4939)**, 198-201, doi:10.1126/science.247.4939.198.

Bakun, A. et al., 2015: Anticipated Effects of Climate Change on Coastal Upwelling Ecosystems. *Current Climate Change Reports*, **1(2)**, 85-93, doi:10.1007/s40641-015-0008-4.

Baldwin, A. and E. Fornalé, 2017: Adaptive migration: pluralising the debate on climate change and migration. *The Geographical Journal*, **183(4)**, 322-328, doi:10.1111/geoj.12242.

Barange, M. et al., 2014: Impacts of climate change on marine ecosystem production in societies dependent on fisheries. *Nature Climate Change*, **4(3)**, 211-216, doi:10.1038/nclimate2119.

Barati, F. et al., 2008: Meiotic competence and DNA damage of porcine oocytes exposed to an elevated temperature. *Theriogenology*, **69(6)**, 767-772, doi:10.1016/j.theriogenology.2007.08.038.

Barbier, E.B., 2015: Valuing the storm protection service of estuarine and coastal ecosystems. *Ecosystem Services*, **11**, 32-38, doi:10.1016/j.ecoser.2014.06.010.

Barnett, J. et al., 2014: A local coastal adaptation pathway. *Nature Climate Change*, **4(12)**, 1103-1108, doi:10.1038/nclimate2383.

Bassu, S. et al., 2014: How do various maize crop models vary in their responses to climate change factors? *Global Change Biology*, **20(7)**, 2301-2320, doi:10.1111/gcb.12520.

Bates, N.R. and A.J. Peters, 2007: The contribution of atmospheric acid deposition to ocean acidification in the subtropical North Atlantic Ocean. *Marine Chemistry*, **107(4)**, 547-558, doi:10.1016/j.marchem.2007.08.002.

Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF 33 model comparison. *Climatic Change* (in press), doi:doi:10.1007/s10584-018-2226-y.

Bayraktarov, E. et al., 2016: The cost and feasibility of marine coastal restoration. *Ecological Applications*, **26(4)**, 1055-1074, doi:10.1890/15-1077.

Bedarff, H. and C. Jakobeit, 2017: Climate change, migration, and displacement. The understimated disaster.. , 38.

Bednaršek, N., C.J. Harvey, I.C. Kaplan, R.A. Feely, and J. Možina, 2016: Pteropods on the edge: Cumulative effects of ocean acidification, warming, and deoxygenation. *Progress in Oceanography*, **145**, 1-24, doi:10.1016/j.pocean.2016.04.002.

Bednaršek, N. et al., 2012: Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience*, **5(12)**, 881-885, doi:10.1038/ngeo1635.

Bednaršek, N. et al., 2014: Limacina helicina shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. *Proceedings of the Royal Society B: Biological Sciences*, **281(1785)**, 20140123-20140123, doi:10.1098/rspb.2014.0123.

Beetham, E., P.S. Kench, and S. Popinet, 2017: Future Reef Growth Can Mitigate Physical Impacts of Sea-Level Rise on Atoll Islands. *Earth's Future*, **5(10)**, 1002-1014, doi:10.1002/2017EF000589.

Bell, J., 2012: Planning for Climate Change and Sea Level Rise: Queensland's New Coastal Plan. *Environmental and Planning Law Journal*, **29(1)**, 61-74.

Bell, J. and M. Taylor, 2015: Building Climate-Resilient Food Systems for Pacific Islands. *WorldFish*, 72.

Bell, J.D., J.E. Johnson, and A.J. Hobday, 2011: *Vulnerability of tropical pacific fisheries and aquaculture to climate change*. 925 pp.

Bell, J.D. et al., 2013: Mixed responses of tropical Pacific fisheries and aquaculture to climate change. *Nature Climate Change*, **3(6)**, 591-599, doi:10.1038/nclimate1838.

Bell, J.D. et al., 2017: Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. *Marine Policy*, doi:10.1016/j.marpol.2017.05.019.

Bender, M.A. et al., 2010: Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. *Science*, **327(5964)**, 454-458, doi:10.1126/science.1180568.

Benjamini, Y. and Y. Hochberg, 1995: Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society. Series B (Methodological)*,

57, 289-300, doi:10.2307/2346101.

Bertram, C. et al., 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environmental Research Letters* (in press).

Bettini, G., 2017: Where Next? Climate Change, Migration, and the (Bio)politics of Adaptation. *Global Policy*, **8(S1)**, 33-39, doi:10.1111/1758-5899.12404.

Betts, R.A. et al., 2015: Climate and land use change impacts on global terrestrial ecosystems and river flows in the HadGEM2-ES Earth system model using the representative concentration pathways. *Biogeosciences*, **12(5)**, 1317-1338, doi:10.5194/bg-12-1317-2015.

Betts, R.A. et al., 2018: Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5°C and 2°C global warming with a higher-resolution global climate model. *Philisophical Transactions Royal Society A*, **376(2119)**, doi:http://dx.doi.org/10.1098/rsta.2016.0452.

Beyer, H.L. et al., 2018: Risk-sensitive planning for coral reef conservation under rapid climate change. *Conservation Letters*, in press.

Bichet, A. and A. Diedhiou, 2018: West African Sahel becomes wetter during the last 30 years but dry spells are shorter and more frequent. *Climate Research*, https://doi.org/10.3354/cr01515.

Bindoff, N.L. et al., 2013a: Detection and Attribution of Climate Change: from Global to Regional. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. pp. 867-952.

Bindoff, N.L. et al., 2013b: Detection and Attribution of Climate Change: from Global to Regional - Supplementary Material. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. pp. 25.

Bispo, A. et al., 2017: Accounting for Carbon Stocks in Soils and Measuring GHGs Emission Fluxes from Soils: Do We Have the Necessary Standards? *Frontiers in Environmental Science*, **5(July)**, 1-12, doi:10.3389/fenvs.2017.00041.

Bittermann, K., S. Rahmstorf, R.E. Kopp, and A.C. Kemp, 2017: Global mean sea-level rise in a world agreed upon in Paris Global mean sea-level rise in a world agreed upon in Paris. *Environmental Research Letters*.

Blankespoor, B., S. Dasgupta, and B. Laplante, 2014: Sea-Level Rise and Coastal Wetlands. *AMBIO*, **43(8)**, 996-1005, doi:10.1007/s13280-014-0500-4.

Block, P. and K. Strzepek, 2012: Power Ahead: Meeting Ethiopia's Energy Needs Under a Changing Climate. *Review of Development Economics*, **16(3)**, 476-488, doi:10.1111/j.1467-9361.2012.00675.x.

Blume-Werry, G., J. Kreyling, H. Laudon, and A. Milbau, 2016: Short-term climate change manipulation effects do not scale up to long-term legacies: effects of an absent snow cover on boreal forest plants. *Journal of Ecology*, **104(6)**, 1638-1648, doi:10.1111/1365-2745.12636.

Boehlert, B. et al., 2015: Climate change impacts and greenhouse gas mitigation effects on US water quality. *Journal of Advances in Modeling Earth Systems*, **7(3)**, 1326-1338, doi:10.1002/2014MS000400.

Bonal, D., B. Burban, C. Stahl, F. Wagner, and B. Hérault, 2016: The response of tropical rainforests to drought - lessons from recent research and future prospects. *Annals of Forest Science*, **73(1)**, 27-44, doi:10.1007/s13595-015-0522-5.

Bongaerts, P., T. Ridgway, E.M. Sampayo, and O. Hoegh-Guldberg, 2010: Assessing the 'deep reef refugia' hypothesis: focus on Caribbean reefs. *Coral Reefs*, **29(2)**, 309-327, doi:10.1007/s00338-009-0581-x.

Bongaerts, P., C. Riginos, R. Brunner, N. Englebert, and S.R. Smith, 2017: Deep reefs are not universal refuges: reseeding potential varies among coral species. *Science Advances*, **3(2)**, e1602373, doi:10.1126/sciadv.1602373.

Bonsch, M. et al., 2016: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11-24, doi:10.1111/gcbb.12226.

Bonte, M. and J.J.G. Zwolsman, 2010: Climate change induced salinisation of artificial lakes in the Netherlands and consequences for drinking water production. *Water Research*, **44(15)**, 4411-4424, doi:10.1016/j.watres.2010.06.004.

Boone, R.B., R.T. Conant, J. Sircely, P.K. Thornton, and M. Herrero, 2017: Impatti sui cambiamenti climatici su determinati servizi ecosistemici di pascoli globali. *Biologia del cambiamento globale*.

Booth, M.S., 2018: Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy. *Environmental Research Letters*, **13(3)**, 035001, doi:10.1088/1748-9326/aaac88.

Bopp, L. et al., 2013: Multiple stressors of ocean ecosystems in the 21st century: Projections with CMIP5 models. *Biogeosciences*, **10(10)**, 6225-6245, doi:10.5194/bg-10-6225-2013.

Borma, L.S., C.A. Nobre, and M.F. Cardoso, 2013: 2.15 - Response of the Amazon Tropical Forests to Deforestation, Climate, and Extremes, and the Occurrence of Drought and Fire. *Climate Vulnerability*, 153-163, doi:10.1016/B978-0-12-384703-4.00228-8.

Bosello, F. and E. De Cian, 2014: Climate change, sea level rise, and coastal disasters. A review of modeling practices. *Energy Economics*, **46**, 593-605, doi:10.1016/j.eneco.2013.09.002.

Boucher, O. et al., 2012: Reversibility in an Earth System model in response to CO2 concentration changes. *Environmental Research Letters*, **7(2)**, doi:10.1088/1748-9326/7/2/024013.

Boucher, O. et al., 2013a: Rethinking climate engineering categorization in the context of climate change mitigation and adaptation. *WIREs Climate Change*, **5(1)**, 23-35, doi:10.1002/wcc.261.

Boucher, O. et al., 2013b: Clouds and Aerosols. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 573-657.

Bouttes, N., J.M. Gregory, and J.A. Lowe, 2013: The Reversibility of Sea Level Rise. *Journal of Climate*, **26(8)**, 2502-2513, doi:10.1175/JCLI-D-12-00285.1.

Bouzid, M., F.J. Colón-González, T. Lung, I.R. Lake, and P.R. Hunter, 2014: Climate change and the emergence of vector-borne diseases in Europe: case study of dengue fever. *BMC Public Health*, **14(1)**, 781, doi:10.1186/1471-2458-14-781.

Boyd, P.W., 2015: Toward quantifying the response of the oceans' biological pump to climate change. *Frontiers in Marine Science*, **2**, doi:10.3389/fmars.2015.00077.

Boyd, P.W., S. Sundby, and H.–O. Pörtner, 2014: Cross-chapter box on net primary production in the ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 133-136.

Boyd, P.W., S.T. Lennartz, D.M. Glover, and S.C. Doney, 2015: Biological ramifications of climate-change-mediated oceanic multi-stressors. *Nature Climate Change*, **5(1)**, 71-79, doi:10.1038/nclimate2441.

Boysen, L. et al., 2017: The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, **5(5)**, 463-474, doi:10.1002/2016EF000469.

Bozec, Y.–M.M., L. Alvarez-Filip, and P.J. Mumby, 2015: The dynamics of architectural complexity on coral reefs under climate change. *Global Change Biology*, **21(1)**, 223-235, doi:10.1111/gcb.12698.

Bråthen, K., V. González, and N. Yoccoz, 2018: Gatekeepers to the effects of climate warming? Niche construction restricts plant community changes along a temperature gradient. *Perspectives in Plant Ecology, Evolution and Systematics*, **30**, 71-81, doi:https://doi.org/10.1016/j.ppees.2017.06.005.

Breitburg, D. et al., 2018: Declining oxygen in the global ocean and coastal waters. *Science*, **359(6371)**, doi:10.1126/science.aam7240.

Brigham-Grette, J. et al., 2013: Pliocene Warmth, Polar Amplification, and Stepped Pleistocene Cooling Recorded in NE Arctic Russia. *Science*, **340(6139)**, 1421-1427, doi:10.1126/science.1233137.

Bright, R.M. et al., 2017: Local temperature response to land cover and management change driven by non-radiative processes. *Nature Climate Change*, **7(4)**, 296-302, doi:10.1038/nclimate3250.

Bring, A. et al., 2016: Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *Journal of Geophysical Research: Biogeosciences*, **121(3)**, 621-649, doi:10.1002/2015JG003131.

Brito, B.P., L.L. Rodriguez, J.M. Hammond, J. Pinto, and A.M. Perez, 2017: Review of the Global Distribution of Foot-and-Mouth Disease Virus from 2007 to 2014. *Transboundary and Emerging Diseases*, **64(2)**, 316-332, doi:10.1111/tbed.12373.

Brodie, J.E. et al., 2012: Terrestrial pollutant runoff to the Great Barrier Reef: An update of issues, priorities and management responses. *Marine Pollution Bulletin*, **65(4-9)**, 81-100, doi:10.1016/j.marpolbul.2011.12.012.

Brown, S., R.J. Nicholls, J.A. Lowe, and J. Hinkel, 2016: Spatial variations of sea-level rise and impacts: An application of DIVA. *Climatic Change*, **134(3)**, 403-416, doi:10.1007/s10584-013-0925-y.

Brown, S. et al., 2018a: Quantifying Land and People Exposed to Sea-Level Rise with No Mitigation and 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future*, **6(3)**, 583-600, doi:10.1002/2017EF000738.

Brown, S. et al., 2018b: What are the implications of sea-level rise for a 1.5, 2 and 3 °C rise in global mean temperatures in the Ganges-Brahmaputra-Meghna and other vulnerable deltas? *Regional Environmental Change*, 1-14, doi:https://doi.org/10.1007/s10113-018-1311-0.

Bruge, A., P. Alvarez, A. Fontán, U. Cotano, and G. Chust, 2016: Thermal Niche Tracking and Future Distribution of Atlantic Mackerel Spawning in Response to Ocean Warming. *Frontiers in Marine Science*, **3**, doi:10.3389/fmars.2016.00086.

Bruno, J.F. and E.R. Selig, 2007: Regional decline of coral cover in the Indo-Pacific: Timing, extent, and subregional comparisons. *PLoS ONE*, **2(8)**, doi:10.1371/journal.pone.0000711.

Brzoska, M. and C. Fröhlich, 2016: Climate change, migration and violent conflict: vulnerabilities, pathways and adaptation strategies. *Migration and Development*, **5(2)**, 190-210, doi:10.1080/21632324.2015.1022973.

Buhaug, H., 2015: Climate-conflict research: some reflections on the way forward. *Wiley Interdisciplinary Reviews: Climate Change*, **6(3)**, 269-275, doi:10.1002/wcc.336.

Buhaug, H., 2016: Climate Change and Conflict: Taking Stock. *Peace Economics, Peace Science and Public Policy*, **22(4)**, doi:10.1515/peps-2016-0034.

Buhaug, H. et al., 2014: One effect to rule them all? A comment on climate and conflict. *Climatic Change*, **127(3-4)**, 391-397, doi:10.1007/s10584-014-1266-1.

Burge, C.A. et al., 2014: Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society. *Annual Review of Marine Science*, **6(1)**, 249-277, doi:10.1146/annurev-marine-010213-135029.

Burke, E.J. et al., 2017: Quantifying uncertainties of permafrost carbon-climate feedbacks. *Biogeosciences*,

14(12), 3051-3066, doi:10.5194/bg-14-3051-2017.

Burke, L., K. Reytar, M. Spalding, and A. Perry, 2011: *Reefs at risk: Revisited*. 115 pp.

Burke, M., S.M. Hsiang, and E. Miguel, 2015a: Climate and Conflict. *Annual Review of Economics***, 7(1)**, 577-617, doi:10.1146/annurev-economics-080614-115430.

Burke, M., S.M. Hsiang, and E. Miguel, 2015b: Global non-linear effect of temperature on economic production. *Nature***, 527(7577)**, 235-239, doi:10.1038/nature15725.

Burke, M., M. Davis, and N. Diffenbaugh, 2018: Large potential reduction in economic damages under UN mitigation targets. *Nature* (in press).

Burrows, K. and P. Kinney, 2016: Exploring the Climate Change, Migration and Conflict Nexus. *International Journal of Environmental Research and Public Health***, 13(4)**, 443, doi:10.3390/ijerph13040443.

Burrows, M.T. et al., 2014: Geographical limits to species-range shifts are suggested by climate velocity. *Nature***, 507(7493)**, 492-495, doi:10.1038/nature12976.

Butler, E.E. and P. Huybers, 2013: Adaptation of US maize to temperature variations. *Nature Climate Change***, 3(1)**, 68-72, doi:10.1038/nclimate1585.

Buurman, J. and V. Babovic, 2016: Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society***, 35(2)**, 137-150, doi:10.1016/j.polsoc.2016.05.002.

Byers, E. et al., 2018: Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters* (in press).

Cacciapaglia, C. and R. van Woesik, 2015: Reef-coral refugia in a rapidly changing ocean. *Global Change Biology***, 21(6)**, 2272-2282, doi:10.1111/gcb.12851.

Caesar, L., S. Rahmstorf, A. Robinson, G. Feulner, and V. Saba, 2018: Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature***, 556(7700)**, 191-196, doi:10.1038/s41586-018-0006-5.

Cai, R., S. Feng, M. Oppenheimer, and M. Pytlikova, 2016: Climate variability and international migration: The importance of the agricultural linkage. *Journal of Environmental Economics and Management***, 79**, 135-151, doi:10.1016/j.jeem.2016.06.005.

Cai, W. et al., 2012: More extreme swings of the South Pacific convergence zone due to greenhouse warming. *Nature***, 488**, 365.

Cai, W. et al., 2015: Increased frequency of extreme La Niña events under greenhouse warming. *Nature Climate Change***, 5**, 132, doi:10.1038/nclimate2492.

Cai, W.–J. et al., 2011: Acidification of subsurface coastal waters enhanced by eutrophication. *Nature Geoscience***, 4(11)**, 766-770, doi:10.1038/ngeo1297.

Cai, Y., T.M. Lenton, and T.S. Lontzek, 2016: Risk of multiple interacting tipping points should encourage rapid CO2 emission reduction. *Nature Climate Change***, 6(5)**, 520-525, doi:10.1038/nclimate2964.

Caldeira, K., 2013: Coral Bleaching: Coral 'refugia' amid heating seas. *Nature Climate Change***, 3(5)**, 444-445, doi:10.1038/nclimate1888.

Callaway, R. et al., 2012: Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems***, 22(3)**, 389-421, doi:10.1002/aqc.2247.

Camargo, S.J., 2013: Global and Regional Aspects of Tropical Cyclone Activity in the CMIP5 Models. *Journal of Climate***, 26(24)**, 9880-9902, doi:10.1175/JCLI-D-12-00549.1.

Campbell, J. and O. Warrick, 2014: *Climate change and migration issues in the Pacific*. United Nations Economic and Social Commission for Asia and the Pacific Pacific Office, 34 pp.

Cao, L. and K. Caldeira, 2010: Atmospheric carbon dioxide removal: long-term consequences and commitment. *Environmental Research Letters***, 5(2)**, 024011, doi:10.1088/1748-9326/5/2/024011.

Cao, L., K. Caldeira, and A.K. Jain, 2007: Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation. *Geophysical Research Letters*, **34(5)**, doi:10.1029/2006GL028605.

Capo, E. et al., 2017: Tracking a century of changes in microbial eukaryotic diversity in lakes driven by nutrient enrichment and climate warming. *Environmental Microbiology*, **19(7)**, 2873-2892, doi:10.1111/1462-2920.13815.

Capron, E., A. Govin, R. Feng, B.L. Otto-Bliesner, and E.W. Wolff, 2017: Critical evaluation of climate syntheses to benchmark CMIP6/PMIP4 127 ka Last Interglacial simulations in the high-latitude regions. *Quaternary Science Reviews*, **168**, 137-150, doi:https://doi.org/10.1016/j.quascirev.2017.04.019.

Carleton, T., S.M. Hsiang, and M. Burke, 2016: Conflict in a changing climate. *The European Physical Journal Special Topics*, **225(3)**, 489-511, doi:10.1140/epjst/e2015-50100-5.

Carleton, T.A. and S.M. Hsiang, 2016: Social and economic impacts of climate. *Science*, **353(6304)**, aad9837, doi:10.1126/science.aad9837.

Carstensen, J., J.H. Andersen, B.G. Gustafsson, and D.J. Conley, 2014: Deoxygenation of the Baltic Sea during the last century. *Proceedings of the National Academy of Sciences of the United States of America*, **111(15)**, 5628-33, doi:10.1073/pnas.1323156111.

Carter Johnson, W., B. Werner, and G.R. Guntenspergen, 2016: Non-linear responses of glaciated prairie wetlands to climate warming. *Climatic Change*, **134(1-2)**, 209-223, doi:10.1007/s10584-015-1534-8.

Carvalho, D., A. Rocha, M. Gómez-Gesteira, and C. Silva Santos, 2017: Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections. *Renewable Energy*, **101**, 29-40, doi:10.1016/j.renene.2016.08.036.

Castillo, N., L.M. Saavedra, C.A. Vargas, C. Gallardo-Escárate, and C. Détrée, 2017: Ocean acidification and pathogen exposure modulate the immune response of the edible mussel Mytilus chilensis. *Fish and Shellfish Immunology*, **70**, 149-155, doi:10.1016/j.fsi.2017.08.047.

Cazenave, A. and G. Cozannet, 2014: Sea level rise and its coastal impacts. *Earth's Future*, **2(2)**, 15-34, doi:10.1002/2013EF000188.

Cazenave, A. et al., 2014: The rate of sea-level rise. *Nature Climate Change*, **4(5)**, 358-361, doi:10.1038/nclimate2159.

Ceccarelli, S. and J.E. Rabinovich, 2015: Global Climate Change Effects on Venezuela's Vulnerability to Chagas Disease is Linked to the Geographic Distribution of Five Triatomine Species. *Journal of Medical Entomology*, **52(6)**, 1333-1343, doi:10.1093/jme/tjv119.

Chadburn, S.E. et al., 2017: An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change*, 1-6, doi:10.1038/nclimate3262.

Challinor, A.J. et al., 2014: A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, **4(4)**, 287-291, doi:10.1038/nclimate2153.

Chapman, A. and S. Darby, 2016: Evaluating sustainable adaptation strategies for vulnerable mega-deltas using system dynamics modelling: Rice agriculture in the Mekong Delta's An Giang Province, Vietnam. *Science of the Total Environment*, **559**, 326-338, doi:10.1016/j.scitotenv.2016.02.162.

Chapman, A.D., S.E. Darby, H.M. Hồng, E.L. Tompkins, and T.P.D. Van, 2016: Adaptation and development trade-offs: fluvial sediment deposition and the sustainability of rice-cropping in An Giang Province, Mekong Delta. *Climatic Change*, **137(3-4)**, 1-16, doi:10.1007/s10584-016-1684-3.

Cheal, A.J., M.A. MacNeil, M.J. Emslie, and H. Sweatman, 2017: The threat to coral reefs from more intense cyclones under climate change. *Global Change Biology*, **23(4)**, 1511-1524, doi:10.1111/gcb.13593.

Chen, B. et al., 2014: The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. *Agricultural and Forest Meteorology*, **189**, 11-18, doi:10.1016/j.agrformet.2014.01.002.

Chen, C., G.S. Zhou, and L. Zhou, 2014: Impacts of climate change on rice yield in china from 1961 to 2010 based on provincial data. *Journal of Integrative Agriculture*, **13(7)**, 1555-1564, doi:10.1016/S2095-3119(14)60816-9.

Chen, J. et al., 2017: Assessing changes of river discharge under global warming of 1.5 °C and 2 °C in the upper reaches of the Yangtze River Basin: Approach by using multiple- GCMs and hydrological models. *Quaternary International*, **453**, 1-11, doi:10.1016/j.quaint.2017.01.017.

Cheung, W.W.L., R. Watson, and D. Pauly, 2013: Signature of ocean warming in global fisheries catch. *Nature*, **497(7449)**, 365-368, doi:10.1038/nature12156.

Cheung, W.W.L., G. Reygondeau, and T.L. Frölicher, 2016a: Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science*, **354(6319)**, 1591-1594, doi:10.1126/science.aag2331.

Cheung, W.W.L. et al., 2009: Projecting global marine biodiversity impacts under climate change scenarios. *Fish and Fisheries*, **10(3)**, 235-251, doi:10.1111/j.1467-2979.2008.00315.x.

Cheung, W.W.L. et al., 2010: Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Global Change Biology*, **16(1)**, 24-35, doi:10.1111/j.1365-2486.2009.01995.x.

Cheung, W.W.L. et al., 2016b: Structural uncertainty in projecting global fisheries catches under climate change. *Ecological Modelling*, **325**, 57-66, doi:10.1016/j.ecolmodel.2015.12.018.

Chiew, F.H.S. et al., 2014: Observed hydrologic non-stationarity in far south-eastern Australia: Implications for modelling and prediction. *Stochastic Environmental Research and Risk Assessment*, **28(1)**, 3-15, doi:10.1007/s00477-013-0755-5.

Chilkoti, V., T. Bolisetti, and R. Balachandar, 2017: Climate change impact assessment on hydropower generation using multi-model climate ensemble. *Renewable Energy*, **109**, 510-517, doi:10.1016/j.renene.2017.02.041.

Cho, S.J. and B.A. McCarl, 2017: Climate change influences on crop mix shifts in the United States. *Scientific Reports*, **7**, 40845, doi:10.1038/srep40845.

Chollett, I., P.J. Mumby, and J. Cortés, 2010: Upwelling areas do not guarantee refuge for coral reefs in a warming ocean. *Marine Ecology Progress Series*, **416**, 47-56, doi:10.2307/24875251.

Chollett, I., P.J. Mumby, and I.M. Chollett Pj;, 2013: Reefs of last resort: Locating and assessing thermal refugia in the wider Caribbean. *Biological Conservation*, **167(2013)**, 179-186, doi:10.1016/j.biocon.2013.08.010.

Chollett, I., S. Enr?quez, and P.J. Mumby, 2014: Redefining Thermal Regimes to Design Reserves for Coral Reefs in the Face of Climate Change. *PLOS ONE*, **9(10)**, e110634, doi:10.1371/journal.pone.0110634.

Christensen, J.H. et al., 2007: Regional Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 847-940.

Christensen, J.H. et al., 2013: Climate Phenomena and their Relevance for Future Regional Climate Change. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Christiansen, S.M., 2016: Introduction. In: *Climate Conflicts - A Case of International Environmental and Humanitarian Law*. Springer International Publishing, Cham, pp. 1-17.

Chung, E.S., H.–K. Cheong, J.–H. Park, J.–H. Kim, and H. Han, 2017: Current and Projected Burden of Disease From High Ambient Temperature in Korea. *Epidemiology*, **28**, S98-S105.

Church, J. et al., 2013: Sea level change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1137-1216, doi:10.1017/CB09781107415315.026.

Chust, G. et al., 2014a: Biomass changes and trophic amplification of plankton in a warmer ocean. *Global Change Biology***, 20(7)**, 2124-2139, doi:10.1111/gcb.12562.

Chust, G. et al., 2014b: Are Calanus spp. shifting poleward in the North Atlantic? A habitat modelling approach. *ICES Journal of Marine Science***, 71(2)**, 241-253, doi:10.1093/icesjms/fst147.

Ciais, P. et al., 2013: Carbon and other biogeochemical cycles. In: *Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 465-570.

Cinner, J.E. et al., 2012: Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Global Environmental Change***, 22(1)**, 12-20, doi:10.1016/j.gloenvcha.2011.09.018.

Cinner, J.E. et al., 2016: A framework for understanding climate change impacts on coral reef social-ecological systems. *Regional Environmental Change***, 16(4)**, 1133-1146, doi:10.1007/s10113-015-0832-z.

Ciscar, J.C. (ed.), 2014: *Climate impacts in Europe - The JRC PESETA II project*. EUR - Scientific and Technical Research, Publications Office of the European Union.

Clark, P.U. et al., 2016: Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change***, 6(4)**, 360-369, doi:10.1038/NCLIMATE2923.

Clarke, L.E. et al., 2014: Assessing Transformation Pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413-510.

Clausen, K.K. and P. Clausen, 2014: Forecasting future drowning of coastal waterbird habitats reveals a major conservation concern. *Biological Conservation***, 171**, 177-185, doi:10.1016/j.biocon.2014.01.033.

Clements, J.C. and T. Chopin, 2017: Ocean acidification and marine aquaculture in North America: Potential impacts and mitigation strategies. *Reviews in Aquaculture***, 9(4)**, 326341, doi:10.1111/raq.12140.

Clements, J.C., D. Bourque, J. McLaughlin, M. Stephenson, and L.A. Comeau, 2017: Extreme ocean acidification reduces the susceptibility of eastern oyster shells to a polydorid parasite. *Journal of Fish Diseases***, 40(11)**, 1573-1585, doi:10.1111/jfd.12626.

Collier, R.J. and K.G. Gebremedhin, 2015: Thermal Biology of Domestic Animals. *Annual Review of Animal Biosciences***, 3(1)**, 513-532, doi:10.1146/annurev-animal-022114-110659.

Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029-1136.

Colón-González, F.J., C. Fezzi, I.R. Lake, P.R. Hunter, and Y. Sukthana, 2013: The Effects of Weather and Climate Change on Dengue. *PLoS Neglected Tropical Diseases***, 7(11)**, e2503, doi:10.1371/journal.pntd.0002503.

Coniglio, N.D. and G. Pesce, 2015: Climate variability and international migration: an empirical analysis.

Environment and Development Economics, **20(04)**, 434-468, doi:10.1017/S1355770X14000722.

Conlon, K., A. Monaghan, M. Hayden, and O. Wilhelmi, 2016: Potential impacts of future warming and land use changes on intra-urban heat exposure in Houston, Texas. *PLOS ONE*, **11(2)**, e0148890, doi:10.1371/journal.pone.0148890.

Constable, A.L., 2017: Climate change and migration in the Pacific: options for Tuvalu and the Marshall Islands. *Regional Environmental Change*, **17(4)**, 1029-1038, doi:10.1007/s10113-016-1004-5.

Cook, B.I., M.J. Puma, and N.Y. Krakauer, 2011: Irrigation induced surface cooling in the context of modern and increased greenhouse gas forcing. *Climate Dynamics*, **37(7-8)**, 1587-1600, doi:10.1007/s00382-010-0932-x.

Cook, B.I., K.J. Anchukaitis, R. Touchan, D.M. Meko, and E.R. Cook, 2016: Spatiotemporal drought variability in the Mediterranean over the last 900 years. *Journal of Geophysical Research: Atmospheres*, **121(5)**, 2060-2074, doi:10.1002/2015JD023929.

Cooper, E.J., 2014: Warmer Shorter Winters Disrupt Arctic Terrestrial Ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, **45**, 271-295, doi:10.1146/annurev-ecolsys-120213-091620.

Cooper, J.A.G., M.C. O'Connor, and S. McIvor, 2016: Coastal defences versus coastal ecosystems: A regional appraisal. *Marine Policy*, doi:10.1016/j.marpol.2016.02.021.

Costanza, R. et al., 2014: Changes in the global value of ecosystem services. *Global Environmental Change*, **26(1)**, 152-158, doi:10.1016/j.gloenvcha.2014.04.002.

Coumou, D. and A. Robinson, 2013: Historic and future increase in the global land area affected by monthly heat extremes. *Environmental Research Letters*, **8(3)**, 034018, doi:10.1088/1748-9326/8/3/034018.

Cousino, L.K., R.H. Becker, and K.A. Zmijewski, 2015: Modeling the effects of climate change on water, sediment, and nutrient yields from the Maumee River watershed. *Journal of Hydrology: Regional Studies*, **4**, 762-775, doi:10.1016/j.ejrh.2015.06.017.

Cowtan, K. and R.G. Way, 2014: Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society*, **140(683)**, 1935-1944, doi:10.1002/qj.2297.

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall, and I.J. Totterdell, 2000: Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, **408**, 184, doi:10.1038/35041539.

Cox, P.M. et al., 2013: Sensitivity of tropical carbon to climate change constrained by carbon dioxide variability. *Nature*, **494**, 341, doi:10.1038/nature11882.

Craine, J.M., A.J. Elmore, K.C. Olson, and D. Tolleson, 2010: Climate change and cattle nutritional stress. *Global Change Biology*, **16(10)**, 2901-2911, doi:10.1111/j.1365-2486.2009.02060.x.

Cramer, W. et al., 2014: Detection and Attribution of Observed Impacts. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, and M.D. Mastrandrea (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 979-1037.

Crosby, S.C. et al., 2016: Salt marsh persistence is threatened by predicted sea-level rise. *Estuarine, Coastal and Shelf Science*, **181**, 93-99, doi:https://doi.org/10.1016/j.ecss.2016.08.018.

Crowther, T. et al., 2016: Quantifying global soil carbon losses in response to warming. *Nature*, **540**, 104-108.

Croxall, J.P., 1992: Southern-Ocean Environmental-Changes - Effects on Seabird, Seal and Whale Populations. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, **338(1285)**, 319-328, doi:DOI 10.1098/rstb.1992.0152.

Cui, L., Z. Ge, L. Yuan, and L. Zhang, 2015: Vulnerability assessment of the coastal wetlands in the Yangtze Estuary, China to sea-level rise. *Estuarine, Coastal and Shelf Science*, **156(Supplement C)**, 42-51, doi:https://doi.org/10.1016/j.ecss.2014.06.015.

Cunningham, S.C. et al., 2015: Balancing the environmental benefits of reforestation in agricultural regions. *Perspectives in Plant Ecology, Evolution and Systematics***, 17(4)**, 301-317, doi:10.1016/j.ppees.2015.06.001.

Dai, A., 2016: Historical and Future Changes in Streamflow and Continental Runoff. In: *Terrestrial Water Cycle and Climate Change* [Tang, Q. and T. Oki (eds.)]. John Wiley & Sons, Inc. pp. 17-37.

Daioglou, V. et al., 2016: Projections of the availability and cost of residues from agriculture and forestry. *GCB Bioenergy***, 8(2)**, 456-470, doi:10.1111/gcbb.12285.

Dale, V.H. et al., 2017: Status and prospects for renewable energy using wood pellets from the southeastern United States. *GCB Bioenergy***, 9(8)**, 1296-1305, doi:10.1111/gcbb.12445.

Daliakopoulos, I.N. et al., 2017: Yield Response of Mediterranean Rangelands under a Changing Climate. *Land Degradation & Development***, 28(7)**, 1962-1972, doi:10.1002/ldr.2717.

Dalpadado, P. et al., 2014: Productivity in the Barents Sea - Response to recent climate variability. *PLoS ONE***, 9(5)**, e95273, doi:10.1371/journal.pone.0095273.

d'Amour, C.B., L. Wenz, M. Kalkuhl, J.C. Steckel, and F. Creutzig, 2016: Teleconnected food supply shocks. *Environmental Research Letters***, 11(3)**, 35007.

Dargie, G.C. et al., 2017: Age, extent and carbon storage of the central Congo Basin peatland complex. *Nature***, 542(7639)**, 86-90, doi:10.1038/nature21048.

Dasgupta, P. et al., 2014: Rural areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 613-657.

David, C. et al., 2017: Community structure of under-ice fauna in relation to winter sea-ice habitat properties from the Weddell Sea. *Polar Biology***, 40(2)**, 247-261, doi:10.1007/s00300-016-1948-4.

Davin, E.L., S.I. Seneviratne, P. Ciais, A. Olioso, and T. Wang, 2014: Preferential cooling of hot extremes from cropland albedo management. *Proceedings of the National Academy of Sciences of the United States of America***, 111(27)**, 9757-9761, doi:10.1073/pnas.1317323111.

de Jong, J. et al., 2014: *Consequences of an increased extraction of forest biofuel in Sweden - A synthesis from the biofuel research programme 2007-2011, supported by Swedish Energy Agency. Summary of the synthesis report*. ER 2014:09, Swedish Energy Agency, Eskilstuna, Sweden, 37 pp.

de Queiroz, A.R., L.M. Marangon Lima, J.W. Marangon Lima, B.C. da Silva, and L.A. Scianni, 2016: Climate change impacts in the energy supply of the Brazilian hydro-dominant power system. *Renewable Energy***, 99**, 379-389, doi:10.1016/j.renene.2016.07.022.

De Rensis, F., I. García-Ispierto, and F. López-Gatius, 2015: Seasonal Heat Stress: Clinical Implications and Hormone Treatments for the Fertility of Dairy Cows. *Theriogenology***, 84**.

de Sherbinin, A., 2014: Climate change hotspots mapping: what have we learned? *Climatic Change***, 123(1)**, 23-37, doi:10.1007/s10584-013-0900-7.

De Souza, A.P., J.–C. Cocuron, A.C. Garcia, A.P. Alonso, and M.S. Buckeridge, 2015: Changes in Whole-Plant Metabolism during the Grain-Filling Stage in Sorghum Grown under Elevated CO2 and Drought. *Plant Physiology***, 169(3)**, 1755 LP - 1765.

de Vernal, A., R. Gersonde, H. Goosse, M.–S. Seidenkrantz, and E.W. Wolff, 2013: Sea ice in the paleoclimate system: the challenge of reconstructing sea ice from proxies - an introduction. *Quaternary Science Reviews***, 79**, 1-8, doi:https://doi.org/10.1016/j.quascirev.2013.08.009.

de Vrese, P., S. Hagemann, and M. Claussen, 2016: Asian irrigation, African rain: Remote impacts of irrigation. *Geophysical Research Letters***, 43(8)**, 3737-3745, doi:10.1002/2016GL068146.

De'ath, G., K.E. Fabricius, H. Sweatman, and M. Puotinen, 2012: The 27-year decline of coral cover on the

Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences of the United States of America*, **109(44)**, 17995-9, doi:10.1073/pnas.1208909109.

DeBeer, C.M., H.S. Wheater, S.K. Carey, and K.P. Chun, 2016: Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: a review and synthesis. *Hydrology and Earth System Sciences*, **20(4)**, 1573-1598, doi:10.5194/hess-20-1573-2016.

DeConto, R.M. and D. Pollard, 2016: Contribution of Antarctica to past and future sea-level rise. *Nature*, **531(7596)**, 591-7, doi:10.1038/nature17145.

Déqué, M. et al., 2017: A multi-model climate response over tropical Africa at +2°C. *Climate Services*, **7**, 87-95, doi:10.1016/j.cliser.2016.06.002.

Deryng, D., D. Conway, N. Ramankutty, J. Price, and R. Warren, 2014: Global crop yield response to extreme heat stress under multiple climate change futures. *Environmental Research Letters*, **9(3)**, 034011, doi:10.1088/1748-9326/9/3/034011.

Deutsch, C., A. Ferrel, B. Seibel, H.–O. Pörtner, and R.B. Huey, 2015: Climate change tightens a metabolic constraint on marine habitats. *Science*, **348(6239)**, 1132-1135, doi:10.1126/science.aaa1605.

Di Lorenzo, E., 2015: Climate science: The future of coastal ocean upwelling. *Nature*, **518(7539)**, 310-311, doi:10.1038/518310a.

Di Nitto, D. et al., 2014: Mangroves facing climate change: Landward migration potential in response to projected scenarios of sea level rise. *Biogeosciences*, **11(3)**, 857-871, doi:10.5194/bg-11-857-2014.

Diaz, R.J. and R. Rosenberg, 2008: Spreading Dead Zones and Consequences for Marine Ecosystems. *Science*, **321(5891)**, 926-929, doi:10.1126/science.1156401.

Diedhiou, A. et al., 2018: Changes in climate extremes over West and Central Africa at 1.5°C and 2°C global warming. *Environmental Research Letters* (in press), https://doi.org/10.1088/1748-9326/aac3e5.

Dieleman, C.M., Z. Lindo, J.W. McLaughlin, A.E. Craig, and B.A. Branfireun, 2016: Climate change effects on peatland decomposition and porewater dissolved organic carbon biogeochemistry. *Biogeochemistry*, **128(3)**, 385-396, doi:10.1007/s10533-016-0214-8.

Dionisio, K.L. et al., 2017: Characterizing the impact of projected changes in climate and air quality on human exposures to ozone. *Journal of Exposure Science And Environmental Epidemiology*, **27**, 260, doi:10.1038/jes.2016.81.

Do, H.X., S. Westra, and M. Leonard, 2017: A global-scale investigation of trends in annual maximum streamflow. *Journal of Hydrology*, **552**, 28-43, doi:10.1016/J.JHYDROL.2017.06.015.

Döll, P. et al., 2018: Risks for the global freshwater system at 1.5 °C and 2 °C global warming. *Environmental Research Letters*, **13(4)**, 044038, doi:10.1088/1748-9326/aab792.

Dolman, A.J. et al., 2010: A Carbon Cycle Science Update Since IPCC AR4. *Ambio*, **39(5-6)**, 402-412, doi:10.1007/s13280-010-0083-7.

Doney, S., L. Bopp, and M. Long, 2014: Historical and Future Trends in Ocean Climate and Biogeochemistry. *Oceanography*, **27(1)**, 108-119, doi:10.5670/oceanog.2014.14.

Donk, P., E. Uytven, P. Willems, and M.A. Taylor, 2018: Assessment of the potential implications of a 1.5°C versus higher global temperature rise for the Afobaka hydropower scheme in Suriname. *Regional Environmental Change*, doi:10.1007/s10113-018-1339-1.

Donnelly, C. et al., 2017: Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level. *Climatic Change*, **143(1-2)**, 13-26, doi:10.1007/s10584-017-1971-7.

Donner, S.D., 2009: Coping with commitment: Projected thermal stress on coral reefs under different future scenarios. *PLoS ONE*, **4(6)**, doi:10.1371/journal.pone.0005712.

Donner, S.D., W.J. Skirving, C.M. Little, M. Oppenheimer, and O. Hoegh-Gulberg, 2005: Global assessment of coral bleaching and required rates of adaptation under climate change. *Global Change Biology*, **11(12)**, 2251-2265, doi:10.1111/j.1365-2486.2005.01073.x.

Dosio, A., 2017: Projection of temperature and heat waves for Africa with an ensemble of CORDEX Regional Climate Models. *Climate Dynamics*, **49(1)**, 493-519, doi:10.1007/s00382-016-3355-5.

Dosio, A. and E.M. Fischer, 2018: Will half a degree make a difference? Robust projections of indices of mean and extreme climate in Europe under 1.5°C, 2°C, and 3°C global warming. *Geophys. Res. Lett.*, **45**, 935.

Dosio, A., L. Mentaschi, E.M. Fischer, and K. Wyser, 2018: Extreme heat waves under 1.5°C and 2°C global warming. *Environmental Research Letters*, **13(5)**, 54006.

Dove, S.G. et al., 2013: Future reef decalcification under a business-as-usual CO2 emission scenario. *Proceedings of the National Academy of Sciences of the United States of America*, **110(38)**, 15342-15347, doi:10.1073/pnas.1302701110.

Dowsett, H. et al., 2016: The PRISM4 (mid-Piacenzian) paleoenvironmental reconstruction. *Climate of the Past*, **12(7)**, 1519-1538, doi:10.5194/cp-12-1519-2016.

Doyon, B., D. Belanger, and P. Gosselin, 2008: The potential impact of climate change on annual and seasonal mortality for three cities in Québec, Canada. *International Journal of Health Geographics*, **7**, 23, doi:10.1186/1476-072x-7-23.

Draper, F.C. et al., 2014: The distribution and amount of carbon in the largest peatland complex in Amazonia. *Environmental Research Letters*, **9(12)**, 124017, doi:10.1088/1748-9326/9/12/124017.

Drijfhout, S. et al., 2015: Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models. *Proceedings of the National Academy of Sciences of the United States of America*, **112(43)**, E5777-E5786, doi:10.1073/pnas.1511451112.

Drouet, A.S. et al., 2013: Grounding line transient response in marine ice sheet models. *The Cryosphere*, **7(2)**, 395-406, doi:10.5194/tc-7-395-2013.

Duarte, C.M. et al., 2013: Is Ocean Acidification an Open-Ocean Syndrome? Understanding Anthropogenic Impacts on Seawater pH. *Estuaries and Coasts*, **36(2)**, 221-236, doi:10.1007/s12237-013-9594-3.

Duke, N.C. et al., 2017: Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: A severe ecosystem response, coincidental with an unusually extreme weather event. *Marine and Freshwater Research*, **68(10)**, 1816-1829, doi:10.1071/MF16322.

Dunne, J.P., R.J. Stouffer, and J.G. John, 2013: Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, **3(4)**, 1-4, doi:10.1038/nclimate1827.

Duputié, A., A. Rutschmann, O. Ronce, and I. Chuine, 2015: Phenological plasticity will not help all species adapt to climate change. *Global Change Biology*, **21(8)**, 3062-3073, doi:10.1111/gcb.12914.

Durack, P.J., S.E. Wijffels, and R.J. Matear, 2012: Ocean Salinities Reveal Strong Global Water Cycle Intensification During 1950 to 2000. *Science*, **336(6080)**, 455-458, doi:10.1126/science.1212222.

Durand, G. and F. Pattyn, 2015: Reducing uncertainties in projections of Antarctic ice mass loss. *The Cryosphere*, **9(6)**, 2043-2055, doi:10.5194/tc-9-2043-2015.

Durand, J.–L. et al., 2017: How accurately do maize crop models simulate the interactions of atmospheric CO2 concentration levels with limited water supply on water use and yield? *European Journal of Agronomy*, doi:https://doi.org/10.1016/j.eja.2017.01.002.

Dutton, A. et al., 2015: Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science*, **349(6244)**, doi:10.1126/science.aaa4019.

Ebi, K.L., N.H. Ogden, J.C. Semenza, and A. Woodward, 2017: Detecting and Attributing Health Burdens to Climate Change. *Environmental Health Perspectives*, **125(8)**, 085004, doi:10.1289/EHP1509.

Ebi, K.L. et al., 2018: Health risks of warming of 1.5°C, 2°C, and higher, above pre-industrial temperatures. *Environmental Research Letters* (in press), doi:10.1088/1748-9326/aac4bd.

Ekstrom, J.A. et al., 2015: Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nature Climate Change*, **5(3)**, 207-214, doi:10.1038/nclimate2508.

Elliff, C.I. and I.R. Silva, 2017: Coral reefs as the first line of defense: Shoreline protection in face of climate change. *Marine Environmental Research*, **127**, 148-154, doi:10.1016/j.marenvres.2017.03.007.

Elliott, J. et al., 2014: Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences*, **111(9)**, 3239-3244, doi:10.1073/pnas.1222474110.

Ellison, D. et al., 2017: Trees, forests and water: Cool insights for a hot world. *Global Environmental Change*, **43**, 51-61, doi:10.1016/j.gloenvcha.2017.01.002.

Ellison, J.C., 2014: Climate Change Adaptation: Management Options for Mangrove Areas. *Mangrove Ecosystems of Asia: Status, Challenges and Management Strategies*, 391-413, doi:10.1007/978-1-4614-8582-7_18.

Ellsworth, D.S. et al., 2017: Elevated CO2 does not increase eucalypt forest productivity on a low-phosphorus soil. *Nature Climate Change*, **7**, 279, doi:10.1038/nclimate3235.

Elsner, J.B., J.P. Kossin, and T.H. Jagger, 2008: The increasing intensity of the strongest tropical cyclones. *Nature*, **455(7209)**, 92-95, doi:10.1038/nature07234.

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686, doi:10.1038/nature03906.

Emanuel, K., 2017: A fast intensity simulator for tropical cyclone risk analysis. *Natural Hazards*, **88(2)**, 779-796, doi:10.1007/s11069-017-2890-7.

Endres, S., L. Galgani, U. Riebesell, K.G. Schulz, and A. Engel, 2014: Stimulated bacterial growth under elevated pCO2: Results from an off-shore mesocosm study. *PLoS ONE*, **9(6)**, doi:10.1371/journal.pone.0099228.

Engelbrecht, C.J. and F.A. Engelbrecht, 2016: Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theoretical and Applied Climatology*, **123**.

Engelbrecht, F.A., J.L. McGregor, and C.J. Engelbrecht, 2009: Dynamics of the Conformal-Cubic Atmospheric Model projected climate-change signal over southern Africa. *International Journal of Climatology*, **29(7)**, 1013-1033, doi:10.1002/joc.1742.

Engelbrecht, F.A. et al., 2015: Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, **10(8)**, 085004, doi:10.1088/1748-9326/10/8/085004.

Fabricius, K.E. et al., 2011: Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nature Climate Change*, **1(3)**, 165-169, doi:10.1038/nclimate1122.

Fajardy, M. and N. Mac Dowell, 2017: Can BECCS deliver sustainable and resource efficient negative emissions? *Energy & Environmental Science*, **10(6)**, 1389-1426, doi:10.1039/c7ee00465f.

Fang, J.K.H., C.H.L. Schönberg, M.A. Mello-Athayde, O. Hoegh-Guldberg, and S. Dove, 2014: Effects of ocean warming and acidification on the energy budget of an excavating sponge. *Global Change Biology*, **20(4)**, 1043-1054, doi:10.1111/gcb.12369.

Fang, J.K.H. et al., 2013: Sponge biomass and bioerosion rates increase under ocean warming and acidification. *Global Change Biology*, **19(12)**, 3581-3591, doi:10.1111/gcb.12334.

FAO, 2016: *The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, 200 pp.

FAO, IFAD, UNICEF, WFP, and WHO, 2017: *The state of food security and nutrition in the world. Building resilience for peace and food security*. Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, 117 pp.

Farbotko, C. and H. Lazrus, 2012: The first climate refugees? Contesting global narratives of climate change in Tuvalu. *Global Environmental Change*, **22(2)**, 382-390, doi:https://doi.org/10.1016/j.gloenvcha.2011.11.014.

Fasullo, J.T., R.S. Nerem, and B. Hamlington, 2016: Is the detection of accelerated sea level rise imminent? *Scientific Reports*, **6(August)**, 1-7, doi:10.1038/srep31245.

Fawcett, A.A. et al., 2015: Can Paris pledges avert severe climate change? *Science*, **350(6265)**, 1168-1169, doi:10.1126/science.aad5761.

Faye, B. et al., 2018: Impacts of 1.5 versus 2.0 °C on cereal yields in the West African Sudan Savanna. *Environmental Research Letters*, **13(3)**, 34014.

Feely, R.A., C.L. Sabine, J.M. Hernandez-Ayon, D. Ianson, and B. Hales, 2008: Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf. *Science*, **320(5882)**, 1490-1492, doi:10.1126/science.1155676.

Feely, R.A. et al., 2016: Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuarine, Coastal and Shelf Science*, **183**, 260-270, doi:10.1016/j.ecss.2016.08.043.

Feller, I.C., D.A. Friess, K.W. Krauss, and R.R. Lewis, 2017: The state of the world's mangroves in the 21st century under climate change. *Hydrobiologia*, **803(1)**, doi:10.1007/s10750-017-3331-z.

Feng, X. et al., 2016: Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nature Climate Change*, **6(11)**, 1019-1022, doi:10.1038/nclimate3092.

Ferrario, F. et al., 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, **5**, 3794, doi:10.1038/ncomms4794.

Fine, M., H. Gildor, and A. Genin, 2013: A coral reef refuge in the Red Sea. *Global Change Biology*, **19(12)**, 3640-3647, doi:10.1111/gcb.12356.

Fischer, D., S.M. Thomas, F. Niemitz, B. Reineking, and C. Beierkuhnlein, 2011: Projection of climatic suitability for Aedes albopictus Skuse (Culicidae) in Europe under climate change conditions. *Global and Planetary Change*, **78(1-2)**, 54-64, doi:10.1016/j.gloplacha.2011.05.008.

Fischer, D. et al., 2013: Climate change effects on Chikungunya transmission in Europe: geospatial analysis of vector's climatic suitability and virus' temperature requirements. *International Journal of Health Geographics*, **12(1)**, 51, doi:10.1186/1476-072X-12-51.

Fischer, E.M. and R. Knutti, 2015: Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nature Climate Change*, **5(6)**, 560-564, doi:10.1038/nclimate2617.

Fischer, E.M., J. Sedláček, E. Hawkins, and R. Knutti, 2014: Models agree on forced response pattern of precipitation and temperature extremes. *Geophysical Research Letters*, **41(23)**, 8554-8562, doi:10.1002/2014GL062018.

Fischer, H. et al., 2018: Paleoclimate constraints on a future warmer world. *Science* (in press).

Ford, J.D., 2012: Indigenous health and climate change. *American Journal of Public Health*, **102(7)**, 1260-1266, doi:10.2105/AJPH.2012.300752.

Ford, J.D., G. McDowell, and T. Pearce, 2015: The adaptation challenge in the Arctic. *Nature Climate Change*, **5(12)**, 1046-1053, doi:10.1038/nclimate2723.

Forseth, I., 2010: Terrestrial Biomes. *Nature Education Knowledge*, **3(10)**, 11.

Fossheim, M. et al., 2015: Recent warming leads to a rapid borealization of fish communities in the Arctic. *Nature Climate Change*, **5(7)**, 673-677, doi:10.1038/nclimate2647.

Fox, N.J. et al., 2011: Predicting Impacts of Climate Change on Fasciola hepatica Risk. *PLoS ONE*, **6(1)**, e16126, doi:10.1371/journal.pone.0016126.

Frank, D.C. et al., 2010: Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate. *Nature*, **463**, 527.

Fricko, O. et al., 2016: Energy sector water use implications of a 2 °C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.

Frieler, K. et al., 2013: Limiting global warming to 2C is unlikely to save most coral reefs. *Nature Climate Change*, **3(2)**, 165-170, doi:10.1038/nclimate1674.

Frieler, K. et al., 2015: Consistent evidence of increasing Antarctic accumulation with warming. *Nature Climate Change*, **5(4)**, 348-352.

Frieler, K. et al., 2017: Assessing the impacts of 1.5°C global warming - simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). *Geoscientific Model Development*, **10**, 4321-4345, doi:10.5194/gmd-10-4321-2017.

Friend, A.D. et al., 2014: Carbon residence time dominates uncertainty in terrestrial vegetation responses to future climate and atmospheric CO2. *Proceedings of the National Academy of Sciences*, **111(9)**, 3280-3285, doi:10.1073/pnas.1222477110.

Fronzek, S., T.R. Carter, and M. Luoto, 2011: Evaluating sources of uncertainty in modelling the impact of probabilistic climate change on sub-arctic palsa mires. *Natural Hazards and Earth System Science*, **11(11)**, 2981-2995, doi:10.5194/nhess-11-2981-2011.

Frost, A.J. et al., 2011: A comparison of multi-site daily rainfall downscaling techniques under Australian conditions. *Journal of Hydrology*, **408(1)**, 1-18, doi:10.1016/j.jhydrol.2011.06.021.

Fu, X. and J. Song, 2017: Assessing the economic costs of sea level rise and benefits of coastal protection: A spatiotemporal approach. *Sustainability*, **9(8)**, doi:10.3390/su9081495.

Fuerst, J.J., H. Goelzer, and P. Huybrechts, 2015: Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming. *The Cryosphere*, **9(3)**, 1039-1062, doi:10.5194/tc-9-1039-2015.

Fuss, S. et al., 2014: Betting on negative emissions. *Nature Climate Change*, **4(10)**, 850-853, doi:10.1038/nclimate2392.

Fuss, S. et al., 2018: Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Letters* (in press).

Gagne, M.–E., J.C. Fyfe, N.P. Gillett, I. Polyakov, and G.M. Flato, 2017: Aerosol-driven increase in Arctic sea ice over the middle of the twentieth century. *Geophysical Research Letters*, **44(14)**, 7338-7346, doi:10.1002/2016GL071941.

Galaasen, E.V. et al., 2014: Rapid Reductions in North Atlantic Deep Water During the Peak of the Last Interglacial Period. *Science*, **343(6175)**, 1129-1132, doi:10.1126/science.1248667.

Gang, C. et al., 2015: Projecting the dynamics of terrestrial net primary productivity in response to future climate change under the RCP2.6 scenario. *Environmental Earth Sciences*, **74(7)**, 5949-5959, doi:10.1007/s12665-015-4618-x.

García Molinos, J. et al., 2015: Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change*, **6(1)**, 83-88, doi:10.1038/nclimate2769.

Gardner, T.A., I.M. Côté, J.A. Gill, A. Grant, and A.R. Watkinson, 2005: Hurricanes and caribbean coral reefs: Impacts, recovery patterns, and role in long-term decline. *Ecology*, **86(1)**, 174-184, doi:10.1890/04-0141.

Garland, R.M. et al., 2015: Regional Projections of Extreme Apparent Temperature Days in Africa and the Related Potential Risk to Human Health. *International Journal of Environmental Research and Public Health*, **12(10)**, 12577-12604, doi:10.3390/ijerph121012577.

Garrabou, J. et al., 2009: Mass mortality in Northwestern Mediterranean rocky benthic communities: Effects of the 2003 heat wave. *Global Change Biology*, **15(5)**, 1090-1103, doi:10.1111/j.1365-2486.2008.01823.x.

Garrard, S.L. et al., 2014: Indirect effects may buffer negative responses of seagrass invertebrate communities to ocean acidification. *Journal of Experimental Marine Biology and Ecology*, **461**, 31-38, doi:10.1016/j.jembe.2014.07.011.

Gasparrini, A. et al., 2015: Mortality risk attributable to high and low ambient temperature: A multicountry observational study. *The Lancet*, **386(9991)**, 369-375, doi:10.1016/S0140-6736(14)62114-0.

Gass, P., H. Hove, and P. Jo-Ellen, 2011: *Review of Current and Planned Adaptation Action: East and Southeast Asia*. 230 pp.

Gattuso, J.–P. et al., 2015: Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. *Science*, **349(6243)**, aac4722, doi:10.1126/science.aac4722.

Gatusso, J.–P. et al., 2014: Cross-chapter box on ocean acidification. In: *Climate Change 2014: Impacts,* *Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 129-131.

Gauthier, S., P. Bernier, T. Kuuluvainen, A.Z. Shvidenko, and D.G. Schepaschenko, 2015: Boreal forest health and global change. *Science***, 349(6250)**, 819-822, doi:10.1126/science.aaa9092.

Geisler, C. and B. Currens, 2017: Impediments to inland resettlement under conditions of accelerated sea level rise. *Land Use Policy***, 66**, 322-330.

Georgescu, M., M. Moustaoui, A. Mahalov, and J. Dudhia, 2012: Summer-time climate impacts of projected megapolitan expansion in Arizona. *Nature Climate Change***, 3(1)**, 37-41, doi:10.1038/nclimate1656.

Gerten, D., S. Rost, W. von Bloh, and W. Lucht, 2008: Causes of change in 20th century global river discharge. *Geophysical Research Letters***, 35(20)**, L20405, doi:10.1029/2008GL035258.

Gerten, D. et al., 2013: Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. *Environmental Research Letters***, 8(3)**, 034032, doi:10.1088/1748-9326/8/3/034032.

Gharbaoui, D. and J. Blocher, 2016: The Reason Land Matters: Relocation as Adaptation to Climate Change in Fiji Islands. *Migration, Risk Management and Climate Change: Evidence and Policy Responses*, 149-173, doi:10.1007/978-3-319-42922-9_8.

Ghosh, J., 2010: The unnatural coupling: Food and global finance. *Journal of Agrarian Change***, 10(1)**, 72-86, doi:10.1111/j.1471-0366.2009.00249.x.

Giardino, A., K. Nederhoff, and M. Vousdukas, 2018: Coastal hazard risk assessment for small islands: assessing the impact of climate change and disaster reduction measures on Ebeye (Marshall Islands). *Regional Environmental Change*, 1-12, doi:DOI: 10.1007/s10113-018-1353-3.

Goddard, P.B., C.O. Dufour, J. Yin, S.M. Griffies, and M. Winton, 2017: CO2-Induced Ocean Warming of the Antarctic Continental Shelf in an Eddying Global Climate Model. *Journal of Geophysical Research - Oceans***, 122(10)**, 8079-8101, doi:10.1002/2017JC012849.

Goll, D.S. et al., 2012: Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling. *Biogeosciences***, 9(9)**, 3547-3569, doi:10.5194/bg-9-3547-2012.

Golledge, N.R. et al., 2015: The multi-millennial Antarctic commitment to future sea-level rise. *Nature***, 526(7573)**, 421-425, doi:10.1038/nature15706.

González, C., A. Paz, and C. Ferro, 2014: Predicted altitudinal shifts and reduced spatial distribution of Leishmania infantum vector species under climate change scenarios in Colombia. *Acta Tropica***, 129**, 83-90, doi:10.1016/j.actatropica.2013.08.014.

Good, P., C. Jones, J. Lowe, R. Betts, and N. Gedney, 2013: Comparing Tropical Forest Projections from Two Generations of Hadley Centre Earth System Models, HadGEM2-ES and HadCM3LC. *Journal of Climate***, 26(2)**, 495-511, doi:10.1175/JCLI-D-11-00366.1.

Good, P. et al., 2011: Quantifying Environmental Drivers of Future Tropical Forest Extent. *Journal of Climate***, 24(5)**, 1337-1349, doi:10.1175/2010JCLI3865.1.

Goodwin, P., I.D. Haigh, E.J. Rohling, and A. Slangen, 2017: A new approach to projecting 21st century sea-level changes and extremes. *Earth's Future***, 5(2)**, 240-253, doi:10.1002/2016EF000508.

Goodwin, P., S. Brown, I.D. Haigh, R.J. Nicholls, and J.M. Matter, 2018: Adjusting Mitigation Pathways to Stabilize Climate at 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future***, 6(3)**, 601-615, doi:10.1002/2017EF000732.

Gosling, S.N. and N.W. Arnell, 2016: A global assessment of the impact of climate change on water scarcity. *Climatic Change***, 134(3)**, 371-385, doi:10.1007/s10584-013-0853-x.

Gosling, S.N. et al., 2017: A comparison of changes in river runoff from multiple global and catchment-scale hydrological models under global warming scenarios of 1°C, 2°C and 3°C. *Climatic Change***, 141(3)**, 577-595, doi:10.1007/s10584-016-1773-3.

Graham, N.A.J., 2014: Habitat complexity: Coral structural loss leads to fisheries declines. *Current Biology***, 24(9)**, R359-R361, doi:10.1016/j.cub.2014.03.069.

Graham, N.A.J., S. Jennings, M.A. MacNeil, D. Mouillot, and S.K. Wilson, 2015: Predicting climate-driven regime shifts versus rebound potential in coral reefs. *Nature***, 518(7537)**, 1-17, doi:10.1038/nature14140.

Graux, A.–I., G. Bellocchi, R. Lardy, and J.–F. Soussana, 2013: Ensemble modelling of climate change risks and opportunities for managed grasslands in France. *Agricultural and Forest Meteorology***, 170**, 114-131, doi:10.1016/j.agrformet.2012.06.010.

Green, A.L. et al., 2014: Designing Marine Reserves for Fisheries Management, Biodiversity Conservation, and Climate Change Adaptation. *Coastal Management***, 42(2)**, 143-159, doi:10.1080/08920753.2014.877763.

Gregory, J.M. and P. Huybrechts, 2006: Ice-sheet contributions to future sea-level change. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences***, 364(1844)**, 1709-1731, doi:10.1098/rsta.2006.1796.

Gregory, P.J. and B. Marshall, 2012: Attribution of climate change: a methodology to estimate the potential contribution to increases in potato yield in Scotland since 1960. *Global Change Biology***, 18(4)**, 1372-1388, doi:10.1111/j.1365-2486.2011.02601.x.

Greve, P. and S.I. Seneviratne, 2015: Assessment of future changes in water availability and aridity. *Geophysical Research Letters***, 42(13)**, 5493-5499, doi:10.1002/2015GL064127.

Greve, P., L. Gudmundsson, and S.I. Seneviratne, 2018: Regional scaling of annual mean precipitation and water availability with global temperature change. *Earth System Dynamics***, 9(1)**, 227-240, doi:10.5194/esd-9-227-2018.

Greve, P. et al., 2014: Global assessment of trends in wetting and drying over land. *Nature Geoscience***, 7(10)**, 716-721, doi:10.1038/ngeo2247.

Grillakis, M.G., A.G. Koutroulis, K.D. Seiradakis, and I.K. Tsanis, 2016: Implications of 2 °C global warming in European summer tourism. *Climate Services***, 1**, 30-38, doi:10.1016/j.cliser.2016.01.002.

Grillakis, M.G., A.G. Koutroulis, I.N. Daliakopoulos, and I.K. Tsanis, 2017: A method to preserve trends in quantile mapping bias correction of climate modeled temperature. *Earth System Dynamics***, 8**, 889-900, doi:10.5194/esd-8-889-2017.

Griscom, B.W. et al., 2017: Natural climate solutions. *Proceeding of the National Academy of Sciences of the United States of America***, 114(44)**, 11645-11650, doi:10.1073/pnas.1710465114.

Grossman-Clarke, S., S. Schubert, and D. Fenner, 2017: Urban effects on summertime air temperature in Germany under climate change. *International Journal of Climatology***, 37(2)**, 905-917, doi:10.1002/joc.4748.

Grübler, A., 2018: A Global Scenario of Low Energy Demand for Sustainable Development below 1.5°C without Negative Emission Technologies. *(in press)*.

Gu, G. and R.F. Adler, 2013: Interdecadal variability/long-term changes in global precipitation patterns during the past three decades: global warming and/or pacific decadal variability? *Climate Dynamics***, 40(11-12)**, 3009-3022, doi:10.1007/s00382-012-1443-8.

Gu, G. and R.F. Adler, 2015: Spatial patterns of global precipitation change and variability during 1901-2010. *Journal of Climate***, 28(11)**, 4431-4453, doi:10.1175/JCLI-D-14-00201.1.

Gudmundsson, L. and S.I. Seneviratne, 2016: Anthropogenic climate change affects meteorological drought risk in Europe. *Environmental Research Letters***, 11(4)**, 044005, doi:10.1088/1748-9326/11/4/044005.

Gudmundsson, L., S.I. Seneviratne, and X. Zhang, 2017: Anthropogenic climate change detected in European renewable freshwater resources. *Nature Climate Change***, 7**, 813.

Guiot, J. and W. Cramer, 2016: Climate change: The 2015 Paris Agreement thresholds and Mediterranean basin ecosystems. *Science***, 354(6311)**, 4528-4532, doi:10.1126/science.aah5015.

Guis, H. et al., 2012: Modelling the effects of past and future climate on the risk of bluetongue emergence in Europe. *Journal of The Royal Society Interface***, 9(67)**, 339-350, doi:10.1098/rsif.2011.0255.

Guo, Y. et al., 2016: Projecting future temperature-related mortality in three largest Australian cities. *Environmental Pollution***, 208(January 2016)**, 66-73, doi:10.1016/j.envpol.2015.09.041.

Gupta, H., S.–J. Kao, and M. Dai, 2012: The role of mega dams in reducing sediment fluxes: A case study of large Asian rivers. *Journal of Hydrology***, 464-465(Supplement C)**, 447-458, doi:https://doi.org/10.1016/j.jhydrol.2012.07.038.

Gustafson, S., A. Joehl Cadena, and P. Hartman, 2016: Adaptation planning in the Lower Mekong Basin: merging scientific data with local perspective to improve community resilience to climate change. *Climate and Development*, 1-15, doi:10.1080/17565529.2016.1223593.

Gustafson, S. et al., 2017: Merging science into community adaptation planning processes: a cross-site comparison of four distinct areas of the Lower Mekong Basin. *Climatic Change*, doi:10.1007/s10584-016-1887-7.

Gutiérrez, J.L. et al., 2012: Physical Ecosystem Engineers and the Functioning of Estuaries and Coasts. *Treatise on Estuarine and Coastal Science***, 7**, 53-81, doi:10.1016/B978-0-12-374711-2.00705-1.

Haberl, H., T. Beringer, S.C. Bhattacharya, K.–H. Erb, and M. Hoogwijk, 2010: The global technical potential of bio-energy in 2050 considering sustainability constraints. *Current Opinion in Environmental Sustainability***, 2(5)**, 394-403, doi:https://doi.org/10.1016/j.cosust.2010.10.007.

Haberl, H. et al., 2013: Bioenergy: how much can we expect for 2050? *Environmental Research Letters***, 8(3)**, 31004.

Habibi Mohraz, M., A. Ghahri, M. Karimi, and F. Golbabaei, 2016: The Past and Future Trends of Heat Stress Based On Wet Bulb Globe Temperature Index in Outdoor Environment of Tehran City, Iran. *Iranian Journal of Public Health***, 45(6)**, 787-794.

Hadden, D. and A. Grelle, 2016: Changing temperature response of respiration turns boreal forest from carbon sink into carbon source. *Agricultural and Forest Meteorology*, doi:10.1016/j.agrformet.2016.03.020.

Hajat, S., S. Vardoulakis, C. Heaviside, and B. Eggen, 2014: Climate change effects on human health: Projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. *Journal of Epidemiology and Community Health***, 68(7)**, 641-648, doi:10.1136/jech-2013-202449.

Hales, S., S. Kovats, S. Lloyd, and D. Campbell-Lendrum (eds.), 2014: *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s*. World Health Organization (WHO), Geneva, Switzerland, 115 pp.

Hall, J. et al., 2014: Understanding flood regime changes in Europe: a state-of-the-art assessment. *Hydrology and Earth System Sciences***, 18(7)**, 2735-2772, doi:10.5194/hess-18-2735-2014.

Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change***, 7(4)**, 250-256, doi:10.1038/nclimate3253.

Hallegatte, S., C. Green, R. J. Nicholls, and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nature Climate Change***, 3**, 802-806.

Hallegatte, S. et al., 2016: Shock Waves: Managing the Impacts of Climate Change on Poverty. , 227.

Hall-Spencer, J.M. et al., 2008: Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature***, 454(7200)**, 96-99, doi:10.1038/nature07051.

Halpern, B.S. et al., 2015: Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature Communications***, 6**, 7615, doi:10.1038/ncomms8615.

Hamukuaya, H., M. O'Toole, and P. Woodhead, 1998: Observations of severe hypoxia and offshore displacement of Cape hake over the Namibian shelf in 1994. *South African Journal of Marine Science*, **19**, 57-59, doi:10.2989/025776198784126809.

Hanasaki, N. et al., 2013: A global water scarcity assessment under Shared Socio-economic Pathways - Part 2: Water availability and scarcity. *Hydrology and Earth System Sciences*, **17(7)**, 2393-2413, doi:10.5194/hess-17-2393-2013.

Handisyde, N., T.C. Telfer, and L.G. Ross, 2016: Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. *Fish and Fisheries*, **18(3)**, 466-488, doi:10.1111/faf.12186.

Hanna, E.G., T. Kjellstrom, C. Bennett, and K. Dear, 2011: Climate Change and Rising Heat: Population Health Implications for Working People in Australia. *Asia-Pacific Journal of Public Health*, **23(2)**, 14s-26s, doi:10.1177/1010539510391457.

Hansen, G. and D. Stone, 2016: Assessing the observed impact of anthropogenic climate change. *Nature Climate Change*, **6(5)**, 532-537, doi:10.1038/nclimate2896.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Reviews of Geophysics*, **48(4)**, RG4004, doi:10.1029/2010RG000345.

Hanson, S. et al., 2011: A global ranking of port cities with high exposure to climate extremes. *Climatic Change*, **104(1)**, 89-111, doi:10.1007/s10584-010-9977-4.

Harrington, L.J. and F.E.L. Otto, 2018: Changing population dynamics and uneven temperature emergence combine to exacerbate regional exposure to heat extremes under 1.5 °C and 2 °C of warming. *Environmental Research Letters*, **13(3)**, 34011.

Hartmann, D.L. et al., 2013: Observations: Atmosphere and Surface. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 159-254.

Harvey, C.A. et al., 2014: Climate-Smart Landscapes: Opportunities and Challenges for Integrating Adaptation and Mitigation in Tropical Agriculture. *Conservation Letters*, **7(2)**, 77-90, doi:10.1111/conl.12066.

Hasegawa, T., S. Fujimori, K. Takahashi, T. Yokohata, and T. Masui, 2016: Economic implications of climate change impacts on human health through undernourishment. *Climatic Change*, **136(2)**, 189-202, doi:10.1007/s10584-016-1606-4.

Hasegawa, T. et al., 2014: Climate Change Impact and Adaptation Assessment on Food Consumption Utilizing a New Scenario Framework. *Environmental Science & Technology*, **48(1)**, 438-445, doi:10.1021/es4034149.

Hashimoto, H. et al., 2013: Structural Uncertainty in Model-Simulated Trends of Global Gross Primary Production. *Remote Sensing*, **5(3)**, 1258-1273, doi:10.3390/rs5031258.

Hatfield, J.L. et al., 2011: Climate Impacts on Agriculture: Implications for Crop Production. *Agronomy Journal*, **103(2)**, 351, doi:10.2134/agronj2010.0303.

Hauer, M.E., J.M. Evans, and D.R. Mishra, 2016: Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, **6(7)**, 691-695, doi:10.1038/nclimate2961.

Hauri, C., T. Friedrich, and A. Timmermann, 2016: Abrupt onset and prolongation of aragonite undersaturation events in the Southern Ocean. *Nature Climate Change*, **6(2)**, 172-176, doi:10.1038/nclimate2844.

Haustein, K. et al., 2017: A real-time Global Warming Index. *Scientific Reports*, **7(1)**, 15417, doi:10.1038/s41598-017-14828-5.

Haywood, A.M., H.J. Dowsett, and A.M. Dolan, 2016: Integrating geological archives and climate models for the mid-Pliocene warm period. *Nature Communications*, **7**, 10646.

He, Q. and G. Zhou, 2016: Climate-associated distribution of summer maize in China from 1961 to 2010. *Agriculture, Ecosystems & Environment***, 232**, 326-335, doi:10.1016/j.agee.2016.08.020.

Heal, M.R. et al., 2013: Health burdens of surface ozone in the UK for a range of future scenarios. *Environment International***, 61**, 36-44, doi:10.1016/j.envint.2013.09.010.

Heck, V., D. Gerten, W. Lucht, and A. Popp, 2018: Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change***, 8(2)**, 151-155, doi:10.1038/s41558-017-0064-y.

Herbert, E.R. et al., 2015: A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. *Ecosphere***, 6(10)**, doi:10.1890/ES14-00534.1.

Hewitt, A.J. et al., 2016: Sources of Uncertainty in Future Projections of the Carbon Cycle. *Journal of Climate***, 29(20)**, 7203-7213, doi:10.1175/JCLI-D-16-0161.1.

Hidalgo, H.G. et al., 2009: Detection and Attribution of Streamflow Timing Changes to Climate Change in the Western United States. *Journal of Climate***, 22(13)**, 3838-3855, doi:10.1175/2009JCLI2470.1.

HLPE, 2011: *Price volatility and food security*. High Level Panel of Experts on Food Security and Nutrition.

Hill, T.D. and S.C. Anisfeld, 2015: Coastal wetland response to sea level rise in Connecticut and New York. *Estuarine, Coastal and Shelf Science***, 163**, 185-193, doi:10.1016/j.ecss.2015.06.004.

Hinkel, J. et al., 2014: Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America***, 111(9)**, 3292-7, doi:10.1073/pnas.1222469111.

Hirsch, A.L., M. Wilhelm, E.L. Davin, W. Thiery, and S.I. Seneviratne, 2017: Can climate-effective land management reduce regional warming? *Journal of Geophysical Research: Atmospheres***, 122(4)**, 2269-2288, doi:10.1002/2016JD026125.

Hirsch, A.L. et al., 2018: Biogeophysical impacts of land use change on climate extremes in low emissions scenarios: Results from HAPPI-Land. *Earth's Future*.

Hoang, L.P. et al., 2016: Mekong River flow and hydrological extremes under climate change. *Hydrology and Earth System Sciences***, 20(7)**, 3027-3041, doi:10.5194/hess-20-3027-2016.

Hoang, L.P. et al., 2018: Managing flood risks in the Mekong Delta: How to address emerging challenges under climate change and socioeconomic developments. *Ambio*, doi:10.1007/s13280-017-1009-4.

Hobbs, J.P.A. and C.A. Mcdonald, 2010: Increased seawater temperature and decreased dissolved oxygen triggers fish kill at the Cocos (Keeling) Islands, Indian Ocean. *Journal of Fish Biology***, 77(6)**, 1219-1229, doi:10.1111/j.1095-8649.2010.02726.x.

Hobbs, W.R. et al., 2016: A review of recent changes in Southern Ocean sea ice, their drivers and forcings. *Global and Planetary Change***, 143**, 228-250, doi:10.1016/j.gloplacha.2016.06.008.

Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. *Marine and Freshwater Research***, 50(8)**, 839, doi:10.1071/MF99078.

Hoegh-Guldberg, O., 2012: The adaptation of coral reefs to climate change: Is the Red Queen being outpaced? *Scientia Marina***, 76(2)**, 403-408, doi:10.3989/scimar.03660.29A.

Hoegh-Guldberg, O., 2014a: Coral reef sustainability through adaptation: Glimmer of hope or persistent mirage? *Current Opinion in Environmental Sustainability***, 7**, 127-133, doi:10.1016/j.cosust.2014.01.005.

Hoegh-Guldberg, O., 2014b: Coral reefs in the Anthropocene: persistence or the end of the line? *Geological Society, London, Special Publications***, 395(1)**, 167-183, doi:10.1144/SP395.17.

Hoegh-Guldberg, O., E.S. Poloczanska, W. Skirving, and S. Dove, 2017: Coral Reef Ecosystems under Climate Change and Ocean Acidification. *Frontiers in Marine Science***, 4**, doi:10.3389/fmars.2017.00158.

Hoegh-Guldberg, O., E. Kennedy, H.L. Beyer, C. McClennen, and H.P. Possingham, 2018: Securing a long-term future for coral reefs. *Trends in Ecology & Evolution* (in press).

Hoegh-Guldberg, O. et al., 2007: Coral Reefs Under Rapid Climate Change and Ocean Acidification.

*Science***, 318(5857)**, 1737-1742.

Hoegh-Guldberg, O. et al., 2014: The Ocean. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, United Kingdom and New York, NY, USA, pp. 1655-1731.

Hoegh-Guldberg, O. et al., 2015: *Reviving the Ocean Economy: the case for action - 2015*. WWF International, Gland, Switzerland, 60 pp.

Hoffman, J.S., P.U. Clark, A.C. Parnell, and F. He, 2017: Regional and global sea-surface temperatures during the last interglaciation. *Science***, 355(6322)**, 276-279, doi:10.1126/science.aai8464.

Holding, S. and D.M. Allen, 2015: Wave overwash impact on small islands: Generalised observations of freshwater lens response and recovery for multiple hydrogeological settings. *Journal of Hydrology***, 529(Part 3)**, 1324-1335, doi:https://doi.org/10.1016/j.jhydrol.2015.08.052.

Holding, S. et al., 2016: Groundwater vulnerability on small islands. *Nature Climate Change***, 6**, 1100, doi:10.1038/nclimate3128.

Holland, G. and C.L. Bruyère, 2014: Recent intense hurricane response to global climate change. *Climate Dynamics***, 42(3-4)**, 617-627, doi:10.1007/s00382-013-1713-0.

Holland, M.M., C.M. Bitz, and B. Tremblay, 2006: Future abrupt reductions in the summer Arctic sea ice. *Geophysical Research Letters***, 33(23)**, doi:10.1029/2006GL028024.

Hollowed, A.B. and S. Sundby, 2014: Change is coming to the northern oceans. *Science***, 344(6188)**, 1084-1085, doi:10.1126/science.1251166.

Hollowed, A.B. et al., 2013: Projected impacts of climate change on marine fish and fisheries. *ICES Journal of Marine Science***, 70(510)**, 1023-1037, doi:10.1093/icesjms/fst081.

Holmgren, K. et al., 2016: Mediterranean Holocene climate, environment and human societies. *Quaternary Science Reviews***, 136**, 1-4, doi:10.1016/j.quascirev.2015.12.014.

Holstein, D.M., C.B. Paris, A.C. Vaz, and T.B. Smith, 2016: Modeling vertical coral connectivity and mesophotic refugia. *Coral Reefs***, 35(1)**, 23-37, doi:10.1007/s00338-015-1339-2.

Holz, C., L. Siegel, E.B. Johnston, A.D. Jones, and J. Sterman, 2017: Ratcheting Ambition to Limit Warming to 1.5°C - Trade-offs Between Emission Reductions and Carbon Dioxide Removal. *Environmental Research Letters*.

Honda, Y. et al., 2014: Heat-related mortality risk model for climate change impact projection. *Environmental Health and Preventive Medicine***, 19(1)**, 56-63, doi:10.1007/s12199-013-0354-6.

Hong, J. and W.S. Kim, 2015: Weather impacts on electric power load: partial phase synchronization analysis. *Meteorological Applications***, 22(4)**, 811-816, doi:10.1002/met.1535.

Hönisch, B. et al., 2012: The geological record of ocean acidification. *Science***, 335(6072)**, 1058-1063, doi:10.1126/science.1208277.

Horta E Costa, B. et al., 2014: Tropicalization of fish assemblages in temperate biogeographic transition zones. *Marine Ecology Progress Series***, 504**, 241-252, doi:10.3354/meps10749.

Hosking, J.S. et al., 2018: Changes in European wind energy generation potential within a 1.5°C warmer world. *Environmental Research Letters* (in press).

Hossain, M.S., L. Hein, F.I. Rip, and J.A. Dearing, 2015: Integrating ecosystem services and climate change responses in coastal wetlands development plans for Bangladesh. *Mitigation and Adaptation Strategies for Global Change***, 20(2)**, 241-261, doi:10.1007/s11027-013-9489-4.

Hosseini, N., J. Johnston, and K.–E. Lindenschmidt, 2017: Impacts of Climate Change on the Water Quality of a Regulated Prairie River. *Water***, 9(3)**, 199, doi:10.3390/w9030199.

Houghton, R.A. and A.A. Nassikas, 2018: Negative emissions from stopping deforestation and forest degradation, globally. *Global Change Biology***, 24(1)**, 350-359, doi:10.1111/gcb.13876.

Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science***, 356(6345)**, doi:10.1126/science.aal4369.

Hsiang, S.M. and M. Burke, 2014: Climate, conflict, and social stability: what does the evidence say? *Climatic Change***, 123(1)**, 39-55, doi:10.1007/s10584-013-0868-3.

Hsiang, S.M. and A.H. Sobel, 2016: Potentially Extreme Population Displacement and Concentration in the Tropics Under Non-Extreme Warming. *Scientific Reports***, 6**, 25697, doi:10.1038/srep25697.

Hsiang, S.M., M. Burke, and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science***, 341(6151)**, 1235367, doi:10.1126/science.1235367.

Huang, C.R., A.G. Barnett, X.M. Wang, and S.L. Tong, 2012: The impact of temperature on years of life lost in Brisbane, Australia. *Nature Climate Change***, 2(4)**, 265-270, doi:10.1038/Nclimate1369.

Huang, J., H. Yu, A. Dai, Y. Wei, and L. Kang, 2017: Drylands face potential threat under 2 °C global warming target. *Nature Climate Change***, 7(6)**, 417-422, doi:10.1038/nclimate3275.

Huang, M. et al., 2017: Velocity of change in vegetation productivity over northern high latitudes. *Nature Ecology & Evolution***, 1(November)**, 1649-1654, doi:10.1038/s41559-017-0328-y.

Hughes, D.J. and B.E. Narayanaswamy, 2013: Impacts of climate change on deep-sea habitats. In: *MCCIP Science Review*. Marine Climate Change Impacts Partnership (MCCIP), pp. 204-210.

Hughes, T.P., J.T. Kerry, and T. Simpson, 2018: Large-scale bleaching of corals on the Great Barrier Reef. *Ecology***, 99(2)**, 501, doi:10.1002/ecy.2092.

Hughes, T.P. et al., 2017a: Coral reefs in the Anthropocene. *Nature***, 546(7656)**, 82-90, doi:10.1038/nature22901.

Hughes, T.P. et al., 2017b: Global warming and recurrent mass bleaching of corals. *Nature***, 543(7645)**, 373-377, doi:10.1038/nature21707.

Humpenöder, F. et al., 2014: Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environmental Research Letters***, 9(6)**, 064029, doi:10.1088/1748-9326/9/6/064029.

Humpenöder, F. et al., 2018: Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environmental Research Letters***, 13(2)**, 24011.

Huntingford, C. et al., 2013: Simulated resilience of tropical rainforests to CO2-induced climate change. *Nature Geoscience***, 6**, 268, doi:10.1038/ngeo1741.

Hutyra, L.R. et al., 2005: Climatic variability and vegetation vulnerability in Amazônia. *Geophysical Research Letters***, 32(24)**, n/a--n/a, doi:10.1029/2005GL024981.

Huynen, M.M.T.E. and P. Martens, 2015: Climate Change Effects on Heat- and Cold-Related Mortality in the Netherlands: A Scenario-Based Integrated Environmental Health Impact Assessment. *International Journal of Environmental Research and Public Health***, 12(10)**, 13295-13320, doi:10.3390/ijerph121013295.

ICEM, 2013: *USAID Mekong ARCC Climate Change Impact and Adaptation: Summary Prepared for the United States Agency for International Development by ICEM - International Centre for Environmental Management*. 61 pp.

Iida, Y. et al., 2015: Trends in pCO2 and sea-air CO2 flux over the global open oceans for the last two decades. *Journal of Oceanography***, 71(6)**, 637-661, doi:10.1007/s10872-015-0306-4.

Iizumi, T. et al., 2017: Responses of crop yield growth to global temperature and socioeconomic changes. *Scientific Reports***, 7(1)**, 7800, doi:10.1038/s41598-017-08214-4.

IPCC, 2000: Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. [Nakicenovic, N. and R. Swart (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 612 pp.

IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, III to the Fourth

Assessment Report of the International Panel on Climate Change.. [Core Writing Team, R.K. Pachauri, and A. Reisinger (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of IPCC Intergovernmental Panel on Climate Change. [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.–K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, USA, 594 pp.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2014a: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J.. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

IPCC, 2014b: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandre. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 688 pp.

Ishida, H. et al., 2014: Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research. *Environmental Research Letters*, **9(6)**, 064014, doi:10.1088/1748-9326/9/6/064014.

Islam, M.R. and M. Shamsuddoha, 2017: Socioeconomic consequences of climate induced human displacement and migration in Bangladesh. *International Sociology***, 32(3)**, 277-298, doi:10.1177/0268580917693173.

IUCN, 2017: Red List of threatened species. http://www.iucnredlist.org (Accessed: 21 August 2015).

Izaurralde, R.C. et al., 2011: Climate Impacts on Agriculture: Implications for Forage and Rangeland Production. *Agronomy Journal***, 103(2)**, 371, doi:10.2134/agronj2010.0304.

Jacinto, G.S., 2011: Fish Kill in the Philippines - Déjà Vu. *Science Diliman***, 23(December)**, 1-3.

Jackson, J.E. et al., 2010: Public health impacts of climate change in Washington State: projected mortality risks due to heat events and air pollution. *Climatic Change***, 102(1-2)**, 159-186, doi:10.1007/s10584-010-9852-3.

Jackson, L.P., A. Grinsted, and S. Jevrejeva, 2018: 21st Century Sea-Level Rise in Line with the Paris Accord. *Earth's Future***, 6(2)**, 213-229, doi:10.1002/2017EF000688.

Jacob, D. and S. Solman, 2017: IMPACT2C - An introduction. *Climate Services***, 7(Supplement C)**, 1-2, doi:https://doi.org/10.1016/j.cliser.2017.07.006.

Jacob, D. et al., 2014: EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change***, 14(2)**, 563-578, doi:10.1007/s10113-013-0499-2.

Jacob, D. et al., 2018: Climate Impacts in Europe Under +1.5°C Global Warming. *Earth's Future***, 6(2)**, 264-285, doi:10.1002/2017EF000710.

Jacobs, S.S., A. Jenkins, C.F. Giulivi, and P. Dutrieux, 2011: Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf. *Nature Geoscience*, **4(8)**, 519-523, doi:10.1038/NGEO1188.

Jaggard, K.W., A. Qi, and M.A. Semenov, 2007: The impact of climate change on sugarbeet yield in the UK: 1976-2004. *The Journal of Agricultural Science*, **145(04)**, 367, doi:10.1017/S0021859607006922.

Jahn, A., 2018: Reduced probability of ice-free summers for 1.5ºC compared to 2ºC warming. *Nature Climate Change* (in press).

Jahn, A., J.E. Kay, M.M. Holland, and D.M. Hall, 2016: How predictable is the timing of a summer ice-free Arctic? *Geophysical Research Letters*, **43(17)**, 9113-9120, doi:10.1002/2016GL070067.

Jaiswal, D. et al., 2017: Brazilian sugarcane ethanol as an expandable green alternative to crude oil use. *Nature Climate Change*, **7(11)**, 788-792, doi:10.1038/nclimate3410.

Jamero, L., M. Onuki, M. Esteban, and N. Tan, 2018: Community-based adaptation in low-lying islands in the Phillippines: Challenges and lessons learned. *Regional Environmental Change*, 1-12.

Jamero, M.L. et al., 2017: Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nature Climate Change*, **7**.

James, R., R. Washington, C.–F. Schleussner, J. Rogelj, and D. Conway, 2017: Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets. *Wiley Interdisciplinary Reviews: Climate Change*, **8(2)**, e457, doi:10.1002/wcc.457.

Jean-Baptiste, N. et al., 2018: Housing and Informal Settlements. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W.D. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S.E. Ali Ibrahim (eds.)]. Cambridge University Press, Cambride, United Kingdom and New York, USA, pp. 399-431.

Jeong, S.–J. et al., 2014: Effects of double cropping on summer climate of the North China Plain and neighbouring regions. *Nature Climate Change*, **4(7)**, 615-619, doi:10.1038/nclimate2266.

Jevrejeva, S., L.P. Jackson, R.E.M. Riva, A. Grinsted, and J.C. Moore, 2016: Coastal sea level rise with warming above 2 °C. *Proceedings of the National Academy of Sciences of the United States of America*, **113(47)**, 13342-13347, doi:10.1073/pnas.1605312113.

Jiang, D.B. and Z.P. Tian, 2013: East Asian monsoon change for the 21st century: Results of CMIP3 and CMIP5 models. *Chinese Science Bulletin*, **58(12)**, 1427-1435, doi:10.1007/s11434-012-5533-0.

Jiang, L. and B.C.O. Neill, 2017: Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 193-199, doi:10.1016/j.gloenvcha.2015.03.008.

Jiang, Y. et al., 2016: Importance of soil thermal regime in terrestrial ecosystem carbon dynamics in the circumpolar north. *Global and Planetary Change*, **142**, 28-40, doi:10.1016/j.gloplacha.2016.04.011.

Jiao, M., G. Zhou, and Z. Chen (eds.), 2014: *Blue book of agriculture for addressing climate change: Assessment report of climatic change impacts on agriculture in China (No.1)*. Social Sciences Academic Press, Beijing.

Jiao, M., G. Zhou, and Z. Zhang (eds.), 2016: *Blue book of agriculture for addressing climate change: Assessment report of agro-meteorological disasters and yield losses in China (No.2)*. Social Sciences Academic Press, Beijing.

Jiménez Cisneros, B.E. et al., 2014: Freshwater Resources. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269.

Johnson, W.C. and K.A. Poiani, 2016: Climate Change Effects on Prairie Pothole Wetlands: Findings from a

Twenty-five Year Numerical Modeling Project. *Wetlands*, **36(2)**, 273-285, doi:10.1007/s13157-016-0790-3.

Jones, A., 2017: *Global Climate Change and Coastal Tourism - Recognizing Problems, Managing Solutions and Future Expectations*. CABI Publishers, 360 pp.

Jones, C. and L.M. Carvalho, 2013: Climate change in the South American monsoon system: Present climate and CMIP5 projections. *Journal of Climate*, **26(17)**, 6660-6678, doi:10.1175/JCLI-D-12-00412.1.

Jones, C., J. Lowe, S. Liddicoat, and R. Betts, 2009: Committed terrestrial ecosystem changes due to climate change. *Nature Geoscience*, **2**, 484, doi:10.1038/ngeo555.

Jones, C. et al., 2013: Twenty-First-Century Compatible CO2 Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways. *Journal of Climate*, **26(13)**, 4398-4413, doi:10.1175/JCLI-D-12-00554.1.

Jones, C.D. et al., 2016: Simulating the Earth system response to negative emissions. *Environmental Research Letters*, **11(9)**, 095012, doi:10.1088/1748-9326/11/9/095012.

Jonker, J.G.G., M. Junginger, and A. Faaij, 2014: Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. *GCB Bioenergy*, **6(4)**, 371-389, doi:10.1111/gcbb.12056.

Joughin, I., B.E. Smith, and B. Medley, 2014: Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica. *Science*, **344(6185)**, 735-738, doi:10.1126/science.1249055.

Kaiser, K. et al., 2014: Detection and attribution of lake-level dynamics in north-eastern central Europe in recent decades. *Regional Environmental Change*, **14(4)**, 1587-1600, doi:10.1007/s10113-014-0600-5.

Kamahori, H., N. Yamazaki, N. Mannoji, and K. Takahashi, 2006: Variability in Intense Tropical Cyclone Days in the Western North Pacific. *SOLA*, **2**, 104-107, doi:10.2151/sola.2006-027.

Kamei, M., K. Hanaki, and K. Kurisu, 2016: Tokyo's long-term socioeconomic pathways: Towards a sustainable future. *Sustainable Cities and Society*, **27**, 73-82, doi:10.1016/j.scs.2016.07.002.

Kämpf, J. and P. Chapman, 2016: The Functioning of Coastal Upwelling Systems. In: *Upwelling Systems of the World*. pp. 31-65.

Kang, N.–Y. and J.B. Elsner, 2015: Trade-off between intensity and frequency of global tropical cyclones. *Nature Climate Change*, **5(7)**, 661-664, doi:10.1038/nclimate2646.

Kaniewski, D., J.J.J. Guiot, and E. Van Campo, 2015: Drought and societal collapse 3200 years ago in the Eastern Mediterranean: A review. *Wiley Interdisciplinary Reviews: Climate Change*, **6(4)**, 369-382, doi:10.1002/wcc.345.

Kannan, K.P., S.M. Dev, and A.N. Sharma, 2000: Concerns on Food Security. *Economic And Political Weekly*, **35(45)**, 3919-3922.

Karl, T.R. et al., 2015: Possible artifacts of data biases in the recent global surface warming hiatus. *Science*, **348(6242)**.

Karnauskas, K.B., J.P. Donnelly, and K.J. Anchukaitis, 2016: Future freshwater stress for island populations. *Nature Climate Change*, **6**, 720, doi:10.1038/nclimate2987.

Karnauskas, K.B. et al., 2018: Freshwater Stress on Small Island Developing States: Population Projections and Aridity Changes at 1.5°C and 2°C. *Regional Environmental Change*, 1-10, doi:https://doi.org/10.1007/s10113-018-1331-9.

Karstensen, J. et al., 2015: Open ocean dead zones in the tropical North Atlantic Ocean. *Biogeosciences*, **12(8)**, 2597-2605, doi:10.5194/bg-12-2597-2015.

Kawaguchi, S. et al., 2013: Risk maps for Antarctic krill under projected Southern Ocean acidification. *Nature Climate Change*, **3(9)**, 843-847, doi:10.1038/nclimate1937.

Kelley, C.P., S. Mohtadi, M.A. Cane, R. Seager, and Y. Kushnir, 2015: Climate change in the Fertile

Crescent and implications of the recent Syrian drought. *Proceedings of the National Academy of Sciences of the United States of America*, **112(11)**, 3241-6, doi:10.1073/pnas.1421533112.

Kelly, K.A., K. Drushka, L.A. Thompson, D. Le Bars, and E.L. McDonagh, 2016: Impact of slowdown of Atlantic overturning circulation on heat and freshwater transports. *Geophysical Research Letters*, **43(14)**, 7625-7631, doi:10.1002/2016GL069789.

Kench, P., D. Thompson, M. Ford, H. Ogawa, and R. Mclean, 2015: Coral islands defy sea-level rise over the past century: Records from a central Pacific atoll. *Geology*, **43(6)**, 515-518.

Kench, P.S., M.R. Ford, and S.D. Owen, 2018: Patterns of island change and persistence offer alternate adaptation pathways for atoll nations. *Nature Communications*, **9(1)**, 605, doi:10.1038/s41467-018-02954-1.

Kendrovski, V. et al., 2017: Quantifying Projected Heat Mortality Impacts under 21st-Century Warming Conditions for Selected European Countries. *International Journal of Environmental Research and Public Health*, **14(7)**, 729, doi:10.3390/ijerph14070729.

Kennedy, E. et al., 2013: Avoiding Coral Reef Functional Collapse Requires Local and Global Action. *Current Biology*, **23(10)**, 912-918, doi:10.1016/j.cub.2013.04.020.

Kent, C. et al., 2017: Using climate model simulations to assess the current climate risk to maize production. *Environmental Research Letters*, **12(5)**, doi:10.1088/1748-9326/aa6cb9.

Keppel, G. and J. Kavousi, 2015: Effective climate change refugia for coral reefs. *Global Change Biology*, **21(8)**, 2829-2830, doi:10.1111/gcb.12936.

Kersting, D.K., E. Cebrian, J. Verdura, and E. Ballesteros, 2017: A new cladocora caespitosa population with unique ecological traits. *Mediterranean Marine Science*, **18(1)**, 38-42, doi:10.12681/mms.1955.

Kharin, V. et al., 2018: Risks from climate extremes change differently from 1.5°C to 2.0°C depending on rarity. *Earth's Future*, doi:10.1002/2018EF000813.

Khouakhi, A. and G. Villarini, 2017: Attribution of annual maximum sea levels to tropical cyclones at the global scale. *International Journal of Climatology*, **37(1)**, 540-547, doi:10.1002/joc.4704.

Khouakhi, A., G. Villarini, and G.A. Vecchi, 2017: Contribution of Tropical Cyclones to Rainfall at the Global Scale. *Journal of Climate*, **30(1)**, 359-372, doi:10.1175/JCLI-D-16-0298.1.

Kim, H.–Y., J. Ko, S. Kang, and J. Tenhunen, 2013: Impacts of climate change on paddy rice yield in a temperate climate. *Global Change Biology*, **19(2)**, 548-562, doi:10.1111/gcb.12047.

Kim, Y. et al., 2017: A perspective on climate-resilient development and national adaptation planning based on USAID's experience. *Climate and Development*, **9(2)**, 141-151, doi:10.1080/17565529.2015.1124037.

King, A.D., D.J. Karoly, and B.J. Henley, 2017: Australian climate extremes at 1.5 °C and 2 °C of global warming. *Nature Climate Change*, **7(6)**, 412-416, doi:10.1038/nclimate3296.

King, A.D., M.G. Donat, S.C. Lewis, B.J. Henley, and D. M., 2018: Reduced Heat Exposure by Limiting Global Warming to 1.5°C. *Nature Climate Change*.

Kinoshita, Y., M. Tanoue, S. Watanabe, and Y. Hirabayashi, 2018: Quantifying the effect of autonomous adaptation to global river flood projections: Application to future flood risk assessments. *Environmental Research Letters*, **13(1)**, 014006, doi:10.1088/1748-9326/aa9401.

Kipling, R.P. et al., 2016: Modeling European ruminant production systems: Facing the challenges of climate change. *Agricultural Systems*, **147(Supplement C)**, 24-37, doi:https://doi.org/10.1016/j.agsy.2016.05.007.

Kirtman, B. et al., 2013: Near-term Climate Change: Projections and Predictability. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 953-1028.

Kirwan, M. and P. Megonigal, 2013: Tidal wetland stability in the face of human impacts and sea-level rise. *Nature*, **504**, 53-60.

Kittinger, J.N., 2013: Human Dimensions of Small-Scale and Traditional Fisheries in the Asia-Pacific Region. *Pacific Science*, **67(3)**, 315-325, doi:10.2984/67.3.1.

Kittinger, J.N. et al., 2013: Emerging frontiers in social-ecological systems research for sustainability of small-scale fisheries. *Current Opinion in Environmental Sustainability*, **5(3-4)**, 352-357, doi:10.1016/j.cosust.2013.06.008.

Kjellstrom, T., B. Lemke, and M. Otto, 2013: Mapping Occupational Heat Exposure and Effects in South-East Asia: Ongoing Time Trends 1980-2011 and Future Estimates to 2050. *Industrial Health*, **51(1)**, 56-67, doi:10.2486/indhealth.2012-0174.

Kjellstrom, T., C. Freyberg, B. Lemke, M. Otto, and D. Briggs, 2017: Estimating population heat exposure and impacts on working people in conjunction with climate change. *International Journal of Biometeorology*, doi:10.1007/s00484-017-1407-0.

Kline, D.I. et al., 2012: A short-term in situ CO2 enrichment experiment on Heron Island (GBR). *Scientific Reports*, **2**, 413, doi:10.1038/srep00413.

Kline, K.L. et al., 2017: Reconciling food security and bioenergy: priorities for action. *GCB Bioenergy*, **9(3)**, 557-576, doi:10.1111/gcbb.12366.

Kling, H., P. Stanzel, and M. Preishuber, 2014: Impact modelling of water resources development and climate scenarios on Zambezi River discharge. *Journal of Hydrology: Regional Studies*, **1**, 17-43, doi:https://doi.org/10.1016/j.ejrh.2014.05.002.

Kloster, S. et al., 2009: A GCM study of future climate response to aerosol pollution reductions. *Climate Dynamics*, **34(7-8)**, 1177-1194, doi:10.1007/s00382-009-0573-0.

Klotzbach, P., 2006: Trends in global tropical cyclone activity over the past twenty years (1986-2005). *Geophysical Research Letters*, **33(10)**, doi:10.1029/2006GL025881.

Klotzbach, P.J. and C.W. Landsea, 2015: Extremely Intense Hurricanes: Revisiting Webster et al. (2005) after 10 Years. *Journal of Climate*, **28(19)**, 7621-7629, doi:10.1175/JCLI-D-15-0188.1.

Klutse, N.A.B. et al., 2018: Potential Impact of 1.5oC and 2oC global warming on extreme rainfall over West Africa. *Environmental Research Letters*.

Knapp, J.R., G.L. Laur, P.A. Vadas, W.P. Weiss, and J.M. Tricarico, 2014: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *Journal of Dairy Science*, **97(6)**, 3231-3261, doi:10.3168/jds.2013-7234.

Knutson, T.R. et al., 2010: Tropical cyclones and climate change. *Nature Geoscience*, **3(3)**, 157-163, doi:10.1038/ngeo779.

Knutson, T.R. et al., 2013: Dynamical Downscaling Projections of Twenty-First-Century Atlantic Hurricane Activity: CMIP3 and CMIP5 Model-Based Scenarios. *Journal of Climate*, **26(17)**, 6591-6617, doi:10.1175/JCLI-D-12-00539.1.

Knutson, T.R. et al., 2015: Global Projections of Intense Tropical Cyclone Activity for the Late Twenty-First Century from Dynamical Downscaling of CMIP5/RCP4.5 Scenarios. *Journal of Climate*, **28(18)**, 7203-7224, doi:10.1175/JCLI-D-15-0129.1.

Knutti, R. and J. Sedláček, 2012: Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, **3(4)**, 369-373, doi:10.1038/nclimate1716.

Kopp, R. et al., 2016: Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences*, **113(11)**, 1434-1441.

Kopp, R.E., F.J. Simons, J.X. Mitrovica, A.C. Maloof, and M. Oppenheimer, 2013: A probabilistic assessment of sea level variations within the last interglacial stage. *Geophysical Journal International*, **193(2)**, 711-716, doi:10.1093/gji/ggt029.

Kopp, R.E. et al., 2014: Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, **2(8)**, 383-406, doi:10.1002/2014EF000239.

Kossin, J.P. et al., 2013: Trend Analysis with a New Global Record of Tropical Cyclone Intensity. *Journal of Climate*, **26(24)**, 9960-9976, doi:10.1175/JCLI-D-13-00262.1.

Koutroulis, A.G., I.K. Tsanis, I.N. Daliakopoulos, and D. Jacob, 2013: Impact of climate change on water resources status: A case study for Crete Island, Greece. *Journal of Hydrology*, **479**, 146-158, doi:10.1016/j.jhydrol.2012.11.055.

Koven, C.D. et al., 2015: Controls on terrestrial carbon feedbacks by productivity versus turnover in the CMIP5 Earth System Models. *Biogeosciences*, **12(17)**, 5211-5228, doi:10.5194/bg-12-5211-2015.

Krause, A. et al., 2017: Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. *Biogeosciences Discussions*, 1-42, doi:10.5194/bg-2017-160.

Kreidenweis, U. et al., 2016: Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environmental Research Letters*, **11(8)**, 85001.

Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014: Getting from here to there -- energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, **123(3)**, 369-382, doi:10.1007/s10584-013-0947-5.

Krey, V. et al., 2012: Urban and rural energy use and carbon dioxide emissions in Asia. *Energy Economics*, **34**, S272-S283, doi:10.1016/j.eneco.2012.04.013.

Kriegler, E., J.W. Hall, H. Held, R. Dawson, and H.J. Schellnhuber, 2009: Imprecise probability assessment of tipping points in the climate system. *Proceedings of the National Academy of Sciences*, **106(13)**, 5041-5046, doi:10.1073/pnas.0809117106.

Kriegler, E. et al., 2017: Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, **42(Supplement C)**, 297-315, doi:https://doi.org/10.1016/j.gloenvcha.2016.05.015.

Kroeker, K.J. et al., 2013: Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. *Global Change Biology*, **19(6)**, 1884-1896, doi:10.1111/gcb.12179.

Kroon, F.J., P. Thorburn, B. Schaffelke, and S. Whitten, 2016: Towards protecting the Great Barrier Reef from land-based pollution. *Global Change Biology*, **22(6)**, 1985-2002, doi:10.1111/gcb.13262.

Krumhansl, K.A. et al., 2016: Global patterns of kelp forest change over the past half-century. *Proceedings of the National Academy of Sciences*, **113(48)**, 13785-13790, doi:10.1073/pnas.1606102113.

Kumar, L. and S. Taylor, 2015: Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change*, **5**, 992, doi:10.1038/nclimate2702.

Kummu, M. et al., 2016: The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports*, **6(1)**, 38495, doi:10.1038/srep38495.

Kusaka, H., A. Suzuki-Parker, T. Aoyagi, S.A. Adachi, and Y. Yamagata, 2016: Assessment of RCM and urban scenarios uncertainties in the climate projections for August in the 2050s in Tokyo. *Climatic Change*, **137(3-4)**, 427-438, doi:10.1007/s10584-016-1693-2.

Lachkar, Z., M. Lévy, and S. Smith, 2018: Intensification and deepening of the Arabian Sea oxygen minimum zone in response to increase in Indian monsoon wind intensity. *Biogeosciences*, **15(1)**, 159-186, doi:10.5194/bg-15-159-2018.

Lacoue-Labarthe, T. et al., 2016: Impacts of ocean acidification in a warming Mediterranean Sea: An overview. *Regional Studies in Marine Science*, **5**, 1-11, doi:10.1016/j.rsma.2015.12.005.

Läderach, P., A. Martinez-Valle, G. Schroth, and N. Castro, 2013: Predicting the future climatic suitability for cocoa farming of the world's leading producer countries, Ghana and Côte d'Ivoire. *Climatic Change*, **119(3)**, 841-854, doi:10.1007/s10584-013-0774-8.

Lal, R., 2014: Soil Carbon Management and Climate Change. In: *Soil Carbon* [Hartemink, A.E. and K. McSweeney (eds.)]. Progress in Soil Science, Springer International Publishing, pp. 339-361.

Lallo, C. et al., 2018: Characterizing Heat Stress on Livestock using the Temperature Humidity Index (THI)

- Prospects for a warmer Caribbean. *Regional Environmental Change* (in press).

Lam, V.W.Y., W.W.L. Cheung, and U.R. Sumaila, 2014: Marine capture fisheries in the Arctic: Winners or losers under climate change and ocean acidification? *Fish and Fisheries***, 17**, 335-357, doi:10.1111/faf.12106.

Lam, V.W.Y., W.W.L. Cheung, W. Swartz, and U.R. Sumaila, 2012: Climate change impacts on fisheries in West Africa: implications for economic, food and nutritional security. *African Journal of Marine Science***, 34(1)**, 103-117, doi:10.2989/1814232X.2012.673294.

Lam, V.W.Y., W.W.L. Cheung, G. Reygondeau, and U.R. Sumaila, 2016: Projected change in global fisheries revenues under climate change. *Scientific Reports***, 6(1)**, 32607, doi:10.1038/srep32607.

Lana, M.A. et al., 2017: Yield stability and lower susceptibility to abiotic stresses of improved open-pollinated and hybrid maize cultivars. *Agronomy for Sustainable Development***, 37(4)**, 30, doi:10.1007/s13593-017-0442-x.

Landsea, C.W., B.A. Harper, K. Hoarau, and J.A. Knaff, 2006: Can We Detect Trends in Extreme Tropical Cyclones? *Science***, 313(5786)**, 452 LP - 454.

Larsen, J.N. et al., 2014: Polar regions. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1567-1612.

Lawrence, P.J. et al., 2012: Simulating the biogeochemical and biogeophysical impacts of transient land cover change and wood harvest in the Community Climate System Model (CCSM4) from 1850 to 2100. *Journal of Climate***, 25(9)**, 3071-3095, doi:10.1175/JCLI-D-11-00256.1.

Le Cozannet, G., M. Garcin, M. Yates, D. Idier, and B. Meyssignac, 2014: Approaches to evaluate the recent impacts of sea-level rise on shoreline changes. *Earth-Science Reviews***, 138**, 47-60, doi:10.1016/j.earscirev.2014.08.005.

Le Dang, H., E. Li, J. Bruwer, and I. Nuberg, 2014: Farmers' perceptions of climate variability and barriers to adaptation: lessons learned from an exploratory study in Vietnam. *Mitigation and adaptation strategies for global change***, 19(5)**, 531-548.

Leadley, P. et al., 2016: *Relationships between the Aichi Targets and land-based climate mitigation*. Convention on Biological Diversity (CBD), 26 pp.

Lebel, L., C.T. Hoanh, C. Krittasudthacheewa, and R. Daniel, 2014: *Climate risks, regional integration and sustainability in the Mekong region*. Strategic Information and Research Development Centre and SUMERNET Stockholm Environment Institute - Asia, Selangor, Malaysia and Bangkok, Thailand, 417 pp.

Lee, J., 2016: *Valuation of Ocean Acidification Effects on Shellfish Fisheries and Aquaculture*. DP 132, Centre for Financial and Management Studies (CeFiMS), School of Oriental and African Studies (SOAS), University of London, London, UK, 14 pp.

Lee, J.Y., S. Hyun Lee, S.–C. Hong, and H. Kim, 2017: Projecting future summer mortality due to ambient ozone concentration and temperature changes. *Atmospheric Environment***, 156**, 88-94.

Lee, M.A., A.P. Davis, M.G.G. Chagunda, and P. Manning, 2017: Forage quality declines with rising temperatures, with implications for livestock production and methane emissions. *Biogeosciences***, 14(6)**, 1403-1417, doi:10.5194/bg-14-1403-2017.

Lee, S.–M. and S.–K. Min, 2018: Heat Stress Changes over East Asia under 1.5° and 2.0°C Global Warming Targets. *Journal of Climate***, 31(7)**, 2819-2831, doi:10.1175/JCLI-D-17-0449.1.

Lehner, F. et al., 2017: Projected drought risk in 1.5°C and 2°C warmer climates. *Geophysical Research Letters***, 44(14)**, 7419-7428, doi:10.1002/2017GL074117.

Lehodey, P., I. Senina, S. Nicol, and J. Hampton, 2015: Modelling the impact of climate change on South Pacific albacore tuna. *Deep Sea Research Part II: Topical Studies in Oceanography***, 113**, 246-259, doi:10.1016/j.dsr2.2014.10.028.

Lemasson, A.J., S. Fletcher, J.M. Hall-Spencer, and A.M. Knights, 2017: Linking the biological impacts of ocean acidification on oysters to changes in ecosystem services: A review. *Journal of Experimental Marine Biology and Ecology***, 492**, 49-62, doi:10.1016/j.jembe.2017.01.019.

Lemelin, H., J. Dawson, and E.J. Stewart (eds.), 2012: *Last Chance Tourism: Adapting Tourism Opportunities in a Changing World*. Routledge, Abingdon, Oxon, UK, 238 pp.

Lemoine, D. and C.P. Traeger, 2016: Economics of tipping the climate dominoes. *Nature Climate Change***, 6(5)**, 514-519, doi:10.1038/nclimate2902.

Lenton, T.M., 2012: Arctic Climate Tipping Points. *AMBIO***, 41(1, SI)**, 10-22, doi:10.1007/s13280-011-0221-x.

Lenton, T.M. et al., 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences of the United States of America***, 105(6)**, 1786-93, doi:10.1073/pnas.0705414105.

Lesk, C., P. Rowhani, and N. Ramankutty, 2016: Influence of extreme weather disasters on global crop production. *Nature***, 529(7584)**, 84-87, doi:10.1038/nature16467.

Lesnikowski, A., J. Ford, R. Biesbroek, L. Berrang-Ford, and S.J. Heymann, 2015: National-level progress on adaptation. *Nature Climate Change***, 6**, 261.

Levermann, A. et al., 2013: The multimillennial sea-level commitment of global warming. *Proceedings of the National Academy of Sciences***, 110(34)**, 13745-13750, doi:10.1073/pnas.1219414110.

Levermann, A. et al., 2014: Projecting Antarctic ice discharge using response functions from SeaRISE ice-sheet models. *Earth System Dynamics***, 5(2)**, 271-293, doi:10.5194/esd-5-271-2014.

Levi, T., F. Keesing, K. Oggenfuss, and R.S. Ostfeld, 2015: Accelerated phenology of blacklegged ticks under climate warming. *Philosophical Transactions of the Royal Society of London B: Biological Sciences***, 370(1665)**.

Levin, L.A. and N. Le Bris, 2015: The deep ocean under climate change. *Science***, 350(6262)**, 766-768, doi:10.1126/science.aad0126.

Li, C., D. Notz, S. Tietsche, and J. Marotzke, 2013: The Transient versus the Equilibrium Response of Sea Ice to Global Warming. *Journal of Climate***, 26(15)**, 5624-5636, doi:10.1175/JCLI-D-12-00492.1.

Li, C. et al., 2018: Midlatitude atmospheric circulation responses under 1.5 and 2.0\\,{\\degree}C warming and implications \\hack{\\break}for regional impacts. *Earth System Dynamics***, 9(2)**, 359-382, doi:10.5194/esd-9-359-2018.

Li, S., Q. Wang, and J.A. Chun, 2017: Impact assessment of climate change on rice productivity in the Indochinese Peninsula using a regional-scale crop model. *International Journal of Climatology***, 37**, 1147-1160, doi:10.1002/joc.5072.

Li, S. et al., 2016: Interactive Effects of Seawater Acidification and Elevated Temperature on the Transcriptome and Biomineralization in the Pearl Oyster Pinctada fucata. *Environmental Science and Technology***, 50(3)**, 1157-1165, doi:10.1021/acs.est.5b05107.

Li, T.T. et al., 2015: Heat-related mortality projections for cardiovascular and respiratory disease under the changing climate in Beijing, China. *Scientific Reports***, 5**, doi:10.1038/srep11441.

Li, T.T. et al., 2016: Aging Will Amplify the Heat-related Mortality Risk under a Changing Climate: Projection for the Elderly in Beijing, China. *Scientific Reports***, 6(28161)**, doi:10.1038/srep28161.

Li, Z. and H. Fang, 2016: Impacts of climate change on water erosion: A review. *Earth-Science Reviews***, 163**, 94-117, doi:10.1016/j.earscirev.2016.10.004.

Likhvar, V. et al., 2015: A multi-scale health impact assessment of air pollution over the 21st century. *Science of The Total Environment***, 514(Supplement C)**, 439-449, doi:https://doi.org/10.1016/j.scitotenv.2015.02.002.

Linares, C. et al., 2015: Persistent natural acidification drives major distribution shifts in marine benthic ecosystems. *Proceedings of the Royal Society B: Biological Sciences*, **282(1818)**, 20150587, doi:10.1098/rspb.2015.0587.

Lindsay, R. and A. Schweiger, 2015: Arctic sea ice thickness loss determined using subsurface, aircraft, and satellite observations. *The Cryosphere*, **9(1)**, 269-283, doi:10.5194/tc-9-269-2015.

Ling, F.H., M. Tamura, K. Yasuhara, K. Ajima, and C. Van Trinh, 2015: Reducing flood risks in rural households: survey of perception and adaptation in the Mekong delta. *Climatic change*, **132(2)**, 209-222.

Ling, S.D., C.R. Johnson, K. Ridgway, A.J. Hobday, and M. Haddon, 2009: Climate-driven range extension of a sea urchin: Inferring future trends by analysis of recent population dynamics. *Global Change Biology*, **15(3)**, 719-731, doi:10.1111/j.1365-2486.2008.01734.x.

Lipper, L. et al., 2014: Climate-smart agriculture for food security. *Nature Climate Change*, **4(12)**, 1068-1072, doi:10.1038/nclimate2437.

Liu, J. et al., 2017: Water scarcity assessments in the past, present, and future. *Earth's Future*, **5(6)**, 545-559, doi:10.1002/2016EF000518.

Liu, L., H. Xu, Y. Wang, and T. Jiang, 2017: Impacts of 1.5 and 2 °C global warming on water availability and extreme hydrological events in Yiluo and Beijiang River catchments in China. *Climatic Change*, **145**, 145-158, doi:10.1007/s10584-017-2072-3.

Liu, W. et al., 2018: Global drought and severe drought-affected populations in 1.5 and 2 °C warmer worlds. *Earth System Dynamics*, **9(1)**, 267-283, doi:10.5194/esd-9-267-2018.

Lluch-Cota, S.E. et al., 2014: Cross-chapter box on uncertain trends in major upwelling ecosystems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E. Kissel, A. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 149-151.

Loarie, S.R. et al., 2009: The velocity of climate change. *Nature*, **462**, 1052.

Lobell, D.B., G. Bala, and P.B. Duffy, 2006: Biogeophysical impacts of cropland management changes on climate. *Geophysical Research Letters*, **33(6)**, L06708, doi:10.1029/2005GL025492.

Lobell, D.B., W. Schlenker, and J. Costa-Roberts, 2011: Climate Trends and Global Crop Production Since 1980. *Science*, **333(6042)**, 616-620, doi:10.1126/science.1204531.

Lobell, D.B. et al., 2014: Greater Sensitivity to Drought Accompanies Maize Yield Increase in the U.S. Midwest. *Science*, **344(6183)**, 516-519, doi:10.1126/science.1251423.

Long, J., C. Giri, J. Primavera, and M. Trivedi, 2016: Damage and recovery assessment of the Philippines' mangroves following Super Typhoon Haiyan. *Marine Pollution Bulletin*, **109(2)**, 734-743, doi:10.1016/j.marpolbul.2016.06.080.

LoPresti, A. et al., 2015: Rate and velocity of climate change caused by cumulative carbon emissions. *Environmental Research Letters*, **10(9)**, 95001.

Lovelock, C.E., I.C. Feller, R. Reef, S. Hickey, and M.C. Ball, 2017: Mangrove dieback during fluctuating sea levels. *Scientific Reports*, **7(1)**, 1680, doi:10.1038/s41598-017-01927-6.

Lovelock, C.E. et al., 2015: The vulnerability of Indo-Pacific mangrove forests to sea-level rise. *Nature*, **526(7574)**, 559-563, doi:10.1038/nature15538.

Lovenduski, N.S. and G.B. Bonan, 2017: Reducing uncertainty in projections of terrestrial carbon uptake. *Environmental Research Letters*, **12(4)**, 44020.

Lu, X.X. et al., 2013: Sediment loads response to climate change: A preliminary study of eight large Chinese rivers. *International Journal of Sediment Research*, **28(1)**, 1-14, doi:10.1016/S1001-6279(13)60013-X.

Lucht, W., S. Schaphoff, T. Erbrecht, U. Heyder, and W. Cramer, 2006: Terrestrial vegetation redistribution and carbon balance under climate change. *Carbon Balance and Management*, **1(1)**, 6, doi:10.1186/1750-0680-1-6.

Luo, K., F. Tao, J.P. Moiwo, D. Xiao, and J. Zhang, 2016: Attribution of hydrological change in Heihe River Basin to climate and land use change in the past three decades. *Scientific Reports*, **6(1)**, 33704, doi:10.1038/srep33704.

Luyssaert, S. et al., 2014: Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nature Climate Change*, **4(5)**, 1-5, doi:10.1038/nclimate2196.

Lyra, A. et al., 2017: Projections of climate change impacts on central America tropical rainforest. *Climatic Change*, **141(1)**, 93-105, doi:10.1007/s10584-016-1790-2.

Macel, M., T. Dostálek, S. Esch, and A. Bucharová, 2017: Evolutionary responses to climate change in a range expanding plant. *Oecologia*, **184(2)**, 543-554, doi:10.1007/s00442-017-3864-x.

Mackenzie, C.L. et al., 2014: Ocean warming, more than acidification, reduces shell strength in a commercial shellfish species during food limitation. *PLOS ONE*, **9(1)**, doi:10.1371/journal.pone.0086764.

Magrin, G.O. et al., 2014: Central and South America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1499-1566.

Mahlstein, I. and R. Knutti, 2012: September Arctic sea ice predicted to disappear near 2°C global warming above present. *Journal of Geophysical Research - Atmospheres*, **117(D6)**, doi:10.1029/2011JD016709.

Mahlstein, I., R. Knutti, S. Solomon, and R.W. Portmann, 2011: Early onset of significant local warming in low latitude countries. *Environmental Research Letters*, **6(3)**, 034009, doi:10.1088/1748-9326/6/3/034009.

Mahowald, N.M., D.S. Ward, S.C. Doney, P.G. Hess, and J.T. Randerson, 2017a: Are the impacts of land use on warming underestimated in climate policy? *Environmental Research Letters*, **12(9)**, 94016.

Mahowald, N.M. et al., 2017b: Aerosol Deposition Impacts on Land and Ocean Carbon Cycles. *Current Climate Change Reports*, **3(1)**, 16-31, doi:10.1007/s40641-017-0056-z.

Maksym, T., S.E. Stammerjohn, S. Ackley, and R. Massom, 2011: Antarctic Sea ice - A polar opposite? *Oceanography*, **24(3)**, 162-173.

Mallakpour, I. and G. Villarini, 2015: The changing nature of flooding across the central United States. *Nature Climate Change*, **5(3)**, 250-254, doi:10.1038/nclimate2516.

Marcinkowski, P. et al., 2017: Effect of climate change on hydrology, sediment and nutrient losses in two lowland catchments in Poland. *Water*, **9(3)**, doi:10.3390/w9030156.

Marcott, S.A., J.D. Shakun, P.U. Clark, and A.C. Mix, 2013: A Reconstruction of Regional and Global Temperature for the Past 11,300 Years. *Science*, **339(6124)**, 1198-1201, doi:10.1126/science.1228026.

Markham, A., E. Osipova, K. Lafrenz Samuels, and A. Caldas, 2016: *World Heritage and Tourism in a Changing Climate*. United Nations Environment Programme (UNEP), Nairobi, Kenya; the United Nations Educational, Scientific and Cultural Organization (UNESCO), and the Union of Concerned Scientists, 108 pp.

Marszelewski, W. and B. Pius, 2016: Long-term changes in temperature of river waters in the transitional zone of the temperate climate: a case study of Polish rivers. *Hydrological Sciences Journal*, **61(8)**, 1430-1442, doi:10.1080/02626667.2015.1040800.

Martínez, M.L., G. Mendoza-González, R. Silva-Casarín, and E. Mendoza-Baldwin, 2014: Land use changes and sea level rise may induce a "coastal squeeze" on the coasts of Veracruz, Mexico. *Global Environmental Change*, **29(Supplement C)**, 180-188, doi:https://doi.org/10.1016/j.gloenvcha.2014.09.009.

Martinez-Baron, D., G. Orjuela, G. Renzoni, A.M. Loboguerrero Rodríguez, and S.D. Prager, 2018: Small-scale farmers in a 1.5°C future: The importance of local social dynamics as an enabling factor for implementation and scaling of climate-smart agriculture. *Current Opinion in Environmental Sustainability*, **31**, 112-119, doi:10.1016/j.cosust.2018.02.013.

Martius, O., S. Pfahl, and C. Chevalier, 2016: A global quantification of compound precipitation and wind extremes. *Geophysical Research Letters*, **43(14)**, 7709-7717, doi:10.1002/2016GL070017.

Marx, A. et al., 2018: Climate change alters low flows in Europe under a 1.5, 2, and 3 degree global warming. *Hydrology and Earth System Sciences Discussions*, 1-24, doi:10.5194/hess-2017-485.

Marzeion, B. and A. Levermann, 2014: Loss of cultural world heritage and currently inhabited places to sea-level rise. *Environmental Research Letters*, **9(3)**, 34001.

Marzeion, B., G. Kaser, F. Maussion, and N. Champollion, 2018: Limited influence of climate change mitigation on short-term glacier mass loss. *Nature Climate Change*, **8**, 305-308, doi:doi:10.1038/s41558-018-0093-1.

Masike, S. and P. Urich, 2008: Vulnerability of traditional beef sector to drought and the challenges of climate change: The case of Kgatleng District, Botswana. *Journal of Geography and Regional Planning*, **1(1)**, 12-18.

Masson-Delmotte, V. et al., 2013: Information from Paleoclimate Archives. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* []. pp. 383-464.

Mastrandrea, M.D. et al., 2010: *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties.*. IPCC.

Mastrorillo, M. et al., 2016: The influence of climate variability on internal migration flows in South Africa. *Global Environmental Change*, **39**, 155-169, doi:10.1016/J.GLOENVCHA.2016.04.014.

Matear, R.J., M.A. Chamberlain, C. Sun, and M. Feng, 2015: Climate change projection for the western tropical Pacific Ocean using a high-resolution ocean model: Implications for tuna fisheries. *Deep Sea Research Part II: Topical Studies in Oceanography*, **113**, 22-46, doi:10.1016/j.dsr2.2014.07.003.

Mathbout, S., J.A. Lopez-bustins, J. Martin-vide, and F.S. Rodrigo, 2017: Spatial and temporal analysis of drought variability at several time scales in Syria during 1961-2012. *Atmospheric Research*, 1-39, doi:10.1016/J.ATMOSRES.2017.09.016.

Matthews, D. and K. Caldeira, 2008: Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, **35(4)**, doi:10.1029/2007GL032388.

Matthews, T.K.R., R.L. Wilby, and C. Murphy, 2017: Communicating the deadly consequences of global warming for human heat stress. *Proceedings of the National Academy of Sciences of the United States of America*, **114(15)**, 3861-3866, doi:10.1073/pnas.1617526114.

Maule, C.F., T. Mendlik, and O.B. Christensen, 2017: The effect of the pathway to a two degrees warmer world on the regional temperature change of Europe. *Climate Services*, **7**, 3-11, doi:10.1016/j.cliser.2016.07.002.

Maúre, G. et al., 2018: The southern African climate under 1.5° and 2°C of global warming as simulated by CORDEX models. *Environmental Research Letters*.

Maynard, J. et al., 2015: Projections of climate conditions that increase coral disease susceptibility and pathogen abundance and virulence. *Nature Climate Change***, 5**, 688, doi:10.1038/nclimate2625.

Mba, W.P. et al., 2018: Consequences of 1.5°C and 2°C global warming levels for temperature and precipitation changes over Central Africa. *Environmental Research Letters*, doi:10.1080/00071668.2012.729130.

McCarthy, M.P., M.J. Best, and R.A. Betts, 2010: Climate change in cities due to global warming and urban effects. *Geophysical Research Letters***, 37(9)**, n/a-n/a, doi:10.1029/2010GL042845.

McClanahan, T.R., E.H. Allison, and J.E. Cinner, 2015: Managing fisheries for human and food security. *Fish and Fisheries***, 16(1)**, 78-103, doi:10.1111/faf.12045.

McClanahan, T.R., J.C. Castilla, A.T. White, and O. Defeo, 2009: Healing small-scale fisheries by facilitating complex socio-ecological systems. *Reviews in Fish Biology and Fisheries***, 19(1)**, 33-47, doi:10.1007/s11160-008-9088-8.

McFarland, J. et al., 2015: Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. *Climatic Change***, 131(1)**, 111-125, doi:10.1007/s10584-015-1380-8.

McGranahan, G., D. Balk, and B. Anderson, 2007: The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization***, 19(1)**, 17-37, doi:10.1177/0956247807076960.

McGrath, J.M. and D.B. Lobell, 2013: Regional disparities in the CO2 fertilization effect and implications for crop yields. *Environmental Research Letters***, 8(1)**, 14054.

McLean, R. and P. Kench, 2015: Destruction or persistence of coral atoll islands in the face of 20th and 21st century sea-level rise? *Wiley Interdisciplinary Reviews: Climate Change***, 6(5)**, 445-463, doi:10.1002/wcc.350.

McNamara, K.E. and H.J. Des Combes, 2015: Planning for Community Relocations Due to Climate Change in Fiji. *International Journal of Disaster Risk Science***, 6(3)**, 315-319, doi:10.1007/s13753-015-0065-2.

Meehl, G.A. et al., 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 747-846.

Mehran, A., O. Mazdiyasni, and A. Aghakouchak, 2015: A hybrid framework for assessing socioeconomic drought: Linking climate variability, local resilience, and demand. *Journal of Geophysical Research-Atmospheres***, 120(15)**, 7520-7533, doi:10.1002/2015jd023147.

Mehran, A. et al., 2017: Compounding Impacts of Human-Induced Water Stress and Climate Change on Water Availability. *Scientific Reports***, 7(1)**, 1-9, doi:10.1038/s41598-017-06765-0.

Meier, K.J.S., L. Beaufort, S. Heussner, and P. Ziveri, 2014: The role of ocean acidification in Emiliania huxleyi coccolith thinning in the Mediterranean Sea. *Biogeosciences***, 11(10)**, 2857-2869, doi:10.5194/bg-11-2857-2014.

Meier, W.N. et al., 2014: Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity. *Reviews of Geophysics***, 52(3)**, 185-217, doi:10.1002/2013RG000431.

Meinshausen, M., S.C.B. Raper, and T.M.L. Wigley, 2011: Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. *Atmospheric Chemistry and Physics***, 11(4)**, 1417-1456, doi:10.5194/acp-11-1417-2011.

Melia, N., K. Haines, and E. Hawkins, 2016: Sea ice decline and 21st century trans-Arctic shipping routes. *Geophysical Research Letters***, 43(18)**, 9720-9728, doi:10.1002/2016GL069315.

Mengel, M., A. Nauels, J. Rogelj, and C.F. Schleussner, 2018: Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action. *Nature Communications*, **9(1)**, 1-10, doi:10.1038/s41467-018-02985-8.

Mengel, M. et al., 2016: Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences*, **113(10)**, doi:10.1073/pnas.1500515113.

Millar, R.J. et al., 2017: Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nature Geoscience*, doi:10.1038/ngeo3031.

Mills, M. et al., 2016: Reconciling Development and Conservation under Coastal Squeeze from Rising Sea Level. *Conservation Letters*, **9(5)**, 361-368, doi:10.1111/conl.12213.

Minasny, B. et al., 2017: Soil carbon 4 per mille. *Geoderma*, **292**, 59-86, doi:10.1016/j.geoderma.2017.01.002.

Minx, J.C. et al., 2017: The fast-growing dependence on negative emissions.

Minx, J.C. et al., 2018: Negative emissions: Part 1 - research landscape and synthesis. *Environmental Research Letters* (in press).

Mitchell, D., 2016: Human influences on heat-related health indicators during the 2015 Egyptian heat wave. *Bulletin of the American Meteorological Society*, **97(12)**, S70-S74, doi:10.1175/BAMS-D-16-0132.1.

Mitchell, D., 2018: Extreme heat-related mortality avoided under Paris Agreement goals. *Nature Climate Change* (in press).

Mitchell, D. et al., 2016: Attributing human mortality during extreme heat waves to anthropogenic climate change. *Environmental Research Letters*, **11(7)**, 074006, doi:10.1088/1748-9326/11/7/074006.

Mitchell, D. et al., 2017: Half a degree additional warming, prognosis and projected impacts (HAPPI): background and experimental design. *Geoscientific Model Development*, **10**, 571-583, doi:10.5194/gmd-10-571-2017.

Mitchell, D. et al., 2018: The myriad challenges of the Paris Agreement. *Philosophical Transactions A*, **376**, 1-5.

Mohammed, K. et al., 2017: Extreme flows and water availability of the Brahmaputra River under 1.5 and 2 °C global warming scenarios. *Climatic Change*, **145(1-2)**, 159-175, doi:10.1007/s10584-017-2073-2.

Mohapatra, M., A.K. Srivastava, S. Balachandran, and B. Geetha, 2017: Inter-annual Variation and Trends in Tropical Cyclones and Monsoon Depressions Over the North Indian Ocean. *Observed Climate Variability and Change over the Indian Region*, 89-106, doi:10.1007/978-981-10-2531-0_6.

Monioudi, I. et al., 2018: Climate change impacts on critical international transportation assets of Caribbean small island developing states: The case of Jamaica and Saint Lucia. *Regional Environmental Change* (in press), doi:10.1007/s10113-018-1360-4.

Montroull, N.B., R.I. Saurral, and I.A. Camilloni, 2018: Hydrological impacts in La Plata basin under 1.5, 2 and 3 °C global warming above the pre-industrial level. *International Journal of Climatology*, doi:10.1002/joc.5505.

Moore, F.C. and D.B. Lobell, 2015: The fingerprint of climate trends on European crop yields. *Proceedings of the National Academy of Sciences*, **112(9)**, 2670-2675, doi:10.1073/pnas.1409606112.

Mora, C. et al., 2017: Global risk of deadly heat. *Nature Climate Change*, **7(June)**, doi:10.1038/nclimate3322.

Moriondo, M. et al., 2013a: Projected shifts of wine regions in response to climate change. *Climatic Change*, **119(3-4)**, 825-839, doi:10.1007/s10584-013-0739-y.

Moriondo, M. et al., 2013b: Olive trees as bio-indicators of climate evolution in the Mediterranean Basin. *Global Ecology and Biogeography*, **22(7)**, 818-833, doi:10.1111/geb.12061.

Moritz, M.A. et al., 2012: Climate change and disruptions to global fire activity. *Ecosphere*, **3(6)**, art49, doi:10.1890/ES11-00345.1.

Mortensen, C.J. et al., 2009: Embryo recovery from exercised mares. *Animal Reproduction Science*, **110(3)**, 237-244, doi:10.1016/j.anireprosci.2008.01.015.

Mortola, J. and P. Frappell, 2000: Ventilatory Responses to Changes in Temperature in Mammals and Other Vertebrates. *Annual review of physiology*, **62**, 847-874.

Mouginot, J., E. Rignot, and B. Scheuchl, 2014: Sustained increase in ice discharge fromthe Amundsen Sea Embayment, West Antarctica, from1973 to 2013. *Geophysical Research Letters*, **41(5)**, 1576-1584, doi:10.1002/2013GL059069.

Moy, A.D., W.R. Howard, S.G. Bray, and T.W. Trull, 2009: Reduced calcification in modern Southern Ocean planktonic foraminifera. *Nature Geoscience*, **2(4)**, 276-280, doi:10.1038/ngeo460.

Mueller, B. and S.I. Seneviratne, 2012: Hot days induced by precipitation deficits at the global scale. *Proceedings of the National Academy of Sciences*, **109(31)**, 12398-12403, doi:10.1073/pnas.1204330109.

Mueller, B. et al., 2015: Lengthening of the growing season in wheat and maize producing regions. *Weather and Climate Extremes*, **9**, 47-56, doi:10.1016/j.wace.2015.04.001.

Mueller, N.D. et al., 2016: Cooling of US Midwest summer temperature extremes from cropland intensification. *Nature Climate Change*, **6(3)**, 317-322, doi:10.1038/nclimate2825.

Mueller, S.A., J.E. Anderson, and T.J. Wallington, 2011: Impact of biofuel production and other supply and demand factors on food price increases in 2008. *Biomass and Bioenergy*, **35(5)**, 1623-1632, doi:https://doi.org/10.1016/j.biombioe.2011.01.030.

Mueller, V., C. Gray, and K. Kosec, 2014: Heat stress increases long-term human migration in rural Pakistan. *Nature Climate Change*, **4(3)**, 182-185, doi:10.1038/nclimate2103.

Mullan, D., D. Favis-Mortlock, and R. Fealy, 2012: Addressing key limitations associated with modelling soil erosion under the impacts of future climate change. *Agricultural and Forest Meteorology*, **156**, 18-30, doi:10.1016/j.agrformet.2011.12.004.

Muller, C., 2011: Agriculture: Harvesting from uncertainties. *Nature Clim. Change*, **1(5)**, 253-254, doi:10.1038/nclimate1179.

Murakami, H., G.A. Vecchi, and S. Underwood, 2017: Increasing frequency of extremely severe cyclonic storms over the Arabian Sea. *Nature Climate Change*, **7(12)**, 885-889, doi:10.1038/s41558-017-0008-6.

Muratori, M., K. Calvin, M. Wise, P. Kyle, and J. Edmonds, 2016: Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters*, **11(9)**, 095004, doi:10.1088/1748-9326/11/9/095004.

Murphy, G.E.P. and T.N. Romanuk, 2014: A meta-analysis of declines in local species richness from human disturbances. *Ecology and Evolution*, **4(1)**, 91-103, doi:10.1002/ece3.909.

Muthige, M.S. et al., 2018: Projected changes in tropical cyclones over the South West Indian Ocean under different extents of global warming. *Environmental Research Letters* (in press).

Mweya, C.N. et al., 2016: Climate Change Influences Potential Distribution of Infected Aedes aegypti Co-Occurrence with Dengue Epidemics Risk Areas in Tanzania. *PLOS ONE*, **11(9)**, e0162649, doi:10.1371/journal.pone.0162649.

Mycoo, M., 2014: Sustainable tourism, climate change and sea level rise adaptation policies in Barbados. *Natural Resources Forum*, **38(1)**, 47-57, doi:10.1111/1477-8947.12033.

Mycoo, M.A., 2017: Beyond 1.5ºC: vulnerabilities and adaptation strategies for Caribbean Small Island Developing States. *Regional Environmental Change*, doi:10.1007/s10113-017-1248-8.

Myers, S.S. et al., 2014: Increasing CO2 threatens human nutrition. *Nature*, **510(7503)**, 139-142, doi:10.1038/nature13179.

Myers, S.S. et al., 2017: Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. *Annual Review of Public Health*, **38(1)**, 259-277, doi:10.1146/annurev-publhealth-

031816-044356.

Myhre, G. et al., 2013: Anthropogenic and natural radiative forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, pp. 658-740.

Narayan, S. et al., 2016: The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS ONE***, 11(5)**, doi:10.1371/journal.pone.0154735.

Naudts, K. et al., 2016: Europes forest management did not mitigate climate warming. *Science***, 351(6273)**, 597-600, doi:10.1126/science.aad7270.

Nauels, A., M. Meinshausen, M. Mengel, K. Lorbacher, and T.M.L. Wigley, 2017: Synthesizing long-term sea level rise projections - the MAGICC sea level model v2.0. *Geoscientific Model Development***, 10(6)**, 2495-2524, doi:10.5194/gmd-10-2495-2017.

Navarro, J. et al., 2017: Future Response of Temperature and Precipitation to Reduced Aerosol Emissions as Compared with Increased Greenhouse Gas Concentrations. *Journal of Climate***, 30**, 939-954, doi:10.1175/JCLI-D-16-0466.1.

Naylor, R.L. and W.P. Falcon, 2010: Food security in an era of economic volatility. *Population and Development Review***, 36(4)**, 693-723, doi:10.1111/j.1728-4457.2010.00354.x.

NCCARF, 2013: *Terrestrial report card 2013: Climate change impacts and adaptation on Australian biodiversity*. National Climate Change Adaptation Research Facility, 8 pp.

Nelson, G.C. et al., 2010: *Food Securiy, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options*. IFPRI Research Monograph, International Food Policy Research Institute (IFPRI), Washington DC, USA, 140 pp.

Nelson, G.C. et al., 2014a: Climate change effects on agriculture: Economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences***, 111(9)**, 3274-3279, doi:10.1073/pnas.1222465110.

Nelson, G.C. et al., 2014b: Agriculture and climate change in global scenarios: why don't the models agree. *Agricultural Economics***, 45(1)**, 85-101, doi:10.1111/agec.12091.

Nemet, G.F. et al., 2018: Negative emissions - Part 3: Innovation and upscaling. *Environmental Research Letters* (in press).

Neumann, K., P.H. Verburg, E. Stehfest, and C. Müller, 2010: The yield gap of global grain production: A spatial analysis. *Agricultural Systems***, 103(5)**, 316-326, doi:10.1016/j.agsy.2010.02.004.

Newbold, T. et al., 2015: Global effects of land use on local terrestrial biodiversity. *Nature***, 520**, 45.

Niang, I. et al., 2014: Africa. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Nicholls, R.J., T. Reeder, S. Brown, and I.D. Haigh, 2015: The risks of sea-level rise in coastal cities. In: *Climate Change: A risk assessment* [King, D., D. Schrag, Z. Dadi, Q. Ye, and A. Ghosh (eds.)]. Foreing and Commonwealth Office, London, pp. 94-98.

Nicholls, R.J. et al., 2007: Coastal systems and low-lying areas. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* [Parry, M.L., O.F. Canziani, J.P. Palutikof, P.J. Linden, and C.E. Hanson (eds.)]. Cambridge University Press, Cambridge, UK, pp. 315-356.

Nicholls, R.J. et al., 2018: Stabilisation of global temperature at 1.5°C and 2.0°C: Implications for coastal areas. *Philosophical Transactions of the Royal Society A*, doi:10.1098/rsta.2016.0448.

Nicholson, C.T.M., 2014: Climate change and the politics of causal reasoning: the case of climate change and migration. *The Geographical Journal***, 180(2)**, 151-160, doi:10.1111/geoj.12062.

Niederdrenk, A.L. and D. Notz, 2018: Arctic Sea Ice in a 1.5°C Warmer World. *Geophysical Research Letters***, 45(4)**, 1963-1971, doi:10.1002/2017GL076159.

Njeru, J., K. Henning, M.W. Pletz, R. Heller, and H. Neubauer, 2016: Q fever is an old and neglected zoonotic disease in Kenya: a systematic review. *BMC Public Health***, 16**, 297, doi:10.1186/s12889-016-2929-9.

Nobre, C.A. et al., 2016: Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm.. *Proceedings of the National Academy of Sciences of the United States of America***, 113(39)**, 10759-68, doi:10.1073/pnas.1605516113.

Notenbaert, A.M.O., J.A. Cardoso, N. Chirinda, M. Peters, and A. Mottet, 2017: Climate change impacts on livestock and implications for adaptation. In: *Climate impacts on land use, food production and productivity session*. International Center for Tropical Agriculture (CIAT), Rome, Italy.

Notz, D., 2015: How well must climate models agree with observations? *Philosophical Transactions of the Royal Society A - Mathematical, Physical and Engineering Sciences***, 373(2052)**, doi:10.1098/rsta.2014.0164.

Notz, D. and J. Stroeve, 2016: Observed Arctic sea-ice loss directly follows anthropogenic CO 2 emission. *Science***, 354(6313)**, 747-750, doi:10.1126/science.aag2345.

Nunn, P.D., J. Runman, M. Falanruw, and R. Kumar, 2017: Culturally grounded responses to coastal change on islands in the Federated States of Micronesia, northwest Pacific Ocean. *Regional Environmental Change***, 17(4)**, 959-971, doi:10.1007/s10113-016-0950-2.

Nurse, L.A. et al., 2014: Small islands. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1613-1654.

Oberbauer, S.F. et al., 2013: Phenological response of tundra plants to background climate variation tested using the International Tundra Experiment. *Phil Trans R Soc B***, 368**, 20120481, doi:10.1098/rstb.2012.0481.

Obersteiner, M. et al., 2016: Assessing the land resource-food price nexus of the Sustainable Development Goals. *Science Advances***, 2(9)**, doi:10.1126/sciadv.1501499.

Obersteiner, M. et al., 2018: How to spend a dwindling greenhouse gas budget. *Nature Climate Change***, 8(1)**, 7-10, doi:10.1038/s41558-017-0045-1.

Ogden, N.H., R. Milka, C. Caminade, and P. Gachon, 2014a: Recent and projected future climatic suitability of North America for the Asian tiger mosquito Aedes albopictus. *Parasites & Vectors***, 7(1)**, 532, doi:10.1186/s13071-014-0532-4.

Ogden, N.H. et al., 2014b: Estimated effects of projected climate change on the basic reproductive number of the Lyme disease vector Ixodes scapularis. *Environmental Health Perspectives***, 122(6)**, 631-638, doi:10.1289/ehp.1307799.

Okada, M., T. Iizumi, Y. Hayashi, and M. Yokozawa, 2011: Modeling the multiple effects of temperature and radiation on rice quality. *Environmental Research Letters***, 6(3)**, 034031, doi:10.1088/1748-9326/6/3/034031.

O'Leary, J.K. et al., 2017: The Resilience of Marine Ecosystems to Climatic Disturbances. *BioScience***, 67(3)**, 208-220, doi:10.1093/biosci/biw161.

Oleson, K.W., G.B. Bonan, and J. Feddema, 2010: Effects of white roofs on urban temperature in a global climate model. *Geophysical Research Letters*, **37(3)**, doi:10.1029/2009GL042194.

Oliver, E.C.J. et al., 2018: Longer and more frequent marine heatwaves over the past century. *Nature Communications*, **9(1)**, 1324, doi:10.1038/s41467-018-03732-9.

Olsson, L. et al., 2014: Livelihoods and Poverty. In: *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 793-832.

Omstedt, A., M. Edman, B. Claremar, and A. Rutgersson, 2015: Modelling the contributions to marine acidification from deposited SOx, NOx, and NHx in the Baltic Sea: Past and present situations. *Continental Shelf Research*, **111**, 234-249, doi:10.1016/j.csr.2015.08.024.

O'Neill, B.C. et al., 2017: IPCC Reasons for Concern regarding climate change risks. *Nature Climate Change*, **7**, 28-37, doi:10.1038/nclimate3179.

Ong, E.Z., M. Briffa, T. Moens, and C. Van Colen, 2017: Physiological responses to ocean acidification and warming synergistically reduce condition of the common cockle Cerastoderma edule. *Marine Environmental Research*, **130**, 38-47, doi:10.1016/j.marenvres.2017.07.001.

Oppenheimer, M. et al., 2014: Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1039-1099.

Ordonez, A. et al., 2014: Effects of Ocean Acidification on Population Dynamics and Community Structure of Crustose Coralline Algae. *The Biological Bulletin*, **226(June)**, 255-268.

Orlowsky, B. and S.I. Seneviratne, 2013: Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections. *Hydrology and Earth System Sciences*, **17(5)**, 1765-1781, doi:10.5194/hess-17-1765-2013.

Orr, J.C. et al., 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, **437(7059)**, 681-686, doi:10.1038/nature04095.

Osima, S. et al., 2018: Projected Climate over the Greater Horn of Africa under 1.5 °C and 2°C global warming. *Environmental Research Letters* (in press).

Osorio, J.A., M.J. Wingfield, and J. Roux, 2016: A review of factors associated with decline and death of mangroves, with particular reference to fungal pathogens. *South African Journal of Botany*, **103**, 295-301, doi:10.1016/j.sajb.2014.08.010.

Ourbak, T. and A. Magnan, 2017: The Paris Agreement and climate change negotiations: Small Islands, big players. A commentary. *Regional Environmental Change*.

Paeth, H. et al., 2010: Meteorological characteristics and potential causes of the 2007 flood in sub-Saharan Africa. *International Journal of Climatology*, **31(13)**, 1908-1926, doi:10.1002/joc.2199.

Palazzo, A. et al., 2017: Linking regional stakeholder scenarios and shared socioeconomic pathways: Quantified West African food and climate futures in a global context. *Global Environmental Change*, doi:10.1016/j.gloenvcha.2016.12.002.

Palmer, M.A. et al., 2008: Climate change and the world's river basins: Anticipating management options. *Frontiers in Ecology and the Environment*, **6(2)**, 81-89, doi:10.1890/060148.

Palumbi, S.R., D.J. Barshis, N. Traylor-Knowles, and R.A. Bay, 2014: Mechanisms of reef coral resistance to future climate change. *Science*, **344(6186)**, 895-8, doi:10.1126/science.1251336.

Park, C. et al., 2018: Avoided economic impacts of energy demand changes by 1.5 and 2 °C climate stabilization. *Environmental Research Letters*, **13(4)**, 45010.

Parker, L.M. et al., 2017: Ocean acidification narrows the acute thermal and salinity tolerance of the Sydney rock oyster Saccostrea glomerata. *Marine Pollution Bulletin*, **122(1-2)**, 263-271, doi:10.1016/j.marpolbul.2017.06.052.

Parkes, B., D. Defrance, B. Sultan, P. Ciais, and X. Wang, 2018: Projected changes in crop yield mean and variability over West Africa in a world 1.5 K warmer than the pre-industrial era. *Earth System Dynamics*, **9(1)**, 119-134, doi:10.5194/esd-9-119-2018.

Parmesan, C. and M.E. Hanley, 2015: Plants and climate change: complexities and surprises. *Annals of Botany*, **116(6, SI)**, 849-864, doi:10.1093/aob/mcv169.

Paterson, R.M. and N. Lima, 2010: How will climate change affect mycotoxins in food? *Food Research International*, **43**, 1902-1914.

Patiño, R., D. Dawson, and M.M. VanLandeghem, 2014: Retrospective analysis of associations between water quality and toxic blooms of golden alga (Prymnesium parvum) in Texas reservoirs: Implications for understanding dispersal mechanisms and impacts of climate change. *Harmful Algae*, **33**, 1-11, doi:10.1016/j.hal.2013.12.006.

Pauly, D. and A. Charles, 2015: Counting on small-scale fisheries. *Science*, **347(6219)**, 242-243, doi:10.1126/science.347.6219.242-b.

Paustian, K. et al., 2006: 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Chapter 1. , 1.8.

Pecl, G.T. et al., 2017: Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, **355(6332)**, 9214, doi:10.1126/science.aai9214.

Pendergrass, A.G., F. Lehner, B.M. Sanderson, and Y. Xu, 2015: Does extreme precipitation intensity depend on the emissions scenario? *Geophysical Research Letters*, **42(20)**, 8767-8774, doi:10.1002/2015GL065854.

Pendleton, L. et al., 2016: Coral reefs and people in a high-CO2 world: Where can science make a difference to people? *PLoS ONE*, **11(11)**, 1-21, doi:10.1371/journal.pone.0164699.

Pereira, H.M. et al., 2010: Scenarios for global biodiversity in the 21st century. *Science*, **330(6010)**, 1496-1501, doi:10.1126/science.1196624.

Pérez-Escamilla, R., 2017: Food Security and the 2015-2030 Sustainable Development Goals: From Human to Planetary Health. *Current Developments in Nutrition*, **1(7)**, e000513, doi:10.3945/cdn.117.000513.

Perring, M.P., B.R. Cullen, I.R. Johnson, and M.J. Hovenden, 2010: Modelled effects of rising CO2 concentration and climate change on native perennial grass and sown grass-legume pastures. *Climate Research*, **42(1)**, 65-78, doi:10.3354/cr00863.

Petkova, E.P., R.M. Horton, D.A. Bader, and P.L. Kinney, 2013: Projected Heat-Related Mortality in the U.S. Urban Northeast. *International Journal of Environmental Research and Public Health*, **10(12)**, 6734-6747, doi:10.3390/ijerph10126734.

Petris, F., M. Schwarz, K. Tang, K. Haustein, and M.R. Allen, 2018: Uncertain impacts on economic growth when stabilizing global temperatures at 1.5ºC or 2ºC warming. *Philosophical Transactions A*.

Pierrehumbert, R.T., 2014: Short-Lived Climate Pollution. *Annual Review of Earth and Planetary Sciences*, **42(1)**, 341-379, doi:10.1146/annurev-earth-060313-054843.

Piggott-McKellar, A.E. and K.E. McNamara, 2017: Last chance tourism and the Great Barrier Reef. *Journal of Sustainable Tourism*, **25(3)**, 397-415, doi:10.1080/09669582.2016.1213849.

Piguet, E. and F. Laczko (eds.), 2014: *People on the Move in a Changing Climate: The Regional Impact of Environmental Change on Migration*. Global Migration Issues, Springer Netherlands, Dordrecht, 253 pp.

Piñones, A. and A. Fedorov, 2016: Projected changes of Antarctic krill habitat by the end of the 21st century. *Geophysical Research Letters*, **43(16)**, 8580-8589, doi:10.1002/2016GL069656.

Pinsky, M.L., B. Worm, M.J. Fogarty, J.L. Sarmiento, and S.A. Levin, 2013: Marine Taxa Track Local Climate Velocities. *Science*, **341(6151)**, 1239-1242, doi:10.1126/science.1239352.

Piontek, F. et al., 2014: Multisectoral climate impact hotspots in a warming world. *Proceedings of the National Academy of Sciences*, **111(9)**, 3233-3238, doi:10.1073/pnas.1222471110.

Pistorious, T. and L. Kiff, 2017: *From a biodiversity perspective: risks, trade- offs, and international guidance for Forest Landscape Restoration*. 66 pp.

Pittelkow, C.M. et al., 2014: Productivity limits and potentials of the principles of conservation agriculture. *Nature*, **517(7534)**, 365-367, doi:10.1038/nature13809.

Poloczanska, E.S., O. Hoegh-Guldberg, W. Cheung, H.–O. Pörtner, and M. Burrows, 2014: Cross-chapter box on observed global responses of marine biogeography, abundance, and phenology to climate change. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 123-127.

Poloczanska, E.S. et al., 2013: Global imprint of climate change on marine life. *Nature Climate Change*, **3(10)**, 919-925, doi:10.1038/nclimate1958.

Poloczanska, E.S. et al., 2016: Responses of Marine Organisms to Climate Change across Oceans. *Frontiers in Marine Science*, **3(May)**, 62, doi:10.3389/fmars.2016.00062.

Polyak, L. et al., 2010: History of sea ice in the Arctic. *Quaternary Science Reviews*, **29(15-16)**, 1757-1778, doi:10.1016/j.quascirev.2010.02.010.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42(Supplement C)**, 331-345, doi:https://doi.org/10.1016/j.gloenvcha.2016.10.002.

Porter, J.R. et al., 2014: Food security and food production systems. In: *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros,, D.J. Dokken, K.J. March, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White Field (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

Portmann, F.T., P. Döll, S. Eisner, and M. Flörke, 2013: Impact of climate change on renewable groundwater resources: assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. *Environmental Research Letters*, **8(2)**, 024023, doi:10.1088/1748-9326/8/2/024023.

Pörtner, H.O. et al., 2014: Ocean Systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484.

Potemkina, T.G. and V.L. Potemkin, 2015: Sediment load of the main rivers of Lake Baikal in a changing environment (east Siberia, Russia). *Quaternary International*, **380-381**, 342-349, doi:10.1016/j.quaint.2014.08.029.

Prestele, R. et al., 2016: Hotspots of uncertainty in land-use and land-cover change projections: a global-scale model comparison. *Global Change Biology*, **22(12)**, 3967-3983, doi:10.1111/gcb.13337.

Primavera, J.H. et al., 2016: Preliminary assessment of post-Haiyan mangrove damage and short-term recovery in Eastern Samar, central Philippines. *Marine Pollution Bulletin*, **109(2)**, 744-750, doi:10.1016/j.marpolbul.2016.05.050.

Prober, S.M., D.W. Hilbert, S. Ferrier, M. Dunlop, and D. Gobbett, 2012: Combining community-level spatial modelling and expert knowledge to inform climate adaptation in temperate grassy eucalypt woodlands and related grasslands. *Biodiversity and Conservation*, **21(7)**, 1627-1650, doi:10.1007/s10531-012-0268-4.

Pryor, S.C., R.C. Sullivan, and T. Wright, 2016: Quantifying the Roles of Changing Albedo, Emissivity, and Energy Partitioning in the Impact of Irrigation on Atmospheric Heat Content. *Journal of Applied Meteorology and Climatology*, **55(8)**, 1699-1706, doi:10.1175/JAMC-D-15-0291.1.

Pugh, T.A.M., C. Müller, A. Arneth, V. Haverd, and B. Smith, 2016: Key knowledge and data gaps in modelling the influence of CO2 concentration on the terrestrial carbon sink. *Journal of Plant Physiology*, **203(Supplement C)**, 3-15, doi:https://doi.org/10.1016/j.jplph.2016.05.001.

Qian, B., X. Zhang, K. Chen, Y. Feng, and T. O'Brien, 2010: Observed Long-Term Trends for Agroclimatic Conditions in Canada. *Journal of Applied Meteorology and Climatology*, **49(4)**, 604-618, doi:10.1175/2009JAMC2275.1.

Qian, Y. et al., 2013: A Modeling Study of Irrigation Effects on Surface Fluxes and Land-Air-Cloud Interactions in the Southern Great Plains. *Journal of Hydrometeorology*, **14(3)**, 700-721, doi:10.1175/JHM-D-12-0134.1.

Quataert, E., C. Storlazzi, A. van Rooijen, O. Cheriton, and A. van Dongeren, 2015: The influence of coral reefs and climate change on wave-driven flooding of tropical coastlines. *Geophysical Research Letters*, **42(15)**, 6407-6415, doi:10.1002/2015GL064861.

Raabe, E.A. and R.P. Stumpf, 2016: Expansion of Tidal Marsh in Response to Sea-Level Rise: Gulf Coast of Florida, USA. *Estuaries and Coasts*, **39(1)**, 145-157, doi:10.1007/s12237-015-9974-y.

Rafferty, N.E., 2017: Effects of global change on insect pollinators: multiple drivers lead to novel communities. *Current Opinion in Insect Science*, **23**, 1-6, doi:10.1016/j.cois.2017.06.009.

Rahmstorf, S. et al., 2015a: Corrigendum: Evidence for an exceptional twentieth-century slowdown in Atlantic Ocean overturning. *Nature Climate Change*, **5(10)**, 956-956, doi:10.1038/nclimate2781.

Rahmstorf, S. et al., 2015b: Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change*, **5(5)**, 475-480, doi:10.1038/nclimate2554.

Ramirez-Cabral, N.Y.Z., L. Kumar, and S. Taylor, 2016: Crop niche modeling projects major shifts in common bean growing areas. *Agricultural and Forest Meteorology*, **218-219(Supplement C)**, 102-113, doi:https://doi.org/10.1016/j.agrformet.2015.12.002.

Ranger, N., T. Reeder, and J. Lowe, 2013: Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. *EURO Journal on Decision Processes*, **1(3-4)**, 233-262, doi:10.1007/s40070-013-0014-5.

Rasmussen, D. et al., 2018: Coastal flood implications of 1.5 ◦C, 2.0 ◦C, and 2.5 ◦C temperature stabilization targets in the 21st and 22nd century. *Environmental Research Letters*, **13**, 1-39, doi:https://doi.org/10.1088/1748-9326/aaac87.

Ray, D.K., J.S. Gerber, G.K. MacDonald, and P.C. West, 2015: Climate variation explains a third of global crop yield variability. *Nature Communications*, **6**, 5989.

Reaka-Kudla, M.L., 1997: The Global Biodiversity of Coral Reefs: A comparison with Rain Forests. In: *Biodiversity II: Understanding and Protecting Our Biological Resources* [Reaka-Kudla, M., D.E. Wilson, and E.O. Wilson (eds.)]. Joseph Henry Press, pp. 83-108.

Reasoner, M.A. and W. Tinner, 2009: Holocene Treeline Fluctuations. In: *Encyclopedia of Paleoclimatology and ancient environments*. Springer, New York, NY, USA, pp. 442-446.

Reid, P., S. Stammerjohn, R. Massom, T. Scambos, and J. Lieser, 2015: The record 2013 Southern Hemisphere sea-ice extent maximum. *Annals of Glaciology*, **56(69)**, 99-106, doi:10.3189/2015AoG69A892.

Ren, Z. et al., 2016: Predicting malaria vector distribution under climate change scenarios in China: Challenges for malaria elimination. *Scientific reports*, **6**, 20604, doi:10.1038/srep20604.

Renaud, F.G., T.T.H. Le, C. Lindener, V.T. Guong, and Z. Sebesvari, 2015: Resilience and shifts in agro-ecosystems facing increasing sea-level rise and salinity intrusion in Ben Tre Province, Mekong Delta. *Climatic Change*, **133(1)**, 69-84, doi:10.1007/s10584-014-1113-4.

Renaudeau, D., J.L. Gourdine, and N.R. St-Pierre, 2011: A meta-analysis of the effects of high ambient temperature on growth performance of growing-finishing pigs. *Journal of Animal Science*, **89(7)**, 2220-2230, doi:10.2527/jas.2010-3329.

Revi, A. et al., 2014: Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612.

Reyer, C.P.O. et al., 2017a: Climate change impacts in Latin America and the Caribbean and their implications for development. *Regional Environmental Change*, **17(6)**, 1601-1621, doi:10.1007/s10113-015-0854-6.

Reyer, C.P.O. et al., 2017b: Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests? *Environmental Research Letters*, **12(3)**, 34027.

Reyer, C.P.O. et al., 2017c: Climate change impacts in Central Asia and their implications for development. *Regional Environmental Change*, **17(6)**, 1639-1650, doi:10.1007/s10113-015-0893-z.

Reyer, C.P.O. et al., 2017d: Turn down the heat: regional climate change impacts on development. *Regional Environmental Change*, **17(6)**, 1563-1568, doi:10.1007/s10113-017-1187-4.

Reyes-Nivia, C., G. Diaz-Pulido, and S. Dove, 2014: Relative roles of endolithic algae and carbonate chemistry variability in the skeletal dissolution of crustose coralline algae. *Biogeosciences*, **11(17)**, 4615-4626, doi:10.5194/bg-11-4615-2014.

Reyes-Nivia, C., G. Diaz-Pulido, D. Kline, O.H. Guldberg, and S. Dove, 2013: Ocean acidification and warming scenarios increase microbioerosion of coral skeletons. *Global Change Biology*, **19(6)**, 1919-1929, doi:10.1111/gcb.12158.

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, and D. Chambers, 2013: Observations: Ocean. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, pp. 255-316.

Rhiney, K., 2015: Geographies of Caribbean Vulnerability in a Changing Climate: Issues and Trends. *Geography Compass*, **9(3)**, 97-114, doi:10.1111/gec3.12199.

Ribes, A., F.W. Zwiers, J.–M. Azaïs, and P. Naveau, 2017: A new statistical approach to climate change detection and attribution. *Climate Dynamics*, **48(1)**, 367-386, doi:10.1007/s00382-016-3079-6.

Richardson, M., K. Cowtan, E. Hawkins, and M.B. Stolpe, 2016: Reconciled climate response estimates from climate models and the energy budget of Earth. *Nature Climate Change*, **6**, 931, doi:10.1038/nclimate3066.

Richier, S. et al., 2014: Phytoplankton responses and associated carbon cycling during shipboard carbonate chemistry manipulation experiments conducted around Northwest European shelf seas. *Biogeosciences*, **11(17)**, 4733-4752, doi:10.5194/bg-11-4733-2014.

Ricke, K.L., J.B. Moreno-cruz, J. Schewe, A. Levermann, and K. Caldeira, 2015: Policy thresholds in mitigation. *Nature Geoscience*, **9(1)**, 1-2, doi:10.1038/ngeo2607.

Ridgwell, A. and D.N. Schmidt, 2010: Past constraints on the vulnerability of marine calcifiers to massive carbon dioxide release. *Nature Geoscience*, **3(3)**, 196-200, doi:10.1038/ngeo755.

Ridley, J.K., J.A. Lowe, and H.T. Hewitt, 2012: How reversible is sea ice loss? *The Cryosphere*, **6(1)**, 193-198, doi:10.5194/tc-6-193-2012.

Riebesell, U., J.P.P. Gattuso, T.F.F. Thingstad, and J.J.J. Middelburg, 2013: Arctic ocean acidification: pelagic ecosystem and biogeochemical Dynamics responses during a mesocosm study. *Biogeosciences*, **10(8)**, 5619-5626, doi:10.5194/bg-10-5619-2013.

Rienecker, M.M. et al., 2011: MERRA: NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate*, **24(14)**, 3624-3648, doi:10.1175/JCLI-D-11-00015.1.

Rignot, E., J. Mouginot, M. Morlighem, H. Seroussi, and B. Scheuchl, 2014: Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. *Geophysical Research Lettersl*, **41(10)**, 3502-3509, doi:10.1002/2014GL060140.

Rinkevich, B., 2014: Rebuilding coral reefs: Does active reef restoration lead to sustainable reefs? *Current Opinion in Environmental Sustainability*, **7**, 28-36, doi:10.1016/j.cosust.2013.11.018.

Rinkevich, B., 2015: Climate Change and Active Reef Restoration-Ways of Constructing the "Reefs of Tomorrow". *Journal of Marine Science and Engineering*, **3(1)**, 111-127, doi:10.3390/jmse3010111.

Rippke, U. et al., 2016: Timescales of transformational climate change adaptation in sub-Saharan African agriculture. *Nature Climate Change*, **6(6)**, 605-609, doi:10.1038/nclimate2947.

Risser, M.D. and M.F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters*, n/a--n/a, doi:10.1002/2017GL075888.

Rivetti, I., S. Fraschetti, P. Lionello, E. Zambianchi, and F. Boero, 2014: Global warming and mass mortalities of benthic invertebrates in the Mediterranean Sea. *PLoS ONE*, **9(12)**, doi:10.1371/journal.pone.0115655.

Roberts, A.M.I., C. Tansey, R.J. Smithers, and A.B. Phillimore, 2015: Predicting a change in the order of spring phenology in temperate forests. *Global Change Biology*, **21(7)**, 2603-2611, doi:10.1111/gcb.12896.

Roberts, D., W.R. Howard, D. Moy, J.L. Roberts, and T.W. Trull, 2008: Interannual variability of pteropod shell weights in the high-CO 2 Southern Ocean. *Industrial Research*, 4453-4480.

Roberts, M.J. and W. Schlenker, 2013: Identifying Supply and Demand Elasticities of Agricultural Commodities: Implications for the US Ethanol Mandate. *American Economic Review*, **103(6)**, 2265-2295, doi:10.1257/aer.103.6.2265.

Robinson, A., R. Calov, and A. Ganopolski, 2012: Multistability and critical thresholds of the Greenland ice sheet. *Nature Climate Change*, **2(6)**, 429-432, doi:10.1038/NCLIMATE1449.

Robledo-Abad, C. et al., 2017: Bioenergy production and sustainable development: science base for policymaking remains limited. *GCB Bioenergy*, **9(3)**, 541-556, doi:10.1111/gcbb.12338.

Roderick, M., G. Peter, and F.G. D., 2015: On the assessment of aridity with changes in atmospheric CO2. *Water Resources Research*, **51(7)**, 5450-5463, doi:10.1002/2015WR017031.

Rodrigues, L.C. et al., 2015: Sensitivity of Mediterranean Bivalve Mollusc Aquaculture to Climate Change, Ocean Acidification, and Other Environmental Pressures: Findings from a Producer Survey. *Journal of Shellfish Research*, **34(3)**, 1161-1176, doi:10.2983/035.034.0341.

Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013: Probabilistic cost estimates for climate change mitigation. *Nature*, **493(7430)**, 79-83, doi:10.1038/nature11787.

Rogelj, J. et al., 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change*, **5(6)**, 519-527, doi:10.1038/nclimate2572.

Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change* (in press), doi:doi:10.1038/s41558-018-0091-3.

Romero-Lankao, P. et al., 2014: North America. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1439-1498.

Romine, B., C. Fletcher, M. Barbee, T. R. Anderson, and N. Frazer, 2013: Are beach erosion rates and sea-level rise related in Hawaii? *Global and Planetary Change*, **108**, 149-157.

Rose, G., T. Osborne, H. Greatrex, and T. Wheeler, 2016: Impact of progressive global warming on the global-scale yield of maize and soybean. *Climatic Change*, **134(3)**, 417-428, doi:10.1007/s10584-016-1601-9.

Rosenblum, E. and I. Eisenman, 2016: Faster Arctic Sea Ice Retreat in CMIP5 than in CMIP3 due to Volcanoes. *Journal of Climate*, **29(24)**, 9179-9188, doi:10.1175/JCLI-D-16-0391.1.

Rosenblum, E. and I. Eisenman, 2017: Sea Ice Trends in Climate Models Only Accurate in Runs with Biased Global Warming. *Journal of Climate*, **30(16)**, 6265-6278.

Rosenzweig, C. and W. Solecki, 2014: Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. *Global Environmental Change*, **28**, 395-408, doi:10.1016/j.gloenvcha.2014.05.003.

Rosenzweig, C. and D. Hillel (eds.), 2015: *Handbook of Climate Change and Agroecosystems: The Agricultural Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic Assessments*. ICP Series on Climate Change Impacts, Adaptation, and Mitigation Volume 3, Imperial College Press, London, UK.

Rosenzweig, C. et al., 2013: The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agricultural and Forest Meteorology*, **170**, 166-182, doi:10.1016/j.agrformet.2012.09.011.

Rosenzweig, C. et al., 2014: Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America*, **111(9)**, 3268-73, doi:10.1073/pnas.1222463110.

Rosenzweig, C. et al., 2017: Assessing inter-sectoral climate change risks: the role of ISIMIP. *Environmental Research Letters*, **12(1)**, 10301.

Rosenzweig, C. et al., 2018: Coordinating AgMIP data and models across global and regional scales for 1.5ºC and 2ºC assessments. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, doi:10.1098/rsta.2016.0455.

Ross, A.C. et al., 2015: Sea-level rise and other influences on decadal-scale salinity variability in a coastal plain estuary. *Estuarine, Coastal and Shelf Science*, **157**, 79-92, doi:10.1016/j.ecss.2015.01.022.

Rosselló-Nadal, J., 2014: How to evaluate the effects of climate change on tourism. *Tourism Management*, **42(Supplement C)**, 334-340, doi:https://doi.org/10.1016/j.tourman.2013.11.006.

Roudier, P., B. Sultan, P. Quirion, and A. Berg, 2011: The impact of future climate change on West African crop yields: What does the recent literature say? *Global Environmental Change*, **21(3)**, 1073-1083, doi:10.1016/j.gloenvcha.2011.04.007.

Roudier, P. et al., 2016: Projections of future floods and hydrological droughts in Europe under a +2°C global warming. *Climatic Change*, **135(2)**, 341-355, doi:10.1007/s10584-015-1570-4.

Roy, D.B. et al., 2015: Similarities in butterfly emergence dates among populations suggest local adaptation to climate. *Global Change Biology*, **21(9)**, 3313-3322, doi:10.1111/gcb.12920.

Ruane, A.C. et al., 2018: AgMIP Coordinated Global and Regional Assessments of biophysical and economic implications of +1.5 and +2.0°C global warming on agriculture. *Climate Research* (in press).

Russo, S., A.F. Marchese, J. Sillmann, and G. Immé, 2016: When will unusual heat waves become normal in a warming Africa ? *Environmental Research Letters***, 11(5)**, 1-22, doi:10.1088/1748-9326/11/5/054016.

Sacks, W.J., B.I. Cook, N. Buenning, S. Levis, and J.H. Helkowski, 2009: Effects of global irrigation on the near-surface climate. *Climate Dynamics***, 33(2-3)**, 159-175, doi:10.1007/s00382-008-0445-z.

Saeidi, M., F. Moradi, and M. Abdoli, 2017: Impact of drought stress on yield, photosynthesis rate, and sugar alcohols contents in wheat after anthesis in semiarid region of Iran. *Arid Land Research and Management***, 31(2)**, 1-15, doi:10.1080/15324982.2016.1260073.

Sakalli, A., A. Cescatti, A. Dosio, and M.U. Gücel, 2017: Impacts of 2°C global warming on primary production and soil carbon storage capacity at pan-European level. *Climate Services***, 7**, 64-77, doi:10.1016/j.cliser.2017.03.006.

Salem, G.S.A., S. Kazama, S. Shahid, and N.C. Dey, 2017: Impact of temperature changes on groundwater levels and irrigation costs in a groundwater-dependent agricultural region in Northwest Bangladesh. *Hydrological Research Letters***, 11(1)**, 85-91, doi:10.3178/hrl.11.85.

Salisbury, J., M. Green, C. Hunt, and J. Campbell, 2008: Coastal acidification by rivers: A threat to shellfish? *Eos***, 89(50)**, 513, doi:10.1029/2008EO500001.

Samaniego, L. et al., 2018: Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change***, 8(5)**, 421-426, doi:10.1038/s41558-018-0138-5.

Sanderson, B.M. et al., 2017: Community climate simulations to assess avoided impacts in 1.5ºC and 2 ºC futures. *Earth System Dynamics***, 8(3)**, 827-847, doi:10.5194/esd-8-827-2017.

Sarojini, B.B., P.A. Stott, and E. Black, 2016: Detection and attribution of human influence on regional precipitation. *Nature Climate Change***, 6(7)**, 669-675, doi:10.1038/nclimate2976.

Sasmito, S.D., D. Murdiyarso, D.A. Friess, and S. Kurnianto, 2016: Can mangroves keep pace with contemporary sea level rise? A global data review. *Wetlands Ecology and Management***, 24(2)**, 263-278, doi:10.1007/s11273-015-9466-7.

Saunders, M.I. et al., 2014: Interdependency of tropical marine ecosystems in response to climate change. *Nature Climate Change***, 4(8)**, 724-729, doi:10.1038/NCLIMATE2274.

Scaven, V.L. and N.E. Rafferty, 2013: Physiological effects of climate warming on flowering plants and insect pollinators and potential consequences for their interactions. *Current zoology***, 59(3)**, 418-426.

Schaeffer, M., W. Hare, S. Rahmstorf, and M. Vermeer, 2012: Long-term sea-level rise implied by 1.5 °c and 2 °c warming levels. *Nature Climate Change***, 2(12)**, 867-870, doi:10.1038/nclimate1584.

Schewe, J., A. Levermann, and M. Meinshausen, 2011: Climate change under a scenario near 1.5 degrees C of global warming: monsoon intensification, ocean warming and steric sea level rise. *Earth System Dynamics***, 2(1)**, 25-35, doi:10.5194/esd-2-25-2011.

Schewe, J. et al., 2014: Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences of the United States of America***, 111(9)**, 3245-3250, doi:10.1073/pnas.0709640104.

Schimel, D., B.B. Stephens, and J.B. Fisher, 2015: Effect of increasing CO2 on the terrestrial carbon cycle. *Proceedings of the National Academy of Sciences***, 112(2)**, 436-441, doi:10.1073/pnas.1407302112.

Schipper, L., W. Liu, D. Krawanchid, and C. S., 2010: Review of climate change adaptation methods and tools. MRC Technical Paper No. 34. .

Schlenker, W. and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences of the United States of America***, 106(37)**, 15594-15598, doi:10.1073/pnas.0906865106.

Schleussner, C.–F., P. Pfleiderer, and E.M. Fischer, 2017: In the observational record half a degree matters. *Nature Climate Change***, 7**, 460-462.

Schleussner, C.–F., J.F. Donges, R. Donner, and H.J. Schellnhuber, 2016a: Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. *Proceedings of the National Academy of Sciences of the United States of America***, 113(33)**, 9216-21, doi:10.1073/pnas.1601611113.

Schleussner, C.–F., K. Frieler, M. Meinshausen, J. Yin, and A. Levermann, 2011: Emulating Atlantic overturning strength for low emission scenarios: Consequences for sea-level rise along the North American east coast. *Earth System Dynamics***, 2(2)**, 191-200, doi:10.5194/esd-2-191-2011.

Schleussner, C.–F. et al., 2016b: Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C. *Earth System Dynamics***, 7(2)**, 327-351, doi:10.5194/esd-7-327-2016.

Schmidtko, S., L. Stramma, and M. Visbeck, 2017: Decline in global oceanic oxygen content during the past five decades. *Nature***, 542(7641)**, 335-339, doi:10.1038/nature21399.

Schoof, C., 2007: Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *Journal of Geophysical Research: Earth Surface***, 112(F3)**, doi:10.1029/2006JF000664.

Schroeder, D. and W.M. Connolley, 2007: Impact of instantaneous sea ice removal in a coupled general circulation model. *Geophysical Research Letters***, 34(14)**, doi:10.1029/2007GL030253.

Schulze, E.–D., C. Körner, B.E. Law, H. Haberl, and S. Luyssaert, 2012: Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy***, 4(6)**, 611-616, doi:10.1111/j.1757-1707.2012.01169.x.

Schwartz, J.D. et al., 2015: Projections of temperature-attributable premature deaths in 209 US cities using a cluster-based Poisson approach. *Environmental Health***, 14(1)**, 85, doi:ARTN 85 10.1186/s12940-015-0071-2.

Scott, D. and S. Verkoeyen, 2017: Assessing the Climate Change Risk of a Coastal-Island Destination. In: *Global Climate Change and Coastal Tourism* [Jones, A. and M. Phillips (eds.)]. CAB International.

Scott, D. and S. Gössling, 2018: *Tourism and Climate Change Mitigation- Embracing the Paris Agreement: Pathways to Decarbonisation*. European Travel Commission.

Scott, D., M.C. Simpson, and R. Sim, 2012: The vulnerability of Caribbean coastal tourism to scenarios of climate change related sea level rise. *Journal of Sustainable Tourism***, 20(6)**, 883-898, doi:10.1080/09669582.2012.699063.

Scott, D., C.M. Hall, and S. Gössling, 2016a: A review of the IPCC Fifth Assessment and implications for tourism sector climate resilience and decarbonization. *Journal of Sustainable Tourism***, 24(1)**, 8-30, doi:10.1080/09669582.2015.1062021.

Scott, D., R. Steiger, M. Rutty, and P. Johnson, 2015: The future of the Olympic Winter Games in an era of climate change. *Current Issues in Tourism***, 18(10)**, 913-930, doi:10.1080/13683500.2014.887664.

Scott, D., M. Rutty, B. Amelung, and M. Tang, 2016b: An Inter-Comparison of the Holiday Climate Index (HCI) and the Tourism Climate Index (TCI) in Europe. *Atmosphere***, 7(6)**.

Screen, J.A. and D. Williamson, 2017: Ice-free Arctic at 1.5 °C? *Nature Climate Change***, 7(4)**, 230-231, doi:10.1038/nclimate3248.

Screen, J.A. et al., 2018: Consistency and discrepancy in the atmospheric response to Arctic sea-ice loss across climate models. *Nature Geoscience***, 11(3)**, 155-163, doi:10.1038/s41561-018-0059-y.

Scyphers, S.B., S.P. Powers, K.L. Heck, and D. Byron, 2011: Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLoS ONE***, 6(8)**, doi:10.1371/journal.pone.0022396.

Sebesvari, Z., S. Rodrigues, and F. Renaud, 2017: Mainstreaming ecosystem-based climate change adaptation into integrated water resources management in the Mekong region. *Regional Environmental Change*, 1-14, doi:10.1007/s10113-017-1161-1.

Seddon, A.W.R., M. Macias-Fauria, P.R. Long, D. Benz, and K.J. Willis, 2016: Sensitivity of global terrestrial ecosystems to climate variability. *Nature***, 531(7593)**, 229-232, doi:10.1038/nature16986.

Sedláček, J., O. Martius, and R. Knutti, 2011: Influence of subtropical and polar sea-surface temperature anomalies on temperatures in Eurasia. *Geophysical Research Letters***, 38(12)**, L12803, doi:10.1029/2011GL047764.

Seibel, B.A., 2016: Cephalopod Susceptibility to Asphyxiation via Ocean Incalescence, Deoxygenation, and Acidification. *Physiology***, 31(6)**, 418-429, doi:10.1152/physiol.00061.2015.

Seidl, R. et al., 2017: Forest disturbances under climate change. *Nature Climate Change***, 7**, 395-402, doi:10.1038/nclimate3303.

Seifert, C.A. and D.B. Lobell, 2015: Response of double cropping suitability to climate change in the United States. *Environmental Research Letters***, 10(2)**, 024002, doi:10.1088/1748-9326/10/2/024002.

Selby, J., 2014: Positivist Climate Conflict Research: A Critique. *Geopolitics***, 19(4)**, 829-856, doi:10.1080/14650045.2014.964865.

Semakula, H.M. et al., 2017: Prediction of future malaria hotspots under climate change in sub-Saharan Africa. *Climatic Change***, 143(3)**, 415-428, doi:10.1007/s10584-017-1996-y.

Semenza, J.C. and B. Menne, 2009: Climate change and infectious diseases in Europe. *The Lancet Infectious Diseases***, 9(6)**, 365-375, doi:10.1016/S1473-3099(09)70104-5.

Semenza, J.C. et al., 2016: Climate change projections of West Nile virus infections in Europe: implications for blood safety practices. *Environmental Health***, 15(S1)**, S28, doi:10.1186/s12940-016-0105-4.

Seneviratne, S.I., M.G. Donat, A.J. Pitman, R. Knutti, and R.L. Wilby, 2016: Allowable CO2 emissions based on regional and impact-related climate targets. *Nature***, 529(7587)**, 477-83, doi:10.1038/nature16542.

Seneviratne, S.I. et al., 2012: Changes in Climate Extremes and their Impacts on the Natural Physical Environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of IPCC Intergovernmental Panel on Climate Change* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.–K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 109-230.

Seneviratne, S.I. et al., 2013: Impact of soil moisture-climate feedbacks on CMIP5 projections: First results from the GLACE-CMIP5 experiment. *Geophysical Research Letters***, 40(19)**, 5212-5217, doi:10.1002/grl.50956.

Seneviratne, S.I. et al., 2018a: Land radiative management as contributor to regional-scale climate adaptation and mitigation. *Nature Geoscience***, 11**, 88-96, doi:0.1038/s41561-017-0057-5.

Seneviratne, S.I. et al., 2018b: The many possible climates from the Paris Agreement's aim of 1.5°C warming. *Nature* (in press).

Seneviratne, S.I. et al., 2018c: Climate extremes, land-climate feedbacks, and land-use forcing at 1.5°C. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences***, 376**, 1-23, doi:10.1098/rsta.2016.0450.

Serdeczny, O. et al., 2016: Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. *Regional Environmental Change*, 1-16, doi:10.1007/s10113-015-0910-2.

Serreze, M.C. and J. Stroeve, 2015: Arctic sea ice trends, variability and implications for seasonal ice forecasting. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences***, 373(2045)**, doi:10.1098/rsta.2014.0159.

Settele, J. et al., 2014: Terrestrial and Inland Water Systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and

L.L. White (eds.)]. Cambridge University Press, pp. 271-359.

Shafir, S., J. Van Rijn, and B. Rinkevich, 2006: Steps in the construction of underwater coral nursery, an essential component in reef restoration acts. *Marine Biology*, **149(3)**, 679-687, doi:10.1007/s00227-005-0236-6.

Shearman, P., J. Bryan, and J.P. Walsh, 2013: Trends in Deltaic Change over Three Decades in the Asia-Pacific Region. *Journal of Coastal Research*, **290**, 1169-1183, doi:10.2112/JCOASTRES-D-12-00120.1.

Sheffield, J., E.F. Wood, and M.L. Roderick, 2012: Little change in global drought over the past 60 years. *Nature*, **491(7424)**, 435-438, doi:10.1038/nature11575.

Sheffield, P.E. et al., 2013: Current and future heat stress in Nicaraguan work places under a changing climate. *Industrial Health*, **51**, 123-127, doi:10.2486/indhealth.2012-0156.

Shepherd, J.G., P.G. Brewer, A. Oschlies, and A.J. Watson, 2017: Ocean ventilation and deoxygenation in a warming world: introduction and overview. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **375(2102)**, 20170240, doi:10.1098/rsta.2017.0240.

Shi, H. and G. Wang, 2015: Impacts of climate change and hydraulic structures on runoff and sediment discharge in the middle Yellow River. *Hydrological Processes*, **29(14)**, 3236-3246, doi:10.1002/hyp.10439.

Shi, W. et al., 2016: Ocean acidification increases cadmium accumulation in marine bivalves: a potential threat to seafood safety. *Scientific Reports*, **6(1)**, 20197, doi:10.1038/srep20197.

Shindell, D.T. et al., 2017: A climate policy pathway for near- and long-term benefits. *Science*, **356(6337)**, 493-494.

Short, F.T., S. Kosten, P.A. Morgan, S. Malone, and G.E. Moore, 2016: Impacts of climate change on submerged and emergent wetland plants. *Aquatic Botany*, **135**, 3-17, doi:10.1016/j.aquabot.2016.06.006.

Shrestha, B., T.A. Cochrane, B.S. Caruso, M.E. Arias, and T. Piman, 2016: Uncertainty in flow and sediment projections due to future climate scenarios for the 3S Rivers in the Mekong Basin. *Journal of Hydrology*, **540**, 1088-1104, doi:10.1016/j.jhydrol.2016.07.019.

Sierra-Correa, P.C. and J.R. Cantera Kintz, 2015: Ecosystem-based adaptation for improving coastal planning for sea-level rise: A systematic review for mangrove coasts. *Marine Policy*, **51**, 385-393, doi:10.1016/j.marpol.2014.09.013.

Sigmond, M., J.C. Fyfe, and N.C. Swart, 2018: Ice-free Arctic projections under the Paris Agreement. *Nature Clim. Change*, **8**, 404-408.

Signorini, S.R., B.A. Franz, and C.R. McClain, 2015: Chlorophyll variability in the oligotrophic gyres: mechanisms, seasonality and trends. *Frontiers in Marine Science*, **2(February)**, 1-11, doi:10.3389/fmars.2015.00001.

Sihi, D., P.W. Inglett, S. Gerber, and K.S. Inglett, 2017: Rate of warming affects temperature sensitivity of anaerobic peat decomposition and greenhouse gas production. *Global Change Biology*, n/a--n/a, doi:10.1111/gcb.13839.

Silva, R.A. et al., 2016: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. *Atmospheric Chemistry and Physics*, **16(15)**, 9847-9862, doi:10.5194/acp-16-9847-2016.

Simulundu, E. et al., 2017: Genetic characterization of orf virus associated with an outbreak of severe orf in goats at a farm in Lusaka, Zambia (2015). *Archives of Virology*, **162(8)**, 2363-2367, doi:10.1007/s00705-017-3352-y.

Singh, B.P., V.K. Dua, P.M. Govindakrishnan, and S. Sharma, 2013: Impact of Climate Change on Potato. In: *Climate-Resilient Horticulture: Adaptation and Mitigation Strategies* [Singh, H.C.P., N.K.S.

Rao, and K.S. Shivashankar (eds.)]. Springer India, India, pp. 125-135.

Singh, D., M. Tsiang, B. Rajaratnam, and N.S. Diffenbaugh, 2014: Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. *Nature Climate Change***, 4(6)**, 456-461, doi:10.1038/nclimate2208.

Singh, O.P., 2010: Recent Trends in Tropical Cyclone Activity in the North Indian Ocean. In: *Indian Ocean Tropical Cyclones and Climate Change* [Charabi, Y. (ed.)]. Springer Netherlands, Dordrecht, pp. 51-54.

Singh, O.P., T.M. Ali Khan, and M.S. Rahman, 2000: Changes in the frequency of tropical cyclones over the North Indian Ocean. *Meteorology and Atmospheric Physics***, 75(1-2)**, 11-20, doi:10.1007/s007030070011.

Slade, R., A. Bauen, and R. Gross, 2014: Global bioenergy resources. *Nature Climate Change***, 4(2)**, 99-105, doi:10.1038/nclimate2097.

Slangen, A.B.A. et al., 2016: Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change***, 6(7)**, 701-705, doi:10.1038/nclimate2991.

Slater, A.G. and D.M. Lawrence, 2013: Diagnosing present and future permafrost from climate models. *Journal of Climate***, 26(15)**, 5608-5623, doi:10.1175/JCLI-D-12-00341.1.

Smajgl, A. et al., 2015: Responding to rising sea levels in the Mekong Delta. *Nature Climate Change***, 5(2)**, 167-174.

Smeed, D.A. et al., 2014: Observed decline of the Atlantic meridional overturning circulation 2004-2012. *Ocean Science***, 10(1)**, 29-38, doi:10.5194/os-10-29-2014.

Smirnov, O. et al., 2016: The relative importance of climate change and population growth for exposure to future extreme droughts. *Climatic Change***, 138(1-2)**, 41-53, doi:10.1007/s10584-016-1716-z.

Smith, K.R. et al., 2014: Human Health: Impacts, Adaptation, and Co-Benefits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709-754.

Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology***, 22(3)**, 1315-1324, doi:10.1111/gcb.13178.

Smith, P., J. Price, A. Molotoks, R. Warren, and Y. Malhi, 2018: Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences***, 376(2119)**, 20160456, doi:10.1098/rsta.2016.0456.

Smith, P. et al., 2010: Competition for land. *Phil Trans R Soc***, 365(1554)**, 2941-2957, doi:10.1098/rstb.2010.0127.

Smith, P. et al., 2013: How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology***, 19(8)**, 2285-2302, doi:10.1111/gcb.12160.

Smith, P. et al., 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 811-922.

Smith, P. et al., 2015: Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change***,**

6(1), 42-50, doi:10.1038/nclimate2870.

Smith, T.F., D.C. Thomsen, S. Gould, K. Schmitt, and B. Schlegel, 2013: Cumulative pressures on sustainable livelihoods: Coastal adaptation in the mekong delta. *Sustainability***, 5(1)**, 228-241, doi:10.3390/su5010228.

Sok, S. and X. Yu, 2015: Adaptation, resilience and sustainable livelihoods in the communities of the Lower Mekong Basin, Cambodia. *International Journal of Water Resources Development***, 31(4)**, 575-588, doi:10.1080/07900627.2015.1012659.

Solomon, S., G.–K. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America***, 106(6)**, 1704-1709, doi:10.1073/pnas.0812721106.

Song, A.M. and R. Chuenpagdee, 2015: Interactive Governance for Fisheries. *Interactive Governance for Small-Scale Fisheries***, 5**, 435-456, doi:10.1007/978-3-319-17034-3.

Song, Y. et al., 2016: Spatial distribution estimation of malaria in northern China and its scenarios in 2020, 2030, 2040 and 2050. *Malaria journal***, 15(1)**, 345, doi:10.1186/s12936-016-1395-2.

Sonntag, S., J. Pongratz, C.H. Reick, and H. Schmidt, 2016: Reforestation in a high-CO2 world - Higher mitigation potential than expected, lower adaptation potential than hoped for. *Geophysical Research Letters***, 43(12)**, 6546-6553, doi:10.1002/2016GL068824.

Sovacool, B.K., 2012: Perceptions of climate change risks and resilient island planning in the Maldives. *Mitigation and Adaptation Strategies for Global Change***, 17(7)**, 731-752, doi:10.1007/s11027-011-9341-7.

Spalding, M.D. and B.E. Brown, 2015: Warm-water coral reefs and climate change. *Science***, 350(6262)**, 769-771, doi:10.1126/science.aad0349.

Spalding, M.D. et al., 2014: The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean and Coastal Management***, 90**, 50-57, doi:10.1016/j.ocecoaman.2013.09.007.

Spalding, M.D. et al., 2017: Mapping the global value and distribution of coral reef tourism. *Marine Policy***, 82**, 104-113, doi:10.1016/j.marpol.2017.05.014.

Speelman, L.H., R.J. Nicholls, and J. Dyke, 2017: Contemporary migration intentions in the Maldives: the role of environmental and other factors. *Sustainability Science***, 12(3)**, 433-451, doi:10.1007/s11625-016-0410-4.

Spencer, T. et al., 2016: Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model. *Global and Planetary Change***, 139(Supplement C)**, 15-30, doi:https://doi.org/10.1016/j.gloplacha.2015.12.018.

Springer, J., R. Ludwig, and S. Kienzle, 2015: Impacts of Forest Fires and Climate Variability on the Hydrology of an Alpine Medium Sized Catchment in the Canadian Rocky Mountains. *Hydrology***, 2(1)**, 23-47, doi:10.3390/hydrology2010023.

Springmann, M. et al., 2016: Global and regional health effects of future food production under climate change: a modelling study. *The Lancet***, 387(10031)**, 1937-1946, doi:10.1016/S0140-6736(15)01156-3.

Srokosz, M.A. and H.L. Bryden, 2015: Observing the Atlantic Meridional Overturning Circulation yields a decade of inevitable surprises. *Science***, 348(6241)**.

Stanturf, J.A., B.J. Palik, and R.K. Dumroese, 2014: Contemporary forest restoration: A review emphasizing function. *Forest Ecology and Management***, 331**, 292-323, doi:https://doi.org/10.1016/j.foreco.2014.07.029.

Steiger, R., D. Scott, B. Abegg, M. Pons, and C. Aall, 2017: A critical review of climate change risk for ski tourism. *Current Issues in Tourism*, 1-37, doi:10.1080/13683500.2017.1410110.

Steinberg, D.K. et al., 2015: Long-term (1993-2013) changes in macrozooplankton off the western antarctic peninsula. *Deep-Sea Research Part I: Oceanographic Research Papers***, 101**, 54-70, doi:10.1016/j.dsr.2015.02.009.

Stephens, P.A. et al., 2016: Consistent response of bird populations to climate change on two continents. *Science*, **352(6281)**, 84-87.

Sterling, S.M., A. Ducharne, and J. Polcher, 2012: The impact of global land-cover change on the terrestrial water cycle. *Nature Climate Change*, **3(4)**, 385-390, doi:10.1038/nclimate1690.

Sterman, J.D., L. Siegel, and J.N. Rooney-Varga, 2018: Does replacing coal with wood lower CO 2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environmental Research Letters*, **13(1)**, 015007, doi:10.1088/1748-9326/aaa512.

Stevens, A.J., D. Clarke, and R.J. Nicholls, 2016: Trends in reported flooding in the UK: 1884-2013. *Hydrological Sciences Journal*, **61(1)**, 50-63, doi:10.1080/02626667.2014.950581.

Stewart, E.J. et al., 2016: Implications of climate change for glacier tourism. *Tourism Geographies*, **18(4)**, 377-398, doi:10.1080/14616688.2016.1198416.

Stockdale, A., E. Tipping, S. Lofts, and R.J.G. Mortimer, 2016: Effect of Ocean Acidification on Organic and Inorganic Speciation of Trace Metals. *Environmental Science & Technology*, **50(4)**, 1906-1913, doi:10.1021/acs.est.5b05624.

Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Storlazzi, C.D., E.P.L. Elias, and P. Berkowitz, 2015: Many Atolls May be Uninhabitable Within Decades Due to Climate Change. *Scientific Reports*, **5(1)**, 14546, doi:10.1038/srep14546.

Storlazzi, C.D. et al., 2018: Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, **4(4)**.

Strefler, J. et al., 2018: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environmental Research Letters*, **13(044015)**, 1-6.

Strzepek, K. et al., 2012: *The Zambezi River Basin A Multi-Sector Investment Opportunities Analysis Summary Report*. World Bank, Washington DC, USA.

Suckall, N., E. Fraser, and P. Forster, 2017: Reduced migration under climate change: evidence from Malawi using an aspirations and capabilities framework. *Climate and Development*, **9(4)**, 298-312, doi:10.1080/17565529.2016.1149441.

Sudmeier-Rieux, K., M. Fernández, J.C. Gaillard, L. Guadagno, and M. Jaboyedoff, 2017: Introduction: Exploring Linkages Between Disaster Risk Reduction, Climate Change Adaptation, Migration and Sustainable Development. In: *Identifying Emerging Issues in Disaster Risk Reduction, Migration, Climate Change and Sustainable Development* [Sudmeier-Rieux, K., M. Fernández, I.M. Penna, M. Jaboyedoff, and J.C. Gaillard (eds.)]. Springer International Publishing, Cham, pp. 1-11.

Sugi, M. and J. Yoshimura, 2012: Decreasing trend of tropical cyclone frequency in 228-year high-resolution AGCM simulations. *Geophysical Research Letters*, **39(19)**, n/a-n/a, doi:10.1029/2012GL053360.

Sugi, M., H. Murakami, and K. Yoshida, 2017: Projection of future changes in the frequency of intense tropical cyclones. *Climate Dynamics*, **49(1)**, 619-632, doi:10.1007/s00382-016-3361-7.

Sultan, B. and M. Gaetani, 2016: Agriculture in West Africa in the Twenty-First Century: Climate Change and Impacts Scenarios, and Potential for Adaptation. *Frontiers in Plant Science*, **7**, 1262, doi:10.3389/fpls.2016.01262.

Sun, H. et al., 2017: Exposure of population to droughts in the Haihe River Basin under global warming of 1.5 and 2.0 °C scenarios. *Quaternary International*, **453**, 74-84, doi:10.1016/j.quaint.2017.05.005.

Sun, S., X.– Yang, J. Zhao, and F. Chen, 2015: The possible effects of global warming on cropping systems in China XI The variation of potential light-temperature suitable cultivation zone of winter wheat in

China under climate change. *Scientia Agricultura Sinica*, **48(10)**, 1926-1941, doi:10.3864/J.ISSN.0578-1752.2015.10.006.

Sun, Y., X. Zhang, G. Ren, F.W. Zwiers, and T. Hu, 2016: Contribution of urbanization to warming in China. *Nature Climate Change*, **6**, 706.

Sundby, S., K.F. Drinkwater, and O.S. Kjesbu, 2016: The North Atlantic Spring-Bloom System-Where the Changing Climate Meets the Winter Dark. *Frontiers in Marine Science*, **3**, doi:10.3389/fmars.2016.00028.

Supit, I. et al., 2010: Recent changes in the climatic yield potential of various crops in Europe. *Agricultural Systems*, **103(9)**, 683-694, doi:10.1016/j.agsy.2010.08.009.

Sutton-Grier, A.E. and A. Moore, 2016: Leveraging Carbon Services of Coastal Ecosystems for Habitat Protection and Restoration. *Coastal Management*, **44(3)**, 259-277, doi:10.1080/08920753.2016.1160206.

Suzuki-Parker, A., H. Kusaka, and Y. Yamagata, 2015: Assessment of the Impact of Metropolitan-Scale Urban Planning Scenarios on the Moist Thermal Environment under Global Warming: A Study of the Tokyo Metropolitan Area Using Regional Climate Modeling. *Advances in Meteorology*, **2015**, 1-11, doi:10.1155/2015/693754.

Sweetman, A.K. et al., 2017: Major impacts of climate change on deep-sea benthic ecosystems. *Elem Sci Anth*, **5(0)**, 4, doi:10.1525/elementa.203.

Sydeman, W.J. et al., 2014: Climate change and wind intensification in coastal upwelling ecosystems. *Science*, **345(6192)**, 77-80, doi:10.1126/science.1251635.

Sylla, M.B., N. Elguindi, F. Giorgi, and D. Wisser, 2016: Projected robust shift of climate zones over West Africa in response to anthropogenic climate change for the late 21st century. *Climatic Change*, **134(1)**, 241-253, doi:10.1007/s10584-015-1522-z.

Sylla, M.B. et al., 2015: Projected Changes in the Annual Cycle of High-Intensity Precipitation Events over West Africa for the Late Twenty-First Century. *Journal of Climate*, **28(16)**, 6475-6488, doi:10.1175/JCLI-D-14-00854.1.

Tainio, M. et al., 2013: Future climate and adverse health effects caused by fine particulate matter air pollution: case study for Poland. *Regional Environmental Change*, **13(3)**, 705-715, doi:10.1007/s10113-012-0366-6.

Takagi, H., N. Thao, and L. Tuan Anh, 2016: Sea-Level Rise and Land Subsidence: Impacts on Flood Projections for the Mekong Delta's Largest City. *Sustainability*, **8**, 15 pages.

Takakura, J. et al., 2017: Cost of preventing workplace heat-related illness through worker breaks and the benefit of climate-change mitigation. *Environmental Research Letters*, **12(6)**, 064010, doi:10.1088/1748-9326/aa72cc.

Tanaka, A. et al., 2017: On the scaling of climate impact indicators with global mean temperature increase: a case study of terrestrial ecosystems and water resources. *Climatic Change*, **141(4)**, 775-782, doi:10.1007/s10584-017-1911-6.

Tanoue, M., Y. Hirabayashi, H. Ikeuchi, E. Gakidou, and T. Oki, 2016: Global-scale river flood vulnerability in the last 50 years. *Scientific Reports*, **6(1)**, 36021, doi:10.1038/srep36021.

Tavoni, M. and R. Socolow, 2013: Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climatic Change*, **118(1)**, 1-14, doi:10.1007/s10584-013-0757-9.

Taylor, C.M. et al., 2017: Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, **544(7651)**, 475-478, doi:10.1038/nature22069.

Taylor, M.A. et al., 2018: Future Caribbean Climates in a World of Rising Temperatures: The 1.5 vs 2.0 Dilemma. *Journal of Climate*.

Tebaldi, C. and R. Knutti, 2018: Evaluating the accuracy of climate change pattern emulation for low warming targets. *Environmental Research Letters*, doi:10.1088/1748-9326/aabef2.

Temmerman, S. et al., 2013: Ecosystem-based coastal defence in the face of global change. *Nature*, **504(7478)**, 79-83, doi:10.1038/nature12859.

Terry, J.P. and T.F.M. Chui, 2012: Evaluating the fate of freshwater lenses on atoll islands after eustatic sea-level rise and cyclone-driven inundation: A modelling approach. *Global and Planetary Change*, **88-89(Supplement C)**, 76-84, doi:https://doi.org/10.1016/j.gloplacha.2012.03.008.

Teshager, A.D., P.W. Gassman, J.T. Schoof, and S. Secchi, 2016: Assessment of impacts of agricultural and climate change scenarios on watershed water quantity and quality, and crop production. *Hydrology and Earth System Sciences*, **20(8)**, 3325-3342, doi:10.5194/hess-20-3325-2016.

Tessler, Z.D., C.J. Vörösmarty, I. Overeem, and J.P.M. Syvitski, 2018: A model of water and sediment balance as determinants of relative sea level rise in contemporary and future deltas. *Geomorphology*, **305**, 209-220, doi:https://doi.org/10.1016/j.geomorph.2017.09.040.

Thackeray, S.J. et al., 2016: Phenological sensitivity to climate across taxa and trophic levels. *Nature*, **535(7611)**, 241-245, doi:10.1038/nature18608.

Theisen, O.M., N.P. Gleditsch, and H. Buhaug, 2013: Is climate change a driver of armed conflict? *Climatic Change*, **117(3)**, 613-625, doi:10.1007/s10584-012-0649-4.

Thiery, W. et al., 2017: Present-day irrigation mitigates heat extremes. *Journal of Geophysical Research: Atmospheres*, **122(3)**, 1403-1422, doi:10.1002/2016JD025740.

Thober, T. et al., 2018: Multi-model ensemble projections of European river floods and high flows at 1.5, 2, and 3 degrees global warming. *Environmental Research Letters*, **13(014003)**, 1-11.

Thomas, A. and L. Benjamin, 2017: Management of loss and damage in small island developing states: implications for a 1.5C or warmer world. *Regional Environmental Change*, doi:10.1007/s10113-017-1184-7.

Thornton, P.K., P.G. Jones, P.J. Ericksen, and A.J. Challinor, 2011: Agriculture and food systems in sub-Saharan Africa in a 4°C+ world. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **369(1934)**, 117-136, doi:10.1098/rsta.2010.0246.

Thornton, P.K., P.J. Ericksen, M. Herrero, and A.J. Challinor, 2014: Climate variability and vulnerability to climate change: a review. *Global Change Biology*, **20(11)**, 3313-3328, doi:10.1111/gcb.12581.

Thronson, A. and A. Quigg, 2008: Fifty-five years of fish kills in coastal Texas. *Estuaries and Coasts*, **31(4)**, 802-813, doi:10.1007/s12237-008-9056-5.

Tietsche, S., D. Notz, J.H. Jungclaus, and J. Marotzke, 2011: Recovery mechanisms of Arctic summer sea ice. *Geophysical Research Letters*, **38(2)**, n/a-n/a, doi:10.1029/2010GL045698.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort, 2011: Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, **108(50)**, 20260-20264, doi:10.1073/PNAS.1116437108.

Tjaden, N.B. et al., 2017: Modelling the effects of global climate change on Chikungunya transmission in the 21st century. *Scientific Reports*, **7(1)**, 3813, doi:10.1038/s41598-017-03566-3.

Tobin, I. et al., 2015: Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections. *Climatic Change*, **128(1)**, 99-112, doi:10.1007/s10584-014-1291-0.

Tobin, I. et al., 2016: Climate change impacts on the power generation potential of a European mid-century wind farms scenario. *Environmental Research Letters*, **11(3)**, 34013.

Tobin, I. et al., 2018: Vulnerabilities and resilience of European power generation to 1.5 °C, 2 °C and 3 °C warming. *Environmental Research Letters*, **13(4)**, 44024, doi:10.1088/1748-9326/aab211.

Todd-Brown, K.E.O. et al., 2014: Changes in soil organic carbon storage predicted by Earth system models during the 21st century. *Biogeosciences*, **11(8)**, 2341-2356, doi:10.5194/bg-11-2341-2014.

Tran, T.A., J. Pittock, and L.A. Tuan, 2018: Adaptive co-management in the Vietnamese Mekong Delta: examining the interface between flood management and adaptation. *International Journal of Water Resources Development*, 1-17, doi:10.1080/07900627.2018.1437713.

Trang, N.T.T., S. Shrestha, M. Shrestha, A. Datta, and A. Kawasaki, 2017: Evaluating the impacts of climate and land-use change on the hydrology and nutrient yield in a transboundary river basin: A case study in the 3S River Basin (Sekong, Sesan, and Srepok). *Science of the Total Environment*, **576**, 586-598, doi:10.1016/j.scitotenv.2016.10.138.

Trathan, P.N. and S.L. Hill, 2016: The Importance of Krill Predation in the Southern Ocean. In: *Biology and Ecology of Antarctic Krill* [Siegel, V. (ed.)]. Springer, Cham, Switzerland, pp. 321-350.

Trigo, R.M., C.M. Gouveia, and D. Barriopedro, 2010: The intense 2007-2009 drought in the Fertile Crescent: Impacts and associated atmospheric circulation. *Agricultural and Forest Meteorology*, **150(9)**, 1245-1257, doi:10.1016/j.agrformet.2010.05.006.

Turner, J. et al., 2014: Antarctic climate change and the environment: An update. *Polar Record*, **50(3)**, 237-259, doi:10.1017/S0032247413000296.

Turner, J. et al., 2017a: Atmosphere-ocean-ice interactions in the Amundsen Sea Embayment, West Antarctica. *Reviews of Geophysics*, **55(1)**, 235-276, doi:10.1002/2016RG000532.

Turner, J. et al., 2017b: Unprecedented springtime retreat of Antarctic sea ice in 2016. *Geophysical Research Letters*, **44(13)**, 6868-6875, doi:10.1002/2017GL073656.

Turner, R.E., N.N. Rabalais, and D. Justic, 2008: Gulf of Mexico hypoxia: Alternate states and a legacy. *Environmental Science and Technology*, **42(7)**, 2323-2327, doi:10.1021/es071617k.

Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S. Ali Ibrahim (eds.), 2018: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*. Urban Climate Change Research Network (UCCRN). Cambridge University Press, Cambridge, UK.

Udo, K. and Y. Takeda, 2017: Projections of Future Beach Loss in Japan Due to Sea-Level Rise and Uncertainties in Projected Beach Loss. *Coastal Engineering Journal*.

UN, 2015: Transforming our world: The 2030 agenda for sustainable development. , 1-5, doi:10.1007/s13398-014-0173-7.2.

UN, 2017: *The Sustainable Development Goals Report 2017*. United Nations (UN), New York, NY, USA, 64 pp.

UNEP-WCMC, 2006: *In the front line: Shoreline protection and other ecosystem services from mangroves and coral reefs*. UNEP World Conservation Monitoring Centre (UNEP-WCMC), 33 pp.

UNESCO, 2011: The Impact of Global Change on Water Resources: The Response of UNESCO'S International Hydrology Programme. , 20.

Urban, M.C., 2015: Accelerating extinction risk from climate change. *Science*, **348(6234)**, 571-573.

Utete, B., C. Phiri, S.S. Mlambo, N. Muboko, and B.T. Fregene, 2018: Vulnerability of fisherfolks and their perceptions towards climate change and its impacts on their livelihoods in a peri-urban lake system in Zimbabwe. *Environment, Development and Sustainability*, doi:10.1007/s10668-017-0067-x.

Valle, M. et al., 2014: Projecting future distribution of the seagrass Zostera noltii under global warming and sea level rise. *Biological Conservation*, **170**, 74-85, doi:10.1016/j.biocon.2013.12.017.

van Bruggen, A.H.C., J.W. Jones, J.M.C. Fernandes, K. Garrett, and K.J. Boote, 2015: Crop Diseases and Climate Change in the AgMIP Framework. In: *Handbook of Climate Change and Agroecosystems* [Rosenzweig, C. and D. Hillel (eds.)]. pp. 297-330.

Van Den Hurk, B., E. Van Meijgaard, P. De Valk, K.J. Van Heeringen, and J. Gooijer, 2015: Analysis of a compounding surge and precipitation event in the Netherlands. *Environmental Research Letters*, **10(3)**, doi:10.1088/1748-9326/10/3/035001.

van der Velde, M., F.N. Tubiello, A. Vrieling, and F. Bouraoui, 2012: Impacts of extreme weather on wheat and maize in France: evaluating regional crop simulations against observed data. *Climatic Change*, **113(3-4)**, 751-765, doi:10.1007/s10584-011-0368-2.

Van Dingenen, R. et al., 2009: The global impact of ozone on agricultural crop yields under current and future air quality legislation. *Atmospheric Environment*, **43(3)**, 604-618, doi:10.1016/j.atmosenv.2008.10.033.

van Hooidonk, R. and M. Huber, 2012: Effects of modeled tropical sea surface temperature variability on coral reef bleaching predictions. *Coral Reefs*, **31(1)**, 121-131, doi:10.1007/s00338-011-0825-4.

van Hooidonk, R., J.A. Maynard, and S. Planes, 2013: Temporary refugia for coral reefs in a warming world. *Nature Climate Change*, **3(5)**, 508-511, doi:10.1038/nclimate1829.

van Hooidonk, R. et al., 2016: Local-scale projections of coral reef futures and implications of the Paris Agreement. *Scientific Reports*, **6(1)**, 39666, doi:10.1038/srep39666.

van Oldenborgh, G.J. et al., 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters*, **12(12)**, 124009.

van Oort, P.A.J. and S.J. Zwart, 2018: Impacts of climate change on rice production in Africa and causes of simulated yield changes. *Global Change Biology*, **24(3)**, 1029-1045, doi:10.1111/gcb.13967.

van Oppen, M.J.H., J.K. Oliver, H.M. Putnam, and R.D. Gates, 2015: Building coral reef resilience through assisted evolution. *Proceedings of the National Academy of Sciences*, **112(8)**, 2307-2313, doi:10.1073/pnas.1422301112.

van Oppen, M.J.H. et al., 2017: Shifting paradigms in restoration of the world's coral reefs. *Global Change Biology*, **23(9)**, 3437-3448, doi:10.1111/gcb.13647.

van Vliet, M.T.H. et al., 2016: Multi-model assessment of global hydropower and cooling water discharge potential under climate change. *Global Environmental Change*, **40**, 156-170, doi:10.1016/j.gloenvcha.2016.07.007.

van Vuuren, D.P. et al., 2009: Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy*, **37(12)**, 5125-5139, doi:https://doi.org/10.1016/j.enpol.2009.07.024.

van Vuuren, D.P. et al., 2011a: The representative concentration pathways: an overview. *Climatic Change*, **109(1)**, 5, doi:10.1007/s10584-011-0148-z.

van Vuuren, D.P. et al., 2011b: RCP2.6: exploring the possibility to keep global mean temperature increase below 2ºC. *Climatic Change*, **109(1)**, 95, doi:10.1007/s10584-011-0152-3.

van Vuuren, D.P. et al., 2016: Carbon budgets and energy transition pathways. *Environmental Research Letters*, **11(7)**, 75002.

van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391-397, doi:10.1038/s41558-018-0119-8.

Vardoulakis, S. et al., 2014: Comparative Assessment of the Effects of Climate Change on Heat-and Cold-Related Mortality in the United Kingdom and Australia. *Environmental Health Perspectives*, **122(12)**, 1285-1292, doi:10.1289/ehp.1307524.

Vaughan, D.G. et al., 2013: Observations: Cryosphere. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V.B. And, P.M. Midgley, and Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 317-382.

Vaughan, N.E. and C. Gough, 2016: Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters*, **11(9)**, 095003, doi:10.1088/1748-9326/11/9/095003.

Vaughan, N.E. et al., 2018: Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. *Environmental Research Letters*, **13(4)**, 044014, doi:10.1088/1748-9326/aaaa02.

Vautard, R. et al., 2014: The European climate under a 2 °C global warming. *Environmental Research Letters*, **9(3)**, 034006, doi:10.1088/1748-9326/9/3/034006.

Velez, C., E. Figueira, A.M.V.M. Soares, and R. Freitas, 2016: Combined effects of seawater acidification and salinity changes in Ruditapes philippinarum. *Aquatic Toxicology*, **176**, 141-150, doi:10.1016/j.aquatox.2016.04.016.

Verges, A. et al., 2014: The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts. *Proceedings of the Royal Society B: Biological Sciences***, 281(1789)**, 20140846-20140846, doi:10.1098/rspb.2014.0846.

Vergés, A. et al., 2016: Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. *Proceedings of the National Academy of Sciences***, 113(48)**, 13791-13796, doi:10.1073/pnas.1610725113.

Versini, P.–A., M. Velasco, A. Cabello, and D. Sempere-Torres, 2013: Hydrological impact of forest fires and climate change in a Mediterranean basin. *Natural Hazards***, 66(2)**, 609-628, doi:10.1007/s11069-012-0503-z.

Villamayor, B.M.R., R.N. Rollon, M.S. Samson, G.M.G. Albano, and J.H. Primavera, 2016: Impact of Haiyan on Philippine mangroves: Implications to the fate of the widespread monospecific Rhizophora plantations against strong typhoons. *Ocean and Coastal Management***, 132**, 1-14, doi:10.1016/j.ocecoaman.2016.07.011.

Vitali, A. et al., 2009: Seasonal pattern of mortality and relationships between mortality and temperature-humidity index in dairy cows. *Journal of Dairy Science***, 92(8)**, 3781-3790, doi:10.3168/jds.2009-2127.

Vitousek, S. et al., 2017: Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific Reports***, 7(1)**, 1399, doi:10.1038/s41598-017-01362-7.

Vogel, M.M. et al., 2017: Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture-temperature feedbacks. *Geophysical Research Letters***, 44(3)**, 1511-1519, doi:10.1002/2016GL071235.

von Lampe, M. et al., 2014: Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. *Agricultural Economics***, 45(1)**, 3-20, doi:10.1111/agec.12086.

von Uexkull, N., M. Croicu, H. Fjelde, and H. Buhaug, 2016: Civil conflict sensitivity to growing-season drought. *Proceedings of the National Academy of Sciences***, 113(44)**, 12391-12396, doi:10.1073/pnas.1607542113.

Vörösmarty, C.J. et al., 2010: Global threats to human water security and river biodiversity. *Nature***, 467(7315)**, 555-561, doi:10.1038/nature09440.

Wada, Y. et al., 2017: Human-water interface in hydrological modelling: current status and future directions. *Earth Syst. Sci***, 215194**, 4169-4193, doi:10.5194/hess-21-4169-2017.

Waha, K. et al., 2017: Climate change impacts in the Middle East and Northern Africa (MENA) region and their implications for vulnerable population groups. *Regional Environmental Change***, 17(6)**, 1623-1638, doi:10.1007/s10113-017-1144-2.

Wahl, T., S. Jain, J. Bender, S.D. Meyers, and M.E. Luther, 2015: Increasing risk of compound flooding from storm surge and rainfall for major US cities. *Nature Climate Change***, 5**, 1093.

Wairiu, M., 2017: Land degradation and sustainable land management practices in Pacific Island Countries. *Regional Environmental Change***, 17(4)**, 1053-1064, doi:10.1007/s10113-016-1041-0.

Waldbusser, G.G. et al., 2014: Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nature Climate Change***, 5(3)**, 273-280, doi:10.1038/nclimate2479.

Wall, E., A. Wreford, K. Topp, and D. Moran, 2010: Biological and economic consequences heat stress due to a changing climate on UK livestock. *Advances in Animal Biosciences***, 1**.

Walsh, K.J.E. et al., 2016: Tropical cyclones and climate change. *Wiley Interdisciplinary Reviews: Climate Change***, 7(1)**, 65-89, doi:10.1002/wcc.371.

Wan, H., X. Zhang, and F. Zwiers, 2018: Human influence on Canadian temperatures. *Climate Dynamics,* doi:10.1007/s00382-018-4145-z.

Wang, B., H.H. Shugart, and M.T. Lerdau, 2017: Sensitivity of global greenhouse gas budgets to tropospheric ozone pollution mediated by the biosphere. *Environmental Research Letters***, 12(8)**, 84001.

Wang, D., T.C. Gouhier, B.A. Menge, and A.R. Ganguly, 2015: Intensification and spatial homogenization of coastal upwelling under climate change. *Nature***, 518(7539)**, 390-394, doi:10.1038/nature14235.

Wang, G. et al., 2017: Continued increase of extreme El Niño frequency long after 1.5 °C warming stabilization. *Nature Climate Change***, 7**.

Wang, H., S.P. Xie, and Q. Liu, 2016: Comparison of climate response to anthropogenic aerosol versus greenhouse gas forcing: Distinct patterns. *Journal of Climate***, 29(14)**, 5175-5188, doi:10.1175/JCLI-D-16-0106.1.

Wang, L., J.B. Huang, Y. Luo, Y. Yao, and Z.C. Zhao, 2015: Changes in Extremely Hot Summers over the Global Land Area under Various Warming Targets. *PLOS ONE***, 10(6)**, doi:ARTN e0130660 10.1371/journal.pone.0130660.

Wang, Q. et al., 2016: Effects of ocean acidification on immune responses of the Pacific oyster Crassostrea gigas. *Fish & shellfish immunology***, 49**, 24-33, doi:10.1016/j.fsi.2015.12.025.

Wang, Z. et al., 2017: Scenario dependence of future changes in climate extremes under 1.5 °C and 2 °C global warming.. *Scientific reports***, 7**, 46432, doi:10.1038/srep46432.

Warren, R., J. Price, J. VanDerWal, S. Cornelius, and H. Sohl, 2018a: The implications of the United Nations Paris Agreement on Climate Change for Key Biodiversity Areas. *Climatic change***, 147(3-4)**, 395-409, doi:https://doi.org/10.1007/s10584-018-2158-6.

Warren, R., J. Price, J. Vanderwal, E. Graham, and N. Forstenhauesler, 2018b: How much difference does half a degree of global warming make to insects, vertebrates and plants? *Science* (in press).

Warren, R. et al., 2013: Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Climate Change***, 3(7)**, 678-682, doi:10.1038/nclimate1887.

Warren, R. et al., 2018c: *Risks associated with global warming of 1.5 or 2C. Tyndall briefing note*. Tyndall Centre for Climate Change Research, UK, 4 pp.

Warszawski, L. et al., 2013: A multi-model analysis of risk of ecosystem shifts under climate change. *Environmental Research Letters***, 8(4)**, 044018, doi:10.1088/1748-9326/8/4/044018.

Warszawski, L. et al., 2014: The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): project framework.. *Proceedings of the National Academy of Sciences of the United States of America***, 111(9)**, 3228-32, doi:10.1073/pnas.1312330110.

Wartenburger, R. et al., 2017: Changes in regional climate extremes as a function of global mean temperature: an interactive plotting framework. *Geoscientific Model Development***, 10**, 3609-3634, doi:10.5194/gmd-2017-33.

Watson, C.S. et al., 2015: Unabated global mean sea-level rise over the satellite altimeter era. *Nature Climate Change***, 5(6)**, 565-568, doi:10.1038/nclimate2635.

Watts, G. et al., 2015: Climate change and water in the UK - past changes and future prospects. *Progress in Physical Geography***, 39(1)**, 6-28, doi:10.1177/0309133314542957.

Weatherdon, L., A.K. Magnan, A.D. Rogers, U.R. Sumaila, and W.W.L. Cheung, 2016: Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. *Frontiers in Marine Science***, 3**, 48, doi:10.3389/fmars.2016.00048.

Weber, T. et al., 2018: Analysing regional climate change in Africa in a 1.5°C, 2°C and 3°C global warming world. *Earth's Future***, 6**, 1-13, doi:10.1002/2017EF000714.

Webster, N.S., S. Uthicke, E.S. Botté, F. Flores, and A.P. Negri, 2013: Ocean acidification reduces induction of coral settlement by crustose coralline algae. *Global Change Biology***, 19(1)**, 303-315, doi:10.1111/gcb.12008.

Webster, P.J., G.J. Holland, J.A. Curry, and H.–R. Chang, 2005: Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment. *Science*, **309(5742)**, 1844-1846, doi:10.1126/science.1116448.

Wehner, M. et al., 2018: Changes in extremely hot days under stabilized 1.5 and 2.0C global warming scenarios as simulated by the HAPPI multi-model ensemble. *Earth System Dynamics*, **9(1)**, 299-311, doi:10.5194/esd-9-299-2018.

Wehner, M.F., K.A. Reed, B. Loring, D. Stone, and H. Krishnan, 2017: Changes in tropical cyclones under stabilized 1.5&amp;thinsp;&amp;deg;C and 2.0&amp;thinsp;&amp;deg;C global warming scenarios as simulated by the Community Atmospheric Model under the HAPPI protocols. *Earth System Dynamics Discussions*, 1-18, doi:10.5194/esd-2017-101.

Wei, T., S. Glomsrød, and T. Zhang, 2017: Extreme weather, food security and the capacity to adapt -- the case of crops in China. *Food Security*, **9(3)**, 523-535, doi:10.1007/s12571-015-0420-6.

Weir, T., L. Dovey, and D. Orcherton, 2017: Social and cultural issues raised by climate change in Pacific Island countries: an overview. *Regional Environmental Change*, **17(4)**, 1017-1028, doi:10.1007/s10113-016-1012-5.

Welch, J.R. et al., 2010: Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures.. *Proceedings of the National Academy of Sciences of the United States of America*, **107(33)**, 14562-7, doi:10.1073/pnas.1001222107.

Wernberg, T. et al., 2012: An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Climate Change*, **3(1)**, 78-82, doi:10.1038/nclimate1627.

Whan, K. et al., 2015: Impact of soil moisture on extreme maximum temperatures in Europe. *Weather and Climate Extremes*, **9**, 57-67, doi:https://doi.org/10.1016/j.wace.2015.05.001.

White, I. and T. Falkland, 2010: Management of freshwater lenses on small Pacific islands. *Hydrogeology Journal*, **18(1)**, 227-246, doi:10.1007/s10040-009-0525-0.

Whitfield, S., A.J. Challinor, and R.M. Rees, 2018: Frontiers in climate Smart Food Systems: Outlining the researchSpace. *Frontiers in sustainable food systems*, **2**, 2, doi:doi.org/10.3389/fsufs.2018.00002.

Widlansky, M.J., A. Timmermann, and W. Cai, 2015: Future extreme sea level seesaws in the tropical Pacific. *Science Advances*, **1(8)**, doi:10.1126/sciadv.1500560.

Wieder, W.R., C.C. Cleveland, W.K. Smith, and K. Todd-Brown, 2015: Future productivity and carbon storage limited by terrestrial nutrient availability. *Nature Geoscience*, **8**, 441-444, doi:10.1038/ngeo2413.

Wiens, J.J., 2016: Climate-Related Local Extinctions Are Already Widespread among Plant and Animal Species. *PLOS BIOLOGY*, **14(12)**, doi:10.1371/journal.pbio.2001104.

Wilhelm, M., E.L. Davin, and S.I. Seneviratne, 2015: Climate engineering of vegetated land for hot extremes mitigation: An Earth system model sensitivity study. *Journal of Geophysical Research Atmospheres*, **120(7)**, 2612-2623, doi:10.1002/2014JD022293.

Williams, J.W., B. Shuman, and P.J. Bartlein, 2009: Rapid responses of the prairie-forest ecotone to early Holocene aridity in mid-continental North America. *Global and Planetary Change*, **66(3)**, 195-207, doi:https://doi.org/10.1016/j.gloplacha.2008.10.012.

Williamson, P., 2016: Emissions reduction: Scrutinize CO2 removal methods. *Nature*, **530(7589)**, 153-155, doi:10.1038/530153a.

Willmer, P., 2012: Ecology: Pollinator-Plant Synchrony Tested by Climate Change. *Current Biology*, **22(4)**, R131-R132, doi:10.1016/j.cub.2012.01.009.

Wilson, S.K., N.A.J. Graham, M.S. Pratchett, G.P. Jones, and N.V.C. Polunin, 2006: Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology*, **12(11)**, 2220-2234, doi:10.1111/j.1365-2486.2006.01252.x.

Wiltshire, A. and T. Davies-Barnard, 2015: *Planetary limits to BECCS negative emissions*. AVOID 2, 1-24 pp.

Wine, M.L. and D. Cadol, 2016: Environmental Research Letters Hydrologic effects of large southwestern USA wildfires significantly increase regional water supply: fact or fiction? Hydrologic effects of large southwestern USA wildfires significantly increase regional water supply: fact. *Environ. Res. Lett***, 11**, doi:10.1088/1748-9326/11/8/085006.

Winsemius, H.C. et al., 2016: Global drivers of future river flood risk. *Nature Climate Change***, 6(4)**, 381-385, doi:10.1038/nclimate2893.

Wong, P.P. et al., 2014: Coastal Systems and Low-Lying Areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 361-409.

Woodroffe, C.D. et al., 2010: Response of coral reefs to climate change: Expansion and demise of the southernmost pacific coral reef. *Geophysical Research Letters***, 37(15)**, doi:10.1029/2010GL044067.

Woolf, D., J.E. Amonette, A. Street-Perrott, J. Lehmann, and S. Joseph, 2010: Sustainable bio-char to mitigate global climate change. *Nature Communications***, 1(56)**, doi:doi:10.1038/ncomms1053.

World Bank, 2013: *Turn Down The Heat: Climate Extremes, Regional Impacts and the Case for Resilience*. World Bank, Washington DC, USA, 255 pp.

Wright, B.D., 2011: The Economics of Grain Price Volatility. *Applied Economic Perspectives and Policy***, 33(1)**, 32-58, doi:10.1093/aepp/ppq033.

Wu, D., Z. Yong, P.E.I. Yuan-sheng, and others, 2013: Climate Change and its Effects on Runoff in Upper and Middle Reaches of Lancang-Mekong river. *Journal of Natural Resourses***, 28(9)**, 1569-1582.

Wu, J. and Y. Shi, 2016: Attribution index for changes in migratory bird distributions: The role of climate change over the past 50years in China. *Ecological Informatics*, doi:10.1016/j.ecoinf.2015.11.013.

Wu, P., N. Christidis, and P. Stott, 2013: Anthropogenic impact on Earth's hydrological cycle. *Nature Climate Change***, 3(9)**, 807-810, doi:10.1038/nclimate1932.

Yamagata, Y. et al., 2018: Estimating water-food-ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6). *Sustainability Science***, 13(2)**, 301-313, doi:10.1007/s11625-017-0522-5.

Yamano, H., K. Sugihara, and K. Nomura, 2011: Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. *Geophysical Research Letters***, 38(4)**, doi:10.1029/2010GL046474.

Yang, J. et al., 2015: Century-scale patterns and trends of global pyrogenic carbon emissions and fire influences on terrestrial carbon balance. *Global Biogeochemical Cycles***, 29(9)**, 1549-1566, doi:10.1002/2015GB005160.

Yang, X., P.E. Thornton, D.M. Ricciuto, and W.M. Post, 2014: The role of phosphorus dynamics in tropical forests - a modeling study using CLM-CNP. *Biogeosciences***, 11(6)**, 1667-1681, doi:10.5194/bg-11-1667-2014.

Yang, Z., T. Wang, N. Voisin, and A. Copping, 2015: Estuarine response to river flow and sea-level rise under future climate change and human development. *Estuarine, Coastal and Shelf Science***, 156**, 19-30, doi:10.1016/j.ecss.2014.08.015.

Yang, Z. et al., 2016: Warming increases methylmercury production in an Arctic soil. *Environmental Pollution***, 214**, 504-509, doi:10.1016/j.envpol.2016.04.069.

Yasuhara, M. and R. Danovaro, 2016: Temperature impacts on deep-sea biodiversity. *Biological Reviews***, 91(2)**, 275-287, doi:10.1111/brv.12169.

Yates, M., G. Le Cozannet, M. Garcin, E. Salai, and P. Walker, 2013: Multidecadal Atoll Shoreline Change on Manihi and Manuae, French Polynesia. *Journal of Coastal Research***, 29**, 870-882.

Yazdanpanah, M., M. Thompson, and J. Linnerooth-Bayer, 2016: Do Iranian Policy Makers Truly Understand And Dealing with the Risk of Climate Change Regarding Water Resource Management? *IDRiM*, 367-368.

Yohe, G.W., 2017: Characterizing transient temperature trajectories for assessing the value of achieving alternative temperature targets. *Climatic Change*, **145(3-4)**, 469-479.

Yoshida, K., M. Sugi, M. Ryo, H. Murakami, and I. Masayoshi, 2017: Future Changes in Tropical Cyclone Activity in High-Resolution Large-Ensemble Simulations. *Geophysical Research Letters*, **44(19)**, 9910-9917, doi:10.1002/2017GL075058.

Yu, R. and P. Zhai, 2018: Differentiated changes of temperature and precipitation extremes in China's 1 urban agglomeration areas between 1.5°C and 2°C global warming levels. *International Journal of Climatology* (in press).

Yu, R., Z. Jiang, and P. Zhai, 2016: Impact of urban land-use change in eastern China on the East Asian subtropical monsoon: A numerical study. *Journal of Meteorological Research*, **30(2)**, 203-216, doi:10.1007/s13351-016-5157-4.

Yu, R., P. Zhai, and Y. Lu, 2018: Implications of differential effects between 1.5 and 2°C global warming on temperature and precipitation extremes in China's urban agglomerations. *International Journal of Climatology*, **38(5)**, 2374-2385, doi:10.1002/joc.5340.

Yu, Z., J. Loisel, D. Brosseau, D. Beilman, and S. Hunt, 2010: Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, **37(13)**, L13402, doi:10.1029/2010GL043584.

Yumashev, D., K. van Hussen, J. Gille, and G. Whiteman, 2017: Towards a balanced view of Arctic shipping: estimating economic impacts of emissions from increased traffic on the Northern Sea Route. *Climatic Change*, **143(1-2)**, 143-155, doi:10.1007/s10584-017-1980-6.

Zaehle, S., C.D. Jones, B. Houlton, J.–F. Lamarque, and E. Robertson, 2015: Nitrogen Availability Reduces CMIP5 Projections of Twenty-First-Century Land Carbon Uptake. *Journal of Climate*, **28(6)**, 2494-2511, doi:10.1175/JCLI-D-13-00776.1.

Zaman, A.M. et al., 2017: Impacts on river systems under 2°C warming: Bangladesh Case Study. *Climate Services*, **7**, 96-114, doi:10.1016/j.cliser.2016.10.002.

Zarco-Perello, S., T. Wernberg, T.J. Langlois, and M.A. Vanderklift, 2017: Tropicalization strengthens consumer pressure on habitat-forming seaweeds. *Scientific Reports*, **7(1)**, 820, doi:10.1038/s41598-017-00991-2.

Zhai, R., F. Tao, and Z. Xu, 2017: Spatial-temporal changes in river runoff and terrestrial ecosystem water retention under 1.5 °C and 2 °C warming scenarios across China. *Earth System Dynamics* (in press), doi:10.5194/esd-2017-96.

Zhang, F., J. Tong, B. Su, J. Huang, and X. Zhu, 2016: Simulation and projection of climate change in the south Asian River basin by CMIP5 multi-model ensembles. *Journal of Tropical Meteorology*, **32(5)**, 734-742.

Zhang, K. et al., 2012: The role of mangroves in attenuating storm surges. *Estuarine, Coastal and Shelf Science*, **102-103**, 11-23, doi:10.1016/j.ecss.2012.02.021.

Zhang, Z., Y. Chen, C. Wang, P. Wang, and F. Tao, 2017: Future extreme temperature and its impact on rice yield in China. *International Journal of Climatology*, **37(14)**, 4814-4827, doi:10.1002/joc.5125.

Zhao, C. et al., 2017: Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences*, **114(35)**, 9326-9331, doi:10.1073/pnas.1701762114.

Zhao, X. et al., 2017: Ocean acidification adversely influences metabolism, extracellular pH and calcification of an economically important marine bivalve, Tegillarca granosa. *Marine Environmental Research*, **125**, 82-89, doi:10.1016/j.marenvres.2017.01.007.

Zhao, Y. et al., 2016: Potential escalation of heat-related working costs with climate and socioeconomic changes in China. *Proceedings of the National Academy of Sciences*, **113(17)**, 4640-4645, doi:10.1073/pnas.1521828113.

Zhou, B., P. Zhai, Y. Chen, and R. Yu, 2018: Projected changes of thermal growing season over Northern Eurasia in a 1.5°C and 2°C warming world. *Environ. Res. Lett*, **13**, 1-10.

Zhou, L. et al., 2014: Widespread decline of Congo rainforest greenness in the past decade. *Nature*, **508(7498)**, 86-90, doi:10.1038/nature13265.

Zickfeld, K. et al., 2013: Long-Term climate change commitment and reversibility: An EMIC intercomparison. *Journal of Climate*, **26(16)**, 5782-5809, doi:10.1175/JCLI-D-12-00584.1.

Zittier, Z.M.C., C. Bock, G. Lannig, and H.O. Pörtner, 2015: Impact of ocean acidification on thermal tolerance and acid-base regulation of Mytilus edulis (L.) from the North Sea. *Journal of Experimental Marine Biology and Ecology*, **473**, 16-25, doi:10.1016/j.jembe.2015.08.001.

Zscheischler, J. et al., 2018: Future climate risk from compound events. *Nature Climate Change*, **8(6)**, 469-477, doi:10.1038/s41558-018-0156-3.

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S3-2 Supplementary information to Section 3.2

Climate models and associated simulations available for the present assessment

Climate models allow for policy-relevant calculations such as the assessment of the levels of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions compatible with a specified climate stabilization target, such as the 1.5°C or 2°C global warming scenarios. Climate models are numerical models that can be of varying complexity and resolution (e.g., Le Treut et al. 2007). Presently, global climate models are typically Earth System Models (ESMs), in that they entail a comprehensive representation of Earth system processes, including biogeochemical processes.

In order to assess the impact and risk of projected climate changes on ecosystems or human systems, typical ESM simulations have a too coarse resolution (100 km or more) in many cases. Different approaches can be used to derive higher-resolution information. In some cases, ESMs can be run globally with very-high resolution, however, such simulations are cost-intensive and thus very rare. Another approach is to use Regional Climate Models (RCM) to dynamically downscale the ESM simulations. RCMs are limited-area models with representations of climate processes comparable to those in the atmospheric and land surface components of the global models but with a higher resolution than 100 km, generally down to 10–50 km (e.g., Coordinated Regional climate Downscaling Experiment, CORDEX, Giorgi and Gutowski 2015; Jacob et al. 2014; Cloke et al. 2013; Erfanian et al. 2016; Barlow et al. 2016) and in some cases even higher (convection permitting models, i.e., less than 4 km, e.g., Kendon et al. 2014; Ban et al. 2014; Prein et al. 2015). Statistical downscaling is another approach for downscaling information from global climate models to higher resolution. Its underlying principle is to develop statistical relationships that link large-scale atmospheric variables with local / regional climate variables, and to apply them to coarser-resolution models (Salameh et al. 2009; Su et al. 2016). Nonetheless, at the time of writing, we note that there are only very few studies on 1.5°C climate using regional climate models or statistical downscaling. One exception is an extension of the IMPACT2C project for Europe (see below).

There are various sources of climate model information available for the present assessment. First, there are global simulations that have been used in previous IPCC assessments and which were computed as part of the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP). The IPCC Fourth Assessment Report (AR4) and Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) were mostly based on simulations from the CMIP3 experiment, while the AR5 was mostly based on simulations from the CMIP5 experiment. We note that the simulations of the CMIP3 and CMIP5 experiments were found to be very similar (e.g., Knutti and Sedláček 2012; Mueller and Seneviratne 2014).

In addition to the CMIP3 and CMIP5 experiments, there are results from CORDEX, which are available for different regions (Giorgi and Gutowski 2015). For instance, assessments based on publications from an extension of the IMPACT2C project (Vautard et al. 2014; Jacob and Solman 2017) are newly available for 1.5°C projections.

Recently, simulations from the ‘Half a degree Additional warming, Prognosis and Projected Impacts’ (HAPPI) multi-model experiment have been performed to specifically assess climate changes at 1.5°C versus 2°C global warming (Mitchell et al. 2017). The HAPPI protocol consists of coupled land-atmosphere initial condition ensemble simulations with prescribed Sea Surface Temperatures (SSTs), sea ice, GHG and aerosol concentrations, solar and volcanic activity that coincide with three forced climate states: present-day (2006–2015), and future (2091–2100) either with 1.5°C or 2°C global warming (prescribed from the modified SST conditions).

Beside climate models, other models are available to assess changes in regional and global climate system (e.g., models for sea level rise, models for floods, droughts, and freshwater input to oceans, cryosphere/snow models, models for sea ice, as well as models for glaciers and ice sheets). Analyses on impacts of a 1.5°C and 2°C warmer climate using such models include e.g., Schleussner et al. (2016) and publications from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Project (Warszawski et al. 2014), which have recently derived new analyses dedicated to assessments for responses to 1.5ºC and 2ºC global warming.

Methods for the attribution of observed changes in climate and their relevance for assessing projected changes at 1.5° or 2°C global warming

As highlighted in previous IPCC Reports, detection and attribution is an approach which is typically applied to assess impacts of GHG forcing on observed changes in climate (e.g., Hegerl et al. 2007; Seneviratne et al. 2012; Bindoff et al. 2013). The reader is referred to these past IPCC reports, as well as to the IPCC Good Practice Guidance Paper on Detection and Attribution related to Anthropogenic Climate Change (Hegerl et al. 2010), for more background on this topic. It is noted that in the IPCC Working Group I (WGI) framework, 'attribution' is focused on the 'attribution to anthropogenic greenhouse gas forcing' (e.g., (Bindoff et al. 2013b) . In past IPCC Working Groups II (WGII) reports, attribution of observed impacts were also made to regional changes in climate, but without consideration of whether the patterns of changes in regional climate had had a detectable influence from GHG forcing. As noted in Section 3.2.2, a recent study (Hansen and Stone 2016) shows that most of the detected temperature-related impacts that were reported in the AR5 (Cramer et al. 2014) can be attributed to anthropogenic climate change, while the signals for precipitation-induced responses are more ambiguous.

Attribution to anthropogenic greenhouse gas forcing is an important field of research for the assessments of projected changes at 1.5°C and 2°C global warming in this Report (see Section 3.3, and in particular Table 3.2). Indeed, observed global warming compared to the pre-industrial conditions up to the 2006–2015 decade was 0.87°C, and approximately 1ºC at around 2017 (Section 3.2). Thus, 'climate at 1.5°C global warming' corresponds to approximately the addition of half a degree warming compared to present-day warming and observed regional climate changes and impacts associated with a ca. 0.5°C global warming can be inferred from the historical record (although there could be non-linear changes at higher levels of warming, Sections 3.2.1 and 3.2.2). This means that methods applied in the attribution of climate changes to human influences can be relevant for assessments of changes in climate at 1.5°C warming, especially in cases where no climate model simulations or analyses are available for the conducted assessments. Indeed, impacts at 1.5°C global warming can be assessed in parts from regional and global climate changes that have already been detected and attributed to human influence (e.g., Schleussner et al. 2017). This is because changes that could already be ascribed to anthropogenic greenhouse gas forcing pinpoint to components of the climate system which are most responsive to this forcing, and thus will continue to be under 1.5°C or 2°C global warming. For this reason, when specific projections are missing for 1.5°C global warming, some of the assessments provided in Section 3.3, in particular in Table 3.2, build upon joint assessments of a) changes that were observed and attributed to human influence up to present, i.e., for 1°C global warming and b) projections for higher levels of warming (e.g., 2°C, 3°C or 4°C) to assess the most likely changes at 1.5°C. Such assessments are for transient changes only (Section 3.2.1). We note that evidence from attribution analyses can also be considered in the assessment of the reliability of climate projections for 1.5°C and 2°C global warming.

The propagation of uncertainties from climate forcings to impacts on the ecosystems

The uncertainties associated with future projections of climate change are calculated using ensembles of model simulations (Flato et al. 2013). However, models are not fully independent, and the use of model spread as an estimator of uncertainty has been called into question (Annan and Hargreaves 2017). Many studies have been devoted to this issue, which is of high relevance policymakers. The sources of uncertainty are diverse (Rougier and Goldstein 2014), and they must be identified to better determine the limits of predictions. The following list includes several key sources of uncertainty:

1. Input uncertainties include a lack of knowledge about the boundary conditions and the noise affecting the forcing variables;
2. Parametric and structural uncertainties are related to the lack of knowledge about some processes (i.e., those that are highly complex or operate at very fine scales) and the lack of clear information about the parameterisations used in models and the differences among the models. It has also been shown that different combinations of parameters can yield plausible simulations (Mauritsen et al. 2012).
3. Observational errors include noise and the unknown covariance structure in the data used.
4. Scale uncertainty originates from the fact that impact studies require a finer scale than Earth System Model (ESM) outputs can provide (Khan and Coulibaly 2010).
5. The offline coupling of climate - impact models introduces uncertainty because this coupling permits only a limited number of linkage variables and does not allow the representation of key feedbacks. This procedure may cause a lack of coherency between the linked climate and impact models (Meinshausen et al. 2011).
6. Important biases also include the consequences of tuning using a restricted range of climate states, i.e., the periods from which climate data are available. Large biases in projections may be produced when future forcings are very different than those used for tuning.
7. It is also assumed that ESMs yield adequate estimates of climate, except for an unknown translation (Rougier and Goldstein 2014). Usually, this translation is estimated by performing an anomaly correction (the difference between the control simulation and the observed field). Such correction represents an additional uncertainty that is often ignored in the final estimate of the error bars.

Due to these uncertainties in the formulation, parametrisation, and initial states of models, any individual simulation represents only one step in the pathway followed by the climate system (Flato et al. 2013). The assessment of these uncertainties must therefore be done in a probabilistic way. It is particularly important when the signal to noise ratio is weak, as it could be when we want to assess the difference of risks between 1.5°C and 2°C global warming.

References

Annan, J. D., and J. C. Hargreaves, 2017: On the meaning of independence in climate science. Earth Syst. Dyn., 8, 211–224, doi:10.5194/esd-8-211-2017.

Ban, N., J. Schmidli, and C. Schär, 2014: Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations. J. Geophys. Res. Atmos., 119, 7889–7907, doi:10.1002/2014JD021478.

Barlow, M., and Coauthors, 2016: A Review of Drought in the Middle East and Southwest Asia. J. Clim., 29, 8547–8574, doi:10.1175/JCLI-D-13-00692.1.

Bindoff, N. L., and Coauthors, 2013a: Detection and Attribution of Climate Change: from Global to Regional Supplementary Material. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker et al., Eds., p. 25.

——, and Coauthors, 2013b: Detection and Attribution of Climate Change: from Global to Regional. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 867–952.

Cloke, H. L., F. Wetterhall, Y. He, J. E. Freer, and F. Pappenberger, 2013: Modelling climate impact on floods with ensemble climate projections. Q. J. R. Meteorol. Soc., 139, 282–297, doi:10.1002/qj.1998.

Cramer, W., and Coauthors, 2014: Detection and Attribution of Observed Impacts. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, and M.D. Mastrandrea, Eds., Cambridge University Press, Cambridge, 979–1037.

Erfanian, A., G. Wang, M. Yu, and R. Anyah, 2016: Multimodel ensemble simulations of present and future climates over West Africa: Impacts of vegetation dynamics. J. Adv. Model. Earth Syst., 8, 1411–1431, doi:10.1002/2016MS000660.

Flato, G., and Coauthors, 2013: Evaluation of Climate Models. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 741–866.

Giorgi, F., and W. J. Gutowski, 2015: Regional Dynamical Downscaling and the CORDEX Initiative. Annu. Rev. Environ. Resour., 40, 467–490, doi:10.1146/annurev-environ-102014-021217.

Hansen, G., and D. Stone, 2016: Assessing the observed impact of anthropogenic climate change. Nat. Clim. Chang., 6, 532–537, doi:10.1038/nclimate2896.

Hegerl, G. C., and Coauthors, 2007: Understanding and Attributing Climate Change. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds., Cambridge University Press, Cambridge, UK and New York, NY, USA, 663–745.

——, O. Hoegh-Guldberg, G. Casassa, M. P. Hoerling, R. S. Kovats, C. Parmesan, D. W. Pierce, and P. A. Stott, 2010: Good Practice Guidance Paper on Detection and Attribution Related to Anthropogenic Climate Change. Meeting Report of the Intergovernmental Panel on Climate Change Expert Meeting on Detection and Attribution of Anthropogenic Climate Change, T.F. Stocker, C.B. Field, D. Qin, V. Barros, G.-K. Plattner, M. Tignor, P.M. Midgley, and K.L. Ebi, Eds., IPCC Working Group I Technical Support Unit, University of Bern, Bern, Switzerland, p. 9.

Jacob, D., and S. Solman, 2017: IMPACT2C – An introduction. Clim. Serv., 7, 1–2, doi:https://doi.org/10.1016/j.cliser.2017.07.006.

——, and Coauthors, 2014: EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Chang., 14, 563–578, doi:10.1007/s10113-013-0499-2.

Kendon, E. J., N. M. Roberts, H. J. Fowler, M. J. Roberts, S. C. Chan, and C. A. Senior, 2014: Heavier summer downpours with climate change revealed by weather forecast resolution model. Nat. Clim. Chang., 4, 570–576, doi:10.1038/nclimate2258.

Khan, M. S., and P. Coulibaly, 2010: Assessing Hydrologic Impact of Climate Change with Uncertainty Estimates: Bayesian Neural Network Approach. J. Hydrometeorol., 11, 482–495, doi:10.1175/2009JHM1160.1.

Knutti, R., and J. Sedláček, 2012: Robustness and uncertainties in the new CMIP5 climate model projections. Nat. Clim. Chang., 3, 369–373, doi:10.1038/nclimate1716.

Mauritsen, T., and Coauthors, 2012: Tuning the climate of a global model. J. Adv. Model. Earth Syst., 4, 1–18, doi:10.1029/2012MS000154.

Meinshausen, M., T. M. L. Wigley, and S. C. B. Raper, 2011: Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 2: Applications. Atmos. Chem. Phys., 11, 1457–1471, doi:10.5194/acp-11-1457-2011.

Mitchell, D., and Coauthors, 2017: Half a degree additional warming, prognosis and projected impacts (HAPPI): background and experimental design. Geosci. Model Dev., 10, 571–583, doi:10.5194/gmd-10-571-2017.

Mueller, B., and S. I. Seneviratne, 2014: Systematic land climate and evapotranspiration biases in CMIP5 simulations. Geophys. Res. Lett., 41, 128–134, doi:10.1002/2013GL058055.

Prein, A. F., and Coauthors, 2015: A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges. Rev. Geophys., 53, 323–361, doi:10.1002/2014RG000475.

Rougier, J., and M. Goldstein, 2014: Climate Simulators and Climate Projections. Annu. Rev. Stat. Its Appl., 1, 103–123, doi:10.1146/annurev-statistics-022513-115652.

Salameh, T., P. Drobinski, M. Vrac, and P. Naveau, 2009: Statistical downscaling of near-surface wind over complex terrain in southern France. Meteorol. Atmos. Phys., 103, 253–265, doi:10.1007/s00703-008-0330-7.

Schleussner, C., P. Pfleiderer, and E. M. Fischer, 2017: In the observational record half a degree matters. Nat. Clim. Chang., 7, 460–462.

Schleussner, C. F. C.-F. C.-F., and Coauthors, 2016: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 degrees C and 2 degrees C. Earth Syst. Dyn., 7, 327–351, doi:10.5194/esd-7-327-2016.

Seneviratne, S. I., and Coauthors, 2012: Changes in Climate Extremes and their Impacts on the Natural Physical Environment. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of IPCC Intergovernmental Panel on Climate Change, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 109–230.

Su, B., J. Huang, M. Gemmer, D. Jian, H. Tao, T. Jiang, and C. Zhao, 2016: Statistical downscaling of CMIP5 multi-model ensemble for projected changes of climate in the Indus River Basin. Atmos. Res., 178–179, 138–149, doi:10.1016/j.atmosres.2016.03.023.

Le Treut, H., R. Somerville, U. Cubasch, Y. Ding, C. Mauritzen, A. Mokssit, T. Peterson, and M. . Prathe, 2007:

Historical Overview of Climate Change. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, Eds., Cambridge University Press, Cambridge, UK and New York, NY, USA, 93–128.

Vautard, R., and Coauthors, 2014: The European climate under a 2°C global warming. Environ. Res. Lett., 9, 034006, doi:10.1088/1748-9326/9/3/034006.

Warszawski, L., K. Frieler, V. Huber, F. Piontek, O. Serdeczny, and J. Schewe, 2014: The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): project framework. Proc. Natl. Acad. Sci. U. S. A., 111, 3228–3232, doi:10.1073/pnas.1312330110.

S3-3 Supplementary information to Section 3.3

S3-3-1 Change in global climate

The Global Mean Surface Temperature (GMST) warming reached approximately 1°C above pre-industrial levels in 2017 (Haustein et al. 2017; see also Chapter 1). At the time of writing of the AR5 WG1 report (i.e., for time frames up to 2012, Stocker et al. 2013), Hartmann et al. (2013) assessed that the globally averaged combined land and ocean surface temperature data as calculated by a linear trend, showed a warming of 0.85°C (0.65–1.06°C), over the period 1880–2012, when multiple independently produced datasets existed, and about 0.72°C (0.49–0.89°C) over the period 1951–2012. Hence most of the global warming has occurred since 1950 and it has continued substantially in recent years. The above values are for global mean warming, however, regional trends can be much more varied (Figure S3.1). With few exceptions, most land regions display stronger trends in the global mean warming, and by 2012, i.e., with a warming of about 0.85°C (see above), some land regions already displayed warming higher than 1.5°C (Figure S3.1).

It should be noted that more recent evaluations of the observational record suggest that the estimates of global warming at the time of the AR5 may have been underestimated (Cowtan and Way 2014; Richardson et al. 2016). Indeed, as highlighted in Section 3.3.1 and also discussed in Chapter 1, sampling biases and different approaches to estimate GMST (e.g., using water versus air temperature over oceans) can sensibly impact estimates of GMST warming as well as differences between model simulations and observations-based estimates (Richardson et al. 2016).

As highlighted in Chapter 1, an area in which substantial new literature has become available since the AR5 is the GMST trend over the period 1998–2012, which has been referred to by some as the “global warming hiatus” (Stocker et al. 2013; Karl et al. 2015; Lewandowsky et al. 2016; Medhaug et al. 2017). This term was used to refer to an apparent slowdown of GMST warming over that time period (although other climate variables continued to display unabated changes during that period, including a particular intense warming of hot extremes over land, Seneviratne et al. 2014). Medhaug et al. (2017) note that from a climate point of view, with 2015 and 2016 being the two warmest years on record (based on GMST), the question of whether ‘global warming has stopped’ is no longer present in the public debate. Nonetheless, the related literature is relevant for the assessment of changes in climate at 1.5°C global warming, since this event illustrates the possibility that the global temperature response may be decoupled from the radiative forcing over short time periods. While this may be associated with cooler global temperatures as experienced during the incorrectly labeled hiatus period, this implies that there could also be time periods with global warming higher than 1.5°C even if the radiative forcing would be consistent with a global warming of 1.5°C in long-term average. Recent publications have highlighted that the ‘slow-down’ in global temperature warming that occurred in the time frame of the hiatus episode was possibly overestimated at the time of the AR5 due to issues with data corrections, in particular related to coverage (Cowtan and Way 2014; Karl et al. 2015; Figure S3.2). This has some relevance for the definition of a ‘1.5°C climate’ (see Chapter 1 and Cross-Chapter Box 8 in Chapter 3 on 1.5°C warmer worlds). Overall, the issue of internal climate variability is the reason why a 1.5°C warming level needs to be determined in terms of ‘human-induced warming’ (see Chapter 1 for additonal background on this issue).

A large fraction of the detected global warming has been attributed to anthropogenic forcing (Bindoff et al. 2013a). The AR5 (Bindoff et al. 2013a) assessed that it is *virtually certain* that human influence has warmed the global climate system and that it is *extremely likely* that human activities caused more than half of the observed increase in GMST from 1951 to 2010 (supplementary Figure S3.3). The AR5 (Bindoff et al. 2013a) assessed that greenhouse gases contributed a GMST increase *likely* to be between 0.5°C and 1.3°C over the period 1951–2010, with the contributions from other anthropogenic forcings *likely* to lie between –0.6°C and 0.1°C, from natural forcings *likely* to be between –0.1°C and 0.1°C, and from internal variability *likely* to be between –0.1°C and 0.1°C. Regarding observed global changes in temperature extremes, Reports from the AR5 cycle assessed that since 1950 it is *very likely* that there has been an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights at the global scale, that is, for land areas with sufficient data (Seneviratne et al. 2012; Hartmann et al. 2013). This assessment is confirmed as part of the present report and highlights that further decreases in cold extremes and increases in hot extremes are projected for a global warming of 1.5°C.

Observed global changes in the water cycle, including precipitation, are more uncertain than observed changes in temperature (Hartmann et al. 2013; Stocker et al. 2013). The AR5 assessed that it is *very likely* that global near surface and tropospheric air specific humidity have increased since the 1970s (Hartmann et al. 2013). However, AR5 also highlighted that during recent years the near surface moistening over land has abated (*medium confidence*), and that as a result, there have been fairly widespread decreases in relative humidity near the surface over the land in recent years (Hartmann et al. 2013). With respect to precipitation, some regional precipitation trends appear to be robust (Stocker et al. 2013), but when virtually all the land area is filled in using a reconstruction method, the resulting time series of global mean land precipitation shows little change since 1900. Hartmann et al. (2013) highlight that confidence in precipitation change averaged over global land areas since 1901 is low for years prior to 1951 and medium after 1951. However, for averages over the mid-latitude land areas of the Northern Hemisphere, Hartmann et al. (2013) assessed that precipitation has likely increased since 1901 (*medium confidence* before and *high confidence* after 1951). For other latitudinal zones, area-averaged long-term positive or negative trends have *low confidence* due to data quality, data completeness or disagreement amongst available estimates (Hartmann et al. 2013). For heavy precipitation, the AR5 assessed that in land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century (Bindoff et al. 2013a).

Figures S3.4 and S3.5 display the same analyses as the left-hand panels of the Figures 3.3. and 3.4 in the main text, but based on Representative Concentration Pathway (RCP)2.6 simulations instead of RCP8.5.

S3-3-2 Regional temperature on land, including extremes

S3-3-2-1 Observed and attributed changes in regional temperature means and extremes

While the quality of temperature measurements obtained through ground observational networks tend to be high compared to that of measurements for other climate variables (Seneviratne et al. 2012), it should be noted that some regions are undersampled. Cowtan and Way (2014) highlighted issues regarding undersampling being concentrated at the Poles and over Africa, which may lead to biases in estimated changes in Global Mean Surface Temperature (GMST) (see also Section 3.3.2 and Chapter 1). This undersampling also affects the confidence of assessments regarding regional observed and projected changes in both mean and extreme temperature.

Despite this partly limited coverage, the attribution chapter of the AR5 (Bindoff et al. 2013a) and recent papers (e.g., Sun et al. 2016; Wan et al. 2018) assessed that over every continental region and in many sub-continental regions, anthropogenic influence has made a substantial contribution to surface temperature increases since the mid-20th century. For Antarctica, while changes are occurring, statistical assessment (presumably to 95% confidence) has not been achieved due primarily to the large natural variability in the weather that occurs there and the comparatively short observational record.

Regarding observed regional changes in temperature extremes, the AR5 (Hartmann et al. 2013) provided the following assessment based in part on the IPCC IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)(Seneviratne et al. 2012):

- *Likely (high confidence)* overall increases in warm days and warm nights, and decreases in cold days and cold nights in North America and Central America, Europe and Mediterranean region, in Asia, in south-east Asia and Oceania (including Australia), and in southern Africa
- *Medium confidence* overall increase in warm days and warm nights, and decreases in cold days and cold nights in South America, and North Africa and Middle East
- *Low to medium confidence* in some African regions lacking observations, but locations with observations display increases in warm days and warm nights, and decreases in cold days and cold nights.

Further, the IPCC SREX assessed (Seneviratne et al. 2012) that globally, in many (but not all) regions with sufficient data there is *medium confidence* that the length and the number of warm spells or heat waves has increased since the middle of the 20th century, and that it is *likely* that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale.

Hence, observed and attributed changes in both mean and extreme temperature consistently point to a widespread influence of human-induced warming in most land regions. We should note that there are new publications regarding observed trends in temperature and precipitation means and extremes in Africa (e.g., Ringard et al. 2016; Moron et al. 2016; Omondi et al. 2013; MacKellar et al. 2014), which may allow to increase the confidence regarding observed changes on this continent.

Specific attribution statements for changes associated with a global warming of 0.5°C are currently not available on a regional scale from the literature, unlike global assessments (Schleussner et al. 2017), although preliminary results suggest that a 0.5°C global warming can also be identified for temperature extremes in a few large regions (Europe, Asia, Russia, North America; see supplementary material of Schleussner et al. 2017).

As highlighted in Section 3.2, the observational record can be used to assess past changes associated with a global warming of of 0.5°C, with this type of assessment being considered as an analogue for the difference between a scenario at 1.5°C and at 2°C global warming. This approach has its limitations. For example, the methodology does not account for non-linearity in responses, including possible regional or global tipping points. Nonetheless, it can provide a first assessment of aspects of the climate system that have been identified as being sensitive to a global warming change of this magnitude. Schleussner et al. (2017) using this approach, assess observed changes in extreme indices for the 1991-2010 versus the 1960–1979 period, which corresponds to just about 0.5°C GMST difference in the observed record (based on the Goddard Institute for Space Studies Surface Temperature Analysis GISTEMP dataset, Hansen et al. 2010). They found that substantial changes due to 0.5°C warming are apparent for indices related to hot and cold extremes, as well as for the Warm Spell Duration Indicator (WSDI). Some results are displayed in Figure S3.6. and S3.7 Using two well established observational datasets (Hadley Centre Global Climate Extremes Index 2 (HadEX2) and Global Historical Climatology Network (GHCN)-Daily climate Extremes (GHCNDEX);, Donat et al. (2013a,b), these analysis show that one quarter of the land has experienced an intensification of hot extremes (TXx) by more than 1°C and a reduction of the intensity of cold extremes by at least 2.5°C (TNn). Half of the global land mass has experienced changes in WSDI of more than 6 days and the emergence of extremes outside the range of natural variability is particularly pronounced for this duration-based indicator (Figure 3.7). Results for TXx based on reanalysis products are similar for the 20CR product, but even more pronounced for the ERA reanalysis (as noted by Schleussner et al. 2017, however, results based on reanalysis products need, however, to be considered with caution). Overall, based on the analysis of Schleussner et al. (2017), the observational record suggest that a 0.5°C change in global warming has noticeable global impacts on temperature extremes.

S-3-3-2-2 Projected changes at 1.5°C vs. 2°C in regional temperature means and extremes

This supplementary information provides more detailed material as background for the assessment of

Section 3.3.2.2.

As noted in Section 3.3.2.2., there is a stronger warming of the regional land-based hot extremes compared to the mean global temperature warming in most land regions (also discussed in Seneviratne et al. 2016). The regions displaying the stronger contrast are Central North America, eastern North America, Central Europe, southern Europe/Mediterranean, Western Asia, Central Asia, and southern Africa. As highlighted in Vogel et al. (2017), these regions are characterized by transitional climate regimes between dry and wet climates, which are associated with strong soil moisture-temperature coupling (related to a transitional soil moisture regime Koster et al. 2004; Seneviratne et al. 2010). Several of these regions display enhanced drying under enhanced greenhouse forcing (see Section 3.3.4), which leads to a decrease of evaporative cooling and an additional regional warming compared to the global temperature response. In a recent study, Karmalkar and Bradley (2017) also found consistent results for the contiguous United States, with all subregions being projected to reach 2°C about 10–20 years before the global mean temperature.

In general, these transitional climate regions also show the largest spread in temperature extremes response, likely related to the impact of the soil moisture-temperature coupling for the overall response. This spread is due to both intermodel variations in the representation of drying trends (Orlowsky and Seneviratne 2013; Greve and Seneviratne 2015)(see also Section 3.3.4) and to differences in soil moisture-temperature coupling in climate models (Seneviratne et al. 2013; Stegehuis et al. 2013; Sippel et al. 2016), whereby feedbacks with clouds and surface radiation are also relevant (Cheruy et al. 2014). Furthermore, in some regions internal climate variability can also explain the spread in projections (Deser et al. 2012). Regions with the most striking spread in projections of hot extremes include Central Europe, with projected regional TXx warming at 1.5°C ranging from 1°C to 5°C warming, and Central North America, which displays projected changes at 1.5°C global warming ranging from no warming to 4°C warming.

Regarding results from regional studies, Vautard et al. (2014) report that most of Europe will experience higher warming than the global average with strong distributional patterns across Europe for global warming of 2°C, which is consistent with the present assessment for 1.5°C warming (Jacob et al. 2018). For instance, a North–South (West–East) warming gradient is found for summer (winter) along with a general increase and summer extreme temperatures.

It should be noted that recent evidence suggests that climate models overestimate the strength of soil moisture-temperature coupling in transitional climate regions, although it is not clear if this behavior would lead to an overestimation of projected changes in hot temperatures (Sippel et al. 2016). In addition, there are discrepancies in projections from regional vs global climate models in Europe, possibly due to differences in prescribed aerosol concentrations (Bartók et al. 2017).

While the above-mentioned hot spots of changes in temperature extremes are located in transitional climate regimes between dry and wet climates, a recent study has also performed a separate analysis of changes in temperature extremes between ‘drylands’ and ‘humid’ lands, defining the first category based on mean precipitation lower than 600 mm and the ratio of mean Precipitation to Potential Evapo-Transpiration (P/PET) being lower than 0.65 (Huang et al. 2017). This study identifies that warming is much larger in drylands compared to humid lands (by 44%), although the latter are mostly responsible for greenhouse gas emissions that underlie this change.

Figure 3.5 in Chapter 3 displays projected changes in the annual maximum daytime temperature (TXx) as a function of Global Mean Surface Temperature (GMST) for the main regions as specified in the IPCC SREX (See Figure 3.2 for a description of the regions) using Empirical Scaling Relationships (ESR; Section 3.2). The underlying model projections include Coupled Model Intercomparison Project Phase 5 (CMIP5)multi-model global climate simulations (based on the analyses of Wartenburger et al. 2017 and Seneviratne et al. 2016) and simulations from the ‘Half a degree Additional warming, Prognosis and Projected Impacts’ (HAPPI) multi-model experiments (Mitchell et al. 2017; based on analyses presented in Seneviratne et al. 2018). The CMIP5 analyses provide continuous estimates of the dependency of the analysed climate extremes as function of GMST, while the HAPPI-derived estimates are only available for the estimation of responses at two global warming levels, 1.5°C and 2°C. The CMIP5-based ESR analyses are computed from historical and RCP8.5 simulations from 26 CMIP5 global climate models (including up to 10 ensemble members per model). For the HAPPI analyses, changes in the indices and in the corresponding global mean temperatures (as indicated in the map and in the bar plots shown in the figures) are based on the 100 first ensemble members (#1 to #100) from five models (Canadian 4th generation Atmospheric global climate Model (CanAM4), Community Atmosphere Model version 4 (CAM4), European Center Hamburg model version 6-3-Default (Low) Resolution (ECHAM6-3-LR), Model for Interdisciplinary Research On Climate version 5 (MIROC5), and Norwegian Earth System Model version 1-HAPPI (NorESM1-happi)) following Seneviratne et al. (2018). For each of the HAPPI models and the two experiments considered (1.5°C relative to pre-industrial and 2°C relative to pre-industrial), we compute differences of the indices (scenario period – reference period, consisting of 10 years of data each per ensemble member). The reader is referred to the mentioned publications for more background on the analyses and data bases. Note that the ESR analyses are based on land data only for all of the considered regions, i.e., with a mask being applied to ocean data within the considered regions. (Ocean data points are, however, included for analyses for island regions provided in this Annex, i.e., a subset of the regions indicated asterisks (*) in Figure 3.2; see e.g., Figure S3.9 and similar).

Figure S3.8 displays similar analyses as Figure 3.5 but for the annual minimum Nighttime Temperatures, TNn. The mean response of these cold extremes displays less discrepancy with the global levels of warming (often close to the 1:1 line in many regions), however, there is a clear amplified warming in regions with snow and ice cover. This is expected given the Arctic warming amplification (Serreze and Barry 2011, see also AR5 overview on 'polar amplification', Masson-Delmotte et al. 2013; IPCC 2013) which is to a large extent due to snow-albedo-temperature feedbacks (Hall and Qu 2006). In some regions and for some model simulations, the warming of TNn at 1.5°C global warming can reach up to 8°C regionally (e.g., Northern Europe, Figure S3.6) and thus be much larger than the global temperature warming.

Figures S3.9 and S3.10 display the same analyses as Figures 3.5 (main text) and S.3.8 for the regions indicated with asterisks in Figure 3.2. It should be noted that for the island regions, the land fraction is often too small to be resolved by standard global climate models. For this reason, as mentioned above, the analyses for island regions (indicated with # sign) are based on both land and ocean air-temperatures and are representative of average climate conditions in the areas in which they are located.

Figure S3.13 displays maps of changes in the Number of Hot Days (NHD) and Number of Frost Days (NFD) at 1.5°C and 2°C GMST warming. These analyses reveal clear patterns of changes between the two warming levels, with decreases in frost days in many regions.

S3-3-3 Regional precipitation on land, including heavy precipitation and monsoons

Observed and attributed changes in regional precipitation

There is overall *low confidence* in observed trends for monsoons because of insufficient evidence (consistent with a previous assessment in the IPCC SREX, Seneviratne et al. 2012). There are, nonetheless, a few new assessments available, although they do not report consistent trends in different monsoon regions (Singh et al. 2014; Taylor et al. 2017; Bichet and Diedhiou 2018). For instance, (Singh et al. 2014) use precipitation observations (1951-2011) of the South Asian summer monsoon and show that there have been significant decreases in peak-season precipitation over the core-monsoon region and significant increases in daily-scale precipitation variability. Furthermore, Taylor et al. (2017) showed that over West African Sahel the frequency of extreme storms tripled since 1982 in satellite observations and (Bichet and Diedhiou 2018) confirm that the region has been wetter during the last 30 years but dry spells are shorter and more frequent with a decreasing precipitation intensity in the western part (over Senegal). However, there is not sufficient evidence to provide higher than *low confidence* in the assessment of observed in overall trends in monsoons

Projected changes at 1.5°C and 2°C in regional precipitation

The AR5 assessed that the global monsoon, aggregated over all monsoon systems, is likely to strengthen (Christensen et al. 2013). There are a few publications that provide more recent evaluations on projections of changes in monsoons for high-emissions scenarios. Jiang and Tian (2013), who compared the results of 31 and 29 reliable climate models under the SRES A1B scenario or the RCP4.5 scenario, respectively, found weak projected changes in the East Asian winter monsoon as a whole relative to the reference period (1980–1999). Regionally, they found a weakening north of about 25°N in East Asia and a strengthening south of this latitude, which resulted from atmospheric circulation changes over the western North Pacific and Northeast Asia. This is linked to the weakening and northward shift of the Aleutian Low, and from decreased northwest-southeast thermal and sea level pressure differences across Northeast Asia. In summer, Jiang and Tian (2013) found a projected strengthening (albeit, slight) of monsoon in East China over the 21st century as a consequence of an increased land-sea thermal contrast between the East Asian continent and the adjacent western North Pacific and South China Sea. Using six CMIP5 model simulations of the RCP8.5 high-emission scenario, Jones and Carvalho (2013) found a 30% increase in the amplitude of the South American Monsoon System (SAMS) from the current level by 2045–2050. They also found an ensemble mean onset date of the SAMS which was 17 days earlier, and a demise date 17 days later, by 2045–2050. The most consistent CMIP5 projections analysed confirmed the increase in the total precipitation over southern Brazil, Uruguay, and northern Argentina. Given that scenarios at 1.5°C or 2°C would include a substantially smaller radiative forcing than those assessed in the studies of Jiang and Tian (2013) and Jones and Carvalho (2013), there is *low confidence* regarding changes in monsoons at these low global warming levels, as well as regarding differences in responses at 1.5°C vs. 2°C.

Several analyses of GCM-RCM simulations in the framework of the Coordinated Regional Climate Downscaling Experiment for Africa (CORDEX-AFRICA) were performed to capture changes in the African climate system in a warmer climate. Sylla et al. (2015, 2016) analyzed the response of the annual cycle of high-intensity daily precipitation events over West Africa to anthropogenic greenhouse gas for the late twenty-first century. The late-21st-century projected changes in mean precipitation exhibit a delay of the monsoon season and a decrease in frequency but increase in intensity of very wet events, particularly in the premonsoon and early mature monsoon stages, more pronounced in RCP8.5 over the Sahel and in RCP4.5 over the Gulf of Guinea. The premonsoon season also experiences the largest changes in daily precipitation statistics, with increased risk of drought associated with a decrease in mean precipitation and frequency of wet days and an increased risk of flood associated with very wet events. Weber et al. assessed the changes in temperature and rainfall related climate change indices in a 1.5°C, 2°C and 3°C global warming world for the Africa continent. The results showed the daily rainfall intensity is also projected to increase for higher global warming scenarios especially for the African Sub-Saharan coastal regions.

Figure S3.14 displays the same analyses as Figure 3.9 for the regions indicated with asterisks in Figure 3.2. For the underlying methodology, a similar approach was used as for Figure 3.5 (see Section S3.3.2.2).

S3-3-4 Drought and dryness

Figure S3.15 displays the same analyses as Figure 3.12 for the regions indicated with asterisks in Figure 3.2. For the underlying methodology, a similar approach was used as for Figure 3.5 (see Section S3.3.2.2).

Supplementary Figures

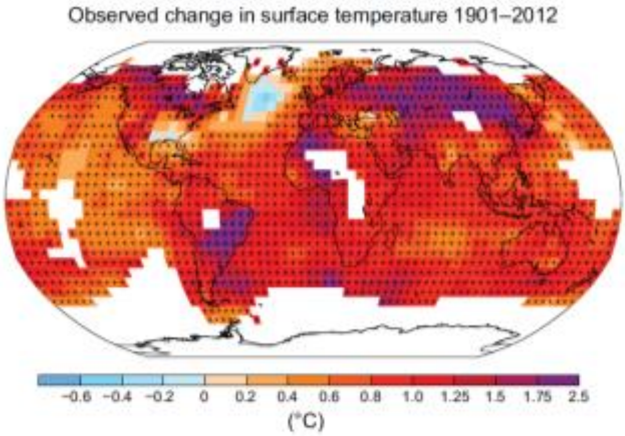


Figure S3.1: Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset. Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Grid boxes where the trend is significant at the 10% level are indicated by a + sign. From Stocker et al. (2013).

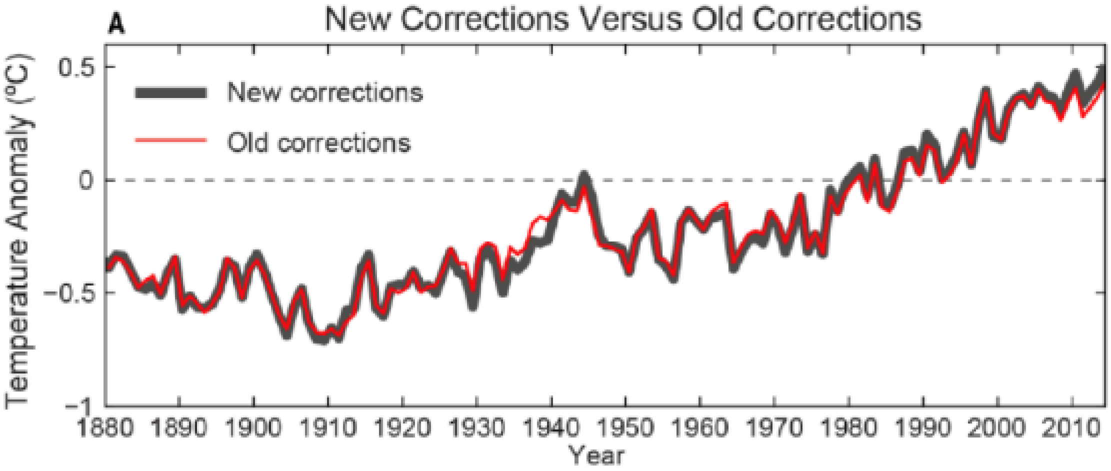
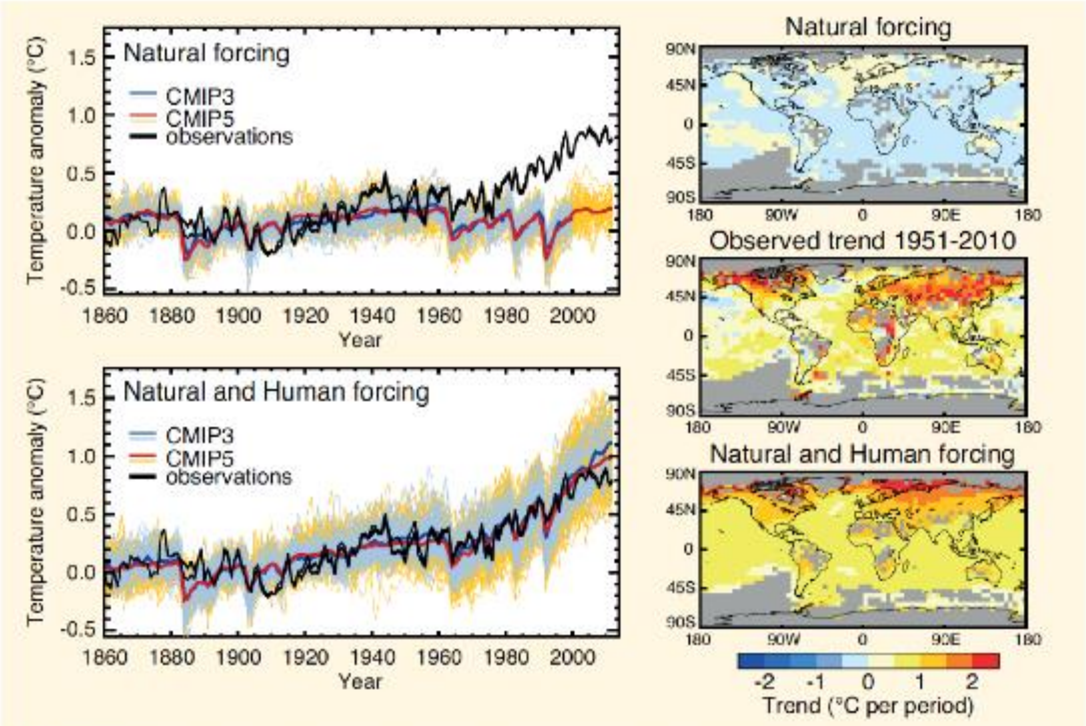


Figure S3.2: Global temperature warming using older and newer corrections (Karl et al. 2015)



FAQ 10.1, Figure 1 | (Left) Time series of global and annual-averaged surface temperature change from 1860 to 2010. The top left panel shows results from two ensemble of climate models driven with just natural forcings, shown as thin blue and yellow lines; ensemble average temperature changes are thick blue and red lines. Three different observed estimates are shown as black lines. The lower left panel shows simulations by the same models, but driven with both natural forcing and human-induced changes in greenhouse gases and aerosols. (Right) Spatial patterns of local surface temperature trends from 1951 to 2010. The upper panel shows the pattern of trends from a large ensemble of Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations driven with just natural forcings. The bottom panel shows trends from a corresponding ensemble of simulations driven with natural + human forcings. The middle panel shows the pattern of observed trends from the Hadley Centre/Climatic Research Unit gridded surface temperature data set 4 (HadCRUT4) during this period.

Figure S3.3. Attribution of global warming change (from IPCC AR5, Bindoff et al. 2013).

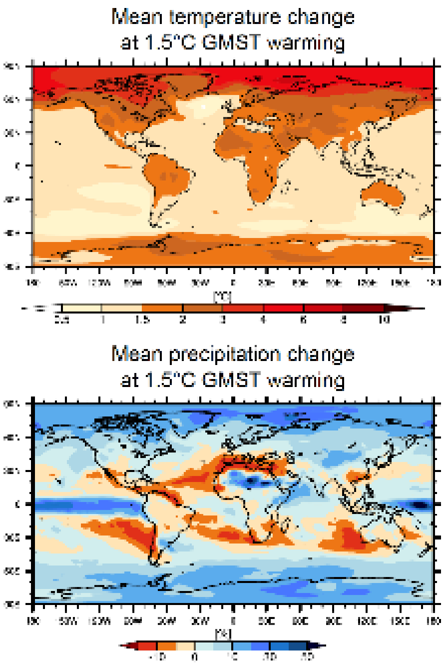


Figure S3.4: Same as left-hand plots of Figure 3.3, but based on the Representative Concentration Pathway (RCP)2.6 scenarios

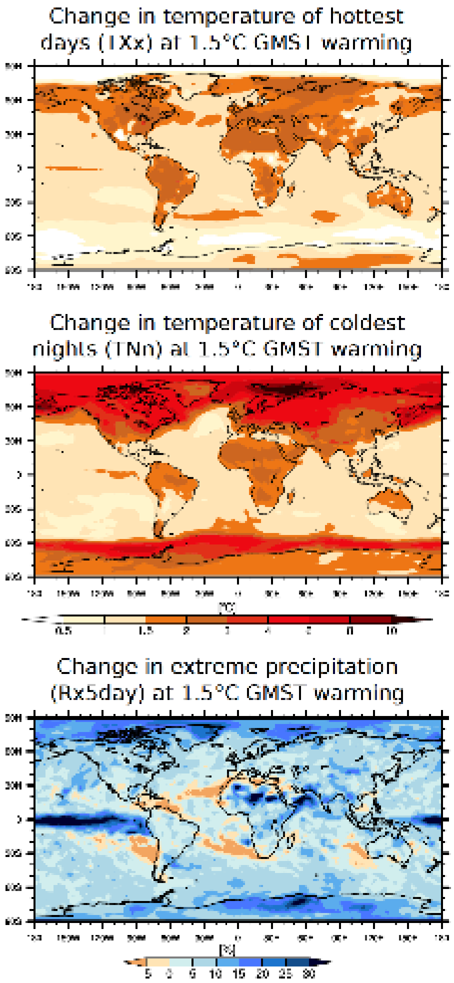


Figure S3.5: Same as left-hand plot of Figure 3.4, but based on the Representative Concentration Pathway (RCP)2.6 scenarios

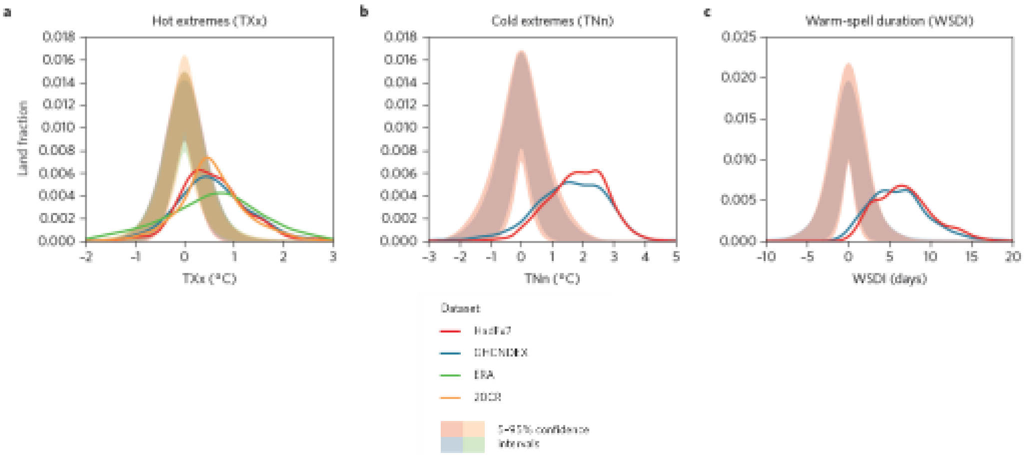


Figure S3.6 : Difference in extreme temperature event indices for 0.5°C warming over the observational record. Probability density functions show the globally aggregated land fraction that experienced a certain change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. For TXx, the analysis includes also reanalysis data from the European Centre for Medium-Range Forecasts (ECMWF) (ECMWF Reanalysis 40 (ERA-40) and Interim (ERA-Interim), used as a combined dataset including ERA-40 until 1979 and ERA-Interim from

1979 onward) and the Twentieth Century Reanalysis (20CR) ERA and 20CR over the global land area. Light-coloured envelopes illustrate the changes expected by internal variability alone, estimated by statistically resampling individual years. From Schleussner et al. (2017)

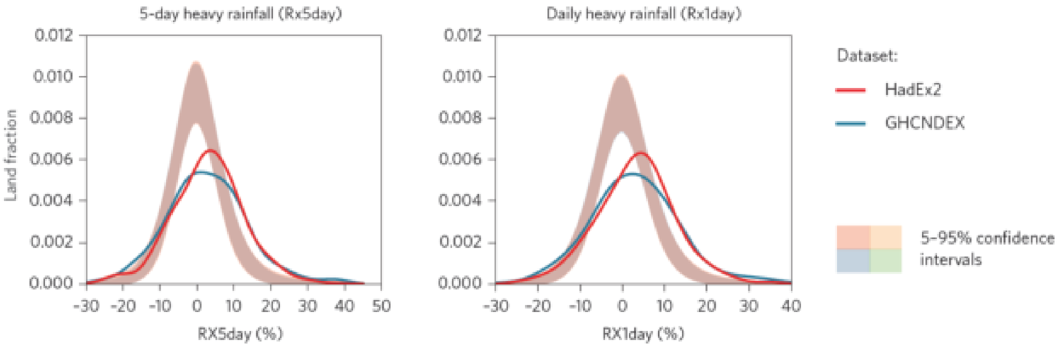


Figure S3.7 : Differences in extreme precipitation event indices for 0.5°C warming over the observational record. Probability density functions show the globally aggregated land fraction that experienced a certain change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. Light-coloured envelopes illustrate the changes expected by internal variability alone, estimated by statistically resampling individual years. From Schleussner et al. (2017)

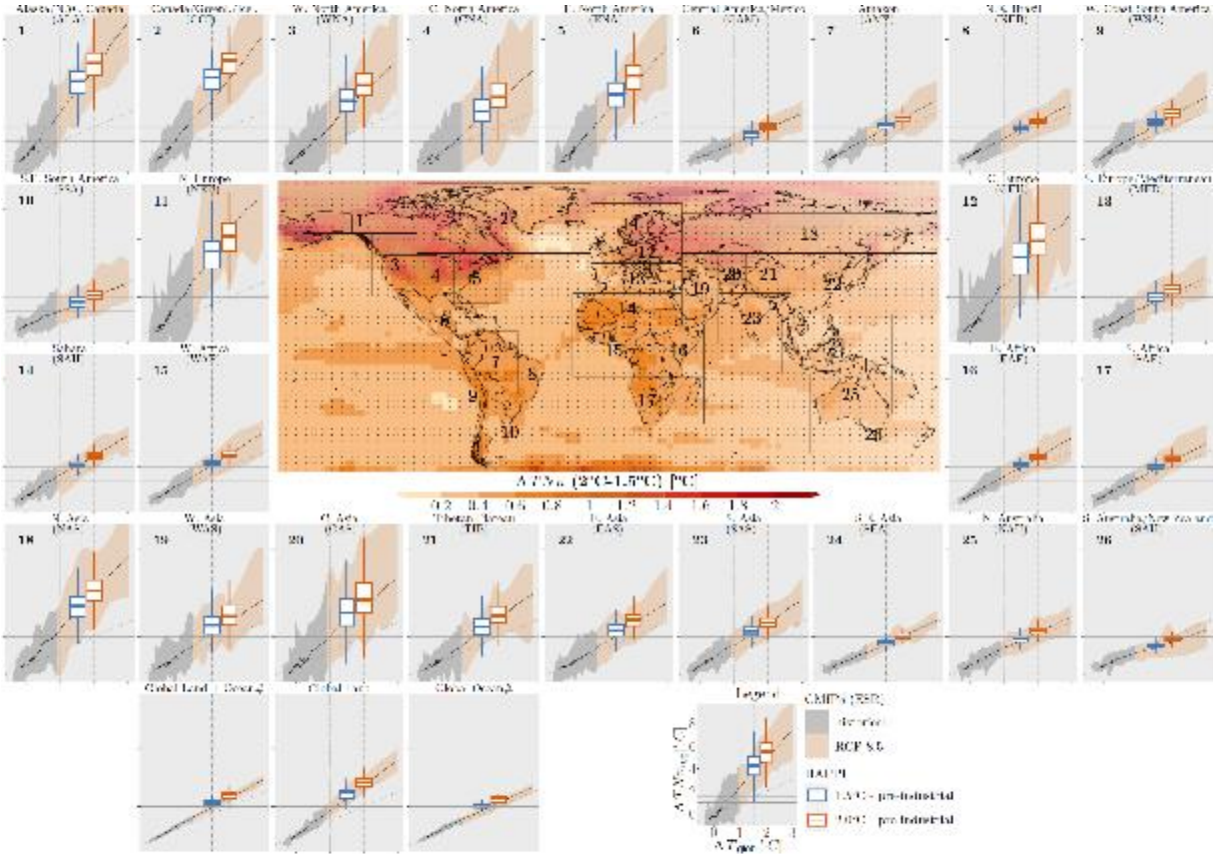


Figure S3.8 : Same analysis as Figure 3.5, but for the annual minimum night-time temperature (TNn). For more details on computation, see description of computation of Figure 3.5 in the present Annex, as well as Wartenburger et al. (2017), Seneviratne et al. (2016) and Seneviratne et al. (2018).

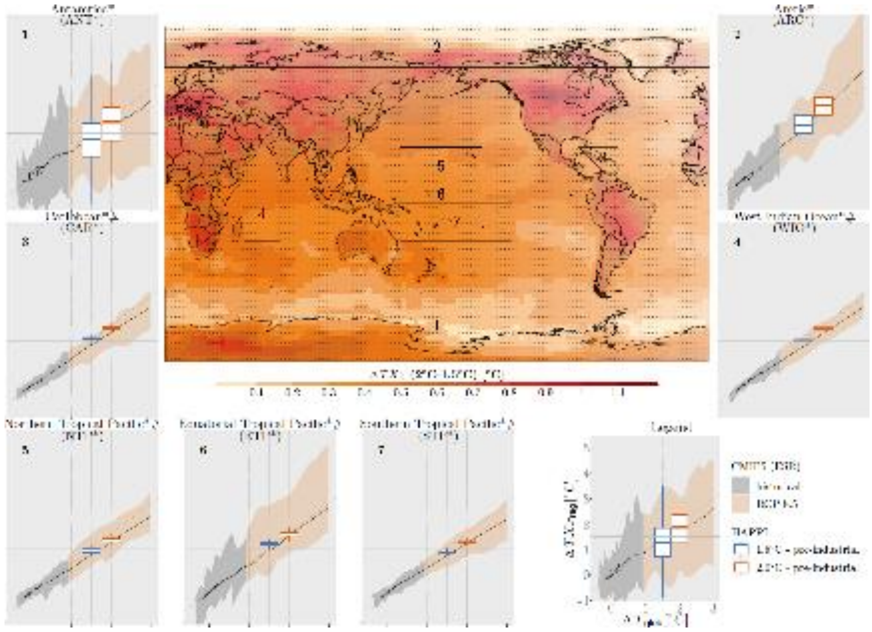


Figure S3.9: Same analysis as Figure 3.5 (projected changes in annual maximum daytime temperature (TXx) as function of global temperature warming) for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses. See description of computation of Figure 3.5 in the present Annex for more details.

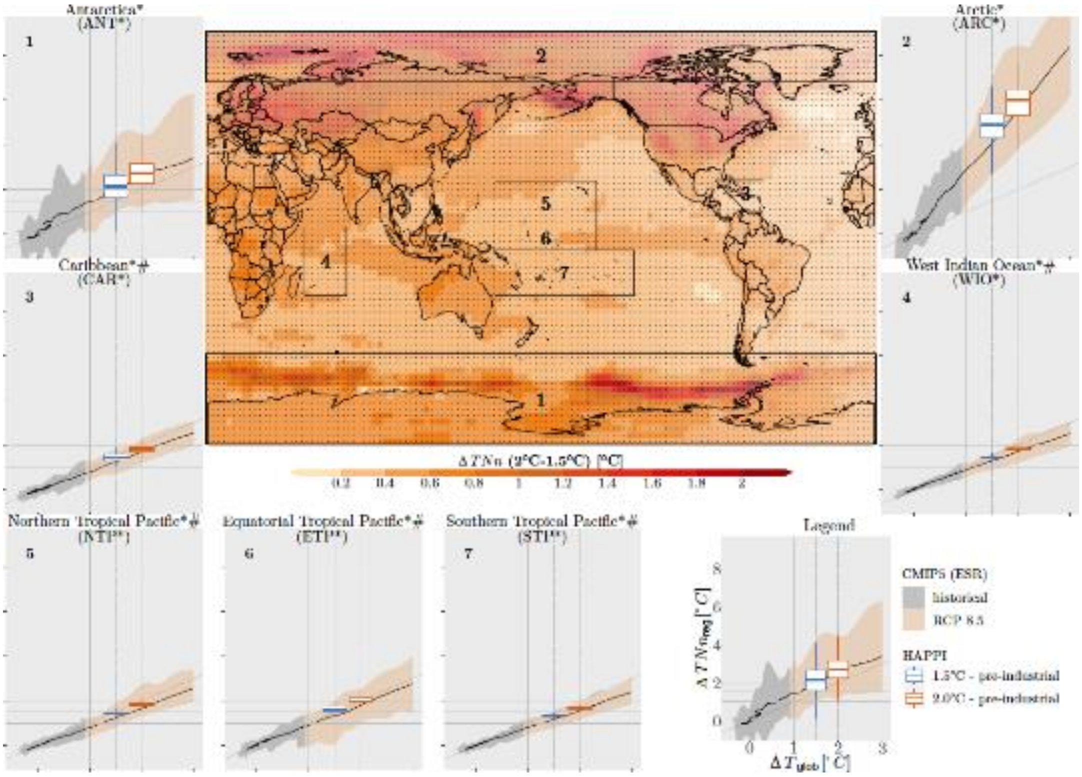


Figure S3.10: Same analysis as Figure S3.8 (projected changes in annual minimum nightime temperature (TNn) as function of global temperature warming) for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

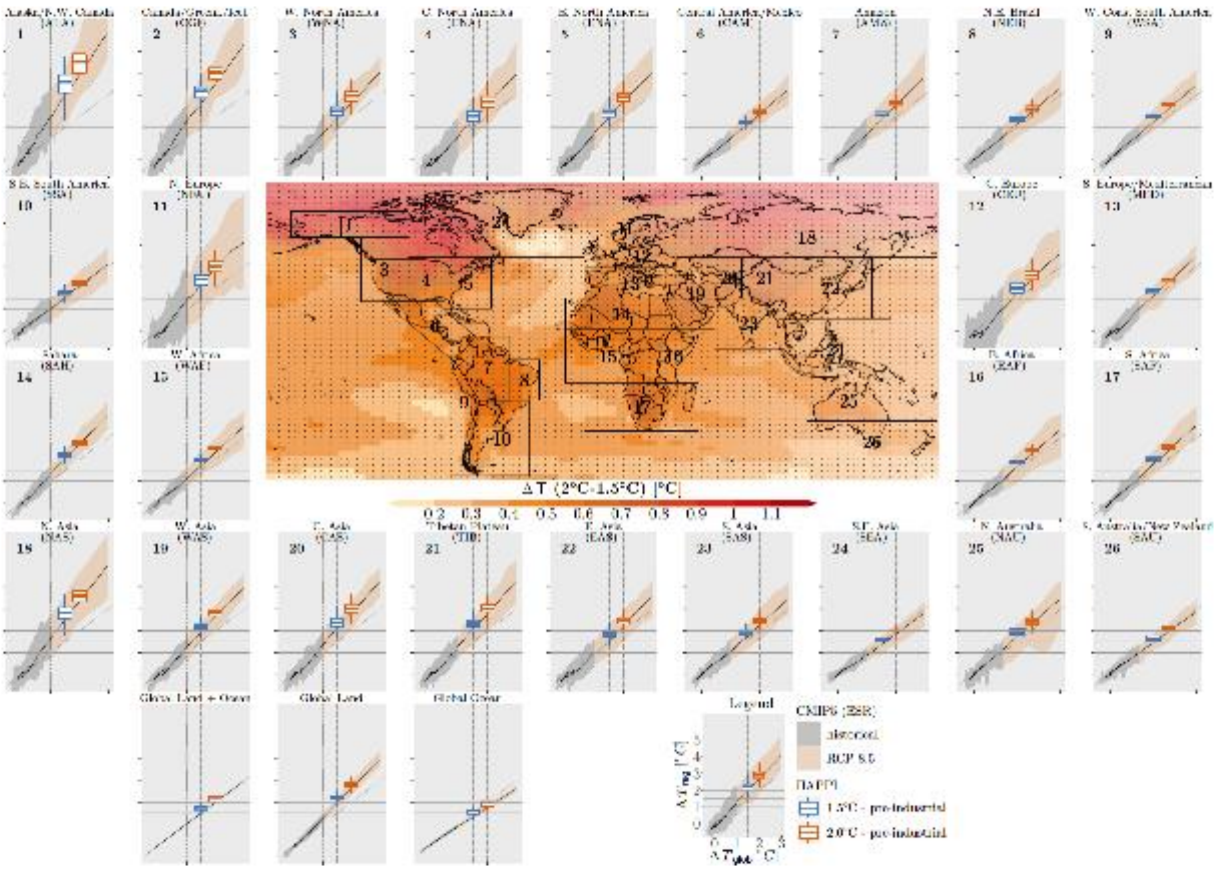


Figure S3.11: Same analysis as Figure 3.5, but for the mean surface temperature (Tmean).

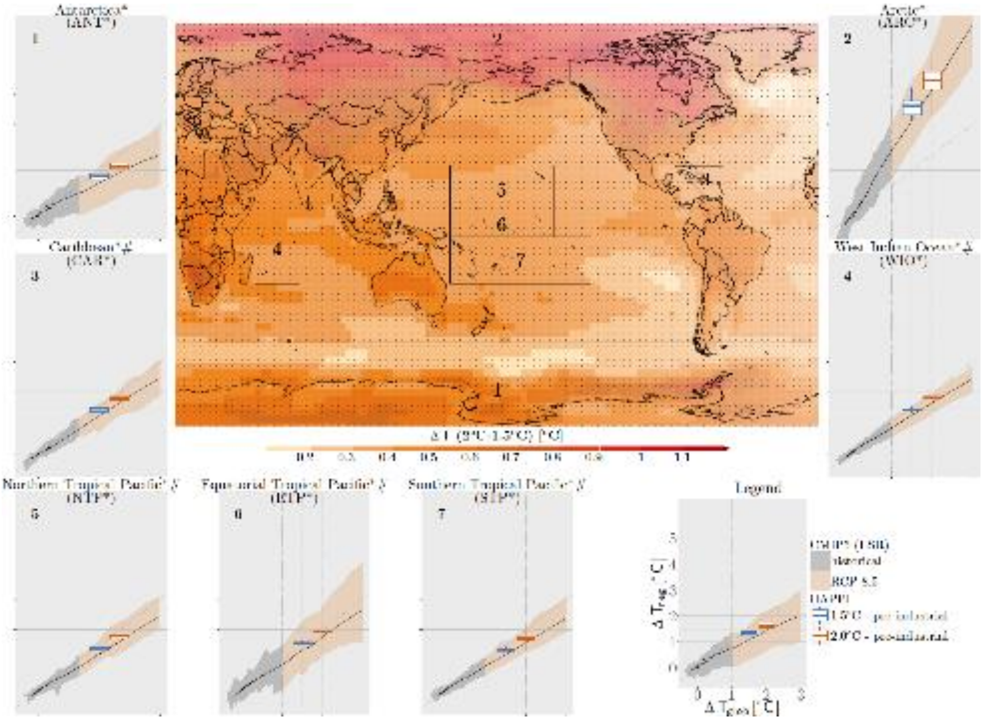


Figure S3.12: Same analysis as Figure 3.11 (projected in the changes in the mean surface temperature (Tmean) as function of the mean global temperature) for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

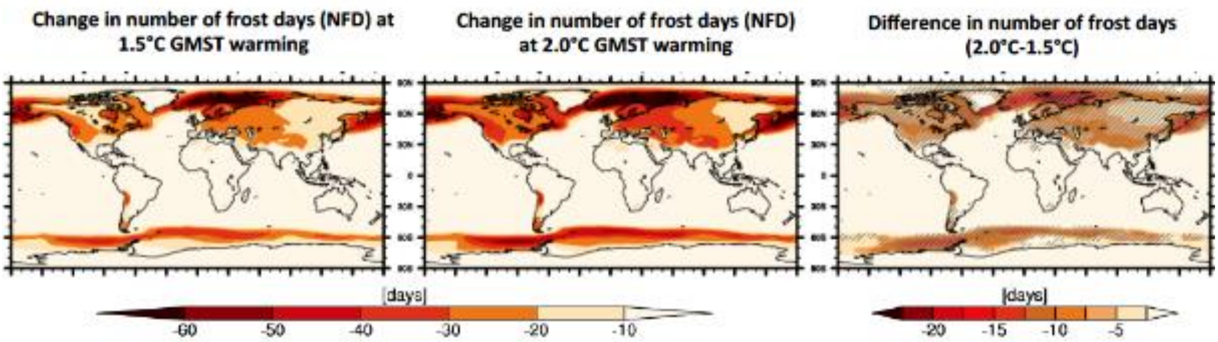


Figure S3.13: Projected changes in number of hot days (10% warmest days, top) and in number of frost days (days with T<0°C, bottom) at 1.5°C (left) and 2°C (right) GMST warming, and their difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Adapted from Wartenburger et al. (2017).

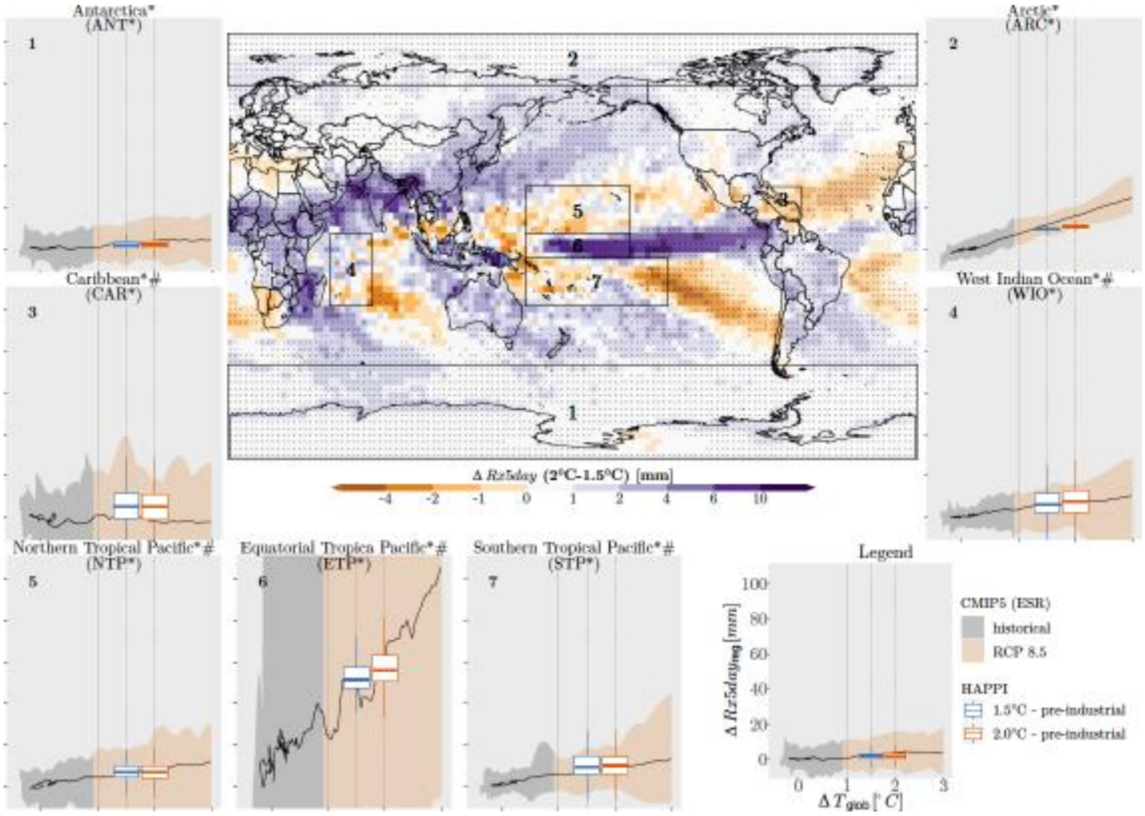


Figure S3.14: Same analysis as Figure 3.9 for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

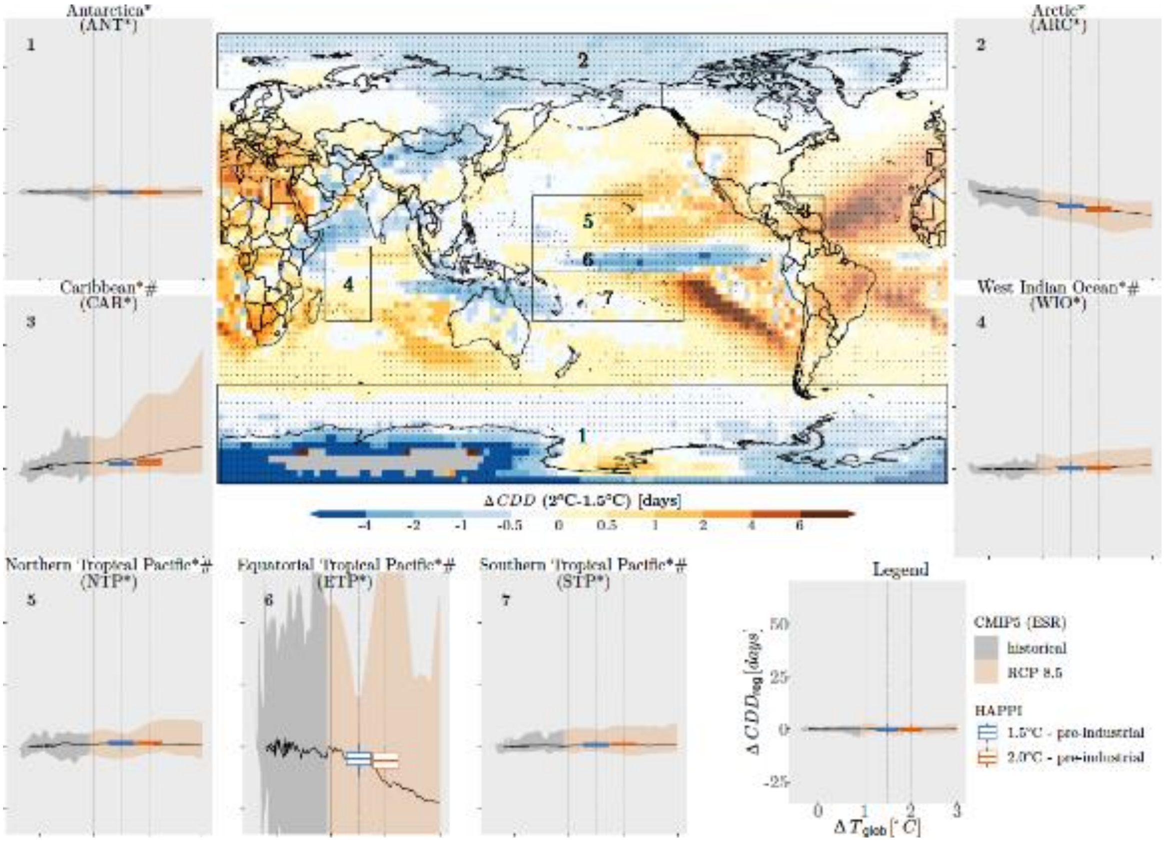


Figure S3.15: Same analysis as Figure 3.12 for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

References

Abatzoglou, J. T., and A. P. Williams, 2016: Impact of anthropogenic climate change on wildfire across western US forests. Proc. Natl. Acad. Sci. U. S. A., 113, 11770–11775, doi:10.1073/pnas.1607171113.

Bartók, B., and Coauthors, 2017: Projected changes in surface solar radiation in CMIP5 global climate models and in EURO-CORDEX regional climate models for Europe. Clim. Dyn., 49, 2665–2683, doi:10.1007/s00382-016-3471-2.

Bichet, A., and A. Diedhiou, 2018: West African Sahel becomes wetter during the last 30 years but dry spells are shorter and more frequent. Clim. Res.,.

Bindoff, N. L., and Coauthors, 2013: Detection and Attribution of Climate Change: from Global to Regional Supplementary Material. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker et al., Eds., p. 25.

Cheruy, F., J. L. Dufresne, F. Hourdin, and A. Ducharne, 2014: Role of clouds and land-atmosphere coupling in midlatitude continental summer warm biases and climate change amplification in CMIP5 simulations. Geophys. Res. Lett., 41, 6493–6500, doi:10.1002/2014GL061145.

Christensen, J. H., and Coauthors, 2013: Climate Phenomena and their Relevance for Future Regional Climate Change. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker et al., Eds., Cambridge University Press, Cambridge, UK and New York, NY, USA.

Coumou, D., and A. Robinson, 2013: Historic and future increase in the global land area affected by monthly heat extremes. Environ. Res. Lett., 8, 34018, doi:10.1088/1748-9326/8/3/034018.

Cowtan, K., and R. G. Way, 2014: Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. Q. J. R. Meteorol. Soc., 140, 1935–1944, doi:10.1002/qj.2297.

Deser, C., R. Knutti, S. Solomon, and A. S. Phillips, 2012: Communication of the role of natural variability in future North American climate. Nat. Clim. Chang., 2, 775–779, doi:10.1038/nclimate1562.

Donat, M. G., and Coauthors, 2013a: Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. J. Geophys. Res. Atmos., 118, 2098–2118, doi:10.1002/jgrd.50150.

Donat, M. G., and Coauthors, 2013b: Global Land-Based Datasets for Monitoring Climatic Extremes. Bull. Am. Meteorol. Soc., 94, 997–1006, doi:10.1175/BAMS-D-12-00109.1.

Greve, P., and S. I. Seneviratne, 2015: Assessment of future changes in water availability and aridity. Geophys. Res. Lett., 42, 5493–5499, doi:10.1002/2015GL064127.

Guo, X., J. Huang, Y. Luo, Z. Zhao, and Y. Xu, 2017: Projection of heat waves over China for eight different global warming targets using 12 CMIP5 models. Theor. Appl. Climatol., 128, 507–522, doi:10.1007/s00704-015-1718-1.

Hall, A., and X. Qu, 2006: Using the current seasonal cycle to constrain snow albedo feedback in future climate change. Geophys. Res. Lett., 33, L03502, doi:10.1029/2005GL025127.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. Rev. Geophys., 48, RG4004, doi:10.1029/2010RG000345.

Hartmann, D. L., and Coauthors, 2013: Observations: Atmosphere and Surface. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T.F. Stocker et al., Eds., Cambridge University Press, Cambridge, UK and New York, NY, USA, 159–254.

Haustein, K., M. R. Allen, P. M. Forster, F. E. L. Otto, D. M. Mitchell, H. D. Matthews, and D. J. Frame, 2017: A real-time Global Warming Index. Sci. Rep., 7, 15417, doi:10.1038/s41598-017-14828-5.

Huang, J., H. Yu, A. Dai, Y. Wei, and L. Kang, 2017: Drylands face potential threat under 2°C global warming target. Nat. Clim. Chang., 7, 417–422, doi:10.1038/nclimate3275.

Jiang, D., and Z. Tian, 2013: East Asian monsoon change for the 21st century: Results of CMIP3 and CMIP5 models. Chinese Sci. Bull., 58, 1427–1435, doi:10.1007/s11434-012-5533-0.

Jones, C., and L. M. V. Carvalho, 2013: Climate change in the South American monsoon system: Present climate and CMIP5 projections. J. Clim., 26, 6660–6678, doi:10.1175/JCLI-D-12-00412.1.

Karl, T. R., and Coauthors, 2015: Possible artifacts of data biases in the recent global surface warming hiatus. Science (80-.)., 348.

Karmalkar, A. V., and R. S. Bradley, 2017: Consequences of Global Warming of 1.5°C and 2°C for Regional Temperature and Precipitation Changes in the Contiguous United States. PLoS One, 12, e0168697, doi:10.1371/journal.pone.0168697.

Koster, R. D., and Coauthors, 2004: Regions of Strong Coupling Between Soil Moisture and Precipitation. Science (80-.)., 305.

Lewandowsky, S., J. S. Risbey, and N. Oreskes, 2016: The pause in global warming: Turning a routine fluctuation into a problem for science. Bull. Am. Meteorol. Soc., 97, 723–733, doi:10.1175/BAMS-D-14-00106.1.

Mahlstein, I., R. Knutti, S. Solomon, and R. W. Portmann, 2011: Early onset of significant local warming in low latitude countries. Environ. Res. Lett., 6, 34009, doi:10.1088/1748-9326/6/3/034009.

Medhaug, I., M. B. Stolpe, E. M. Fischer, and R. Knutti, 2017: Reconciling controversies about the “global warming hiatus.” Nature, 545, 41–47, doi:10.1038/nature22315.

Orlowsky, B., and S. I. Seneviratne, 2013: Elusive drought: uncertainty in observed trends and short- and long-term CMIP5 projections. Hydrol. Earth Syst. Sci., 17, 1765–1781, doi:10.5194/hess-17-1765-2013.

Richardson, M., K. Cowtan, E. Hawkins, and M. B. Stolpe, 2016: Reconciled climate response estimates from climate models and the energy budget of Earth. Nat. Clim. Chang., 6, 931, doi:10.1038/nclimate3066.

Schleussner, C., P. Pfleiderer, and E. M. Fischer, 2017: In the observational record half a degree matters. Nat. Clim. Chang., 7, 460–462.

Seneviratne, S. I., T. Corti, E. L. Davin, M. Hirschi, E. B. Jaeger, I. Lehner, B. Orlowsky, and A. J. Teuling, 2010: Investigating soil moisture-climate interactions in a changing climate: A review. Earth-Science Rev., 99, 125–161, doi:10.1016/j.earscirev.2010.02.004.

Seneviratne, S. I., and Coauthors, 2012: Changes in Climate Extremes and their Impacts on the Natural Physical Environment. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of IPCC Intergovernmental Panel on Climate Change, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 109–230.

Seneviratne, S. I., and Coauthors, 2013: Impact of soil moisture-climate feedbacks on CMIP5 projections: First results from the GLACE-CMIP5 experiment. Geophys. Res. Lett., 40, 5212–5217, doi:10.1002/grl.50956.

——, M. G. Donat, B. Mueller, and L. V. Alexander, 2014: No pause in the increase of hot temperature extremes. Nat. Clim. Chang., 4, 161–163, doi:10.1038/nclimate2145.

——, ——, A. J. Pitman, R. Knutti, and R. L. Wilby, 2016: Allowable CO2 emissions based on regional and impact-related climate targets. Nature, 529, 477–483, doi:10.1038/nature16542.

Serreze, M. C., and R. G. Barry, 2011: Processes and impacts of Arctic amplification: A research synthesis. Glob. Planet. Change, 77, 85–96, doi:10.1016/j.gloplacha.2011.03.004.

Singh, D., M. Tsiang, B. Rajaratnam, and N. S. Diffenbaugh, 2014: Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. Nat. Clim. Chang., 4, 456–461, doi:10.1038/nclimate2208.

Sippel, S., J. Zscheischler, M. D. Mahecha, R. Orth, M. Reichstein, M. Vogel, and S. I. Seneviratne, 2016: Refining multi-model projections of temperature extremes by evaluation against land-atmosphere coupling diagnostics. Earth Syst. Dyn. Discuss., 1–24, doi:10.5194/esd-2016-48.

Stegehuis, A. I., A. J. Teuling, P. Ciais, R. Vautard, and M. Jung, 2013: Future European temperature change uncertainties reduced by using land heat flux observations. Geophys. Res. Lett., 40, 2242–2245, doi:10.1002/grl.50404.

Stocker, T. F., and Coauthors, 2013: Technical Summary. T.F. Stocker et al., Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,.

Sylla, M. B., F. Giorgi, J. S. Pal, P. Gibba, I. Kebe, and M. Nikiema, 2015: Projected Changes in the Annual Cycle of High-Intensity Precipitation Events over West Africa for the Late Twenty-First Century. J. Clim., 28, 6475–6488, doi:10.1175/JCLI-D-14-00854.1.

——, N. Elguindi, F. Giorgi, and D. Wisser, 2016: Projected robust shift of climate zones over West Africa in response to anthropogenic climate change for the late 21st century. Clim. Change, 134, 241–253, doi:10.1007/s10584-015-1522-z.

Taylor, C. M., and Coauthors, 2017: Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. Nature, 544, 475–478, doi:10.1038/nature22069.

Vautard, R., and Coauthors, 2014: The European climate under a 2°C global warming. Environ. Res. Lett., 9, 34006, doi:10.1088/1748-9326/9/3/034006.

Vogel, M. M., R. Orth, F. Cheruy, S. Hagemann, R. Lorenz, B. J. J. M. van den Hurk, and S. I. Seneviratne, 2017: Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture-temperature feedbacks. Geophys. Res. Lett., 44, 1511–1519, doi:10.1002/2016GL071235.

Wartenburger, R., M. Hirschi, M. G. Donat, P. Greve, A. J. Pitman, and S. I. Seneviratne, 2017a: Changes in regional climate extremes as a function of global mean temperature: an interactive plotting framework. *Geosci. Model Dev.*, **10**, 3609–3634, doi:10.5194/gmd-2017-33.

Weber, T., A. Haensler, D. Rechid, S. Pfeifer, B. Eggert, and D. Jacob, 2018: Analysing regional climate change in Africa in a 1.5°C, 2°C and 3°C global warming world. Earth’s Futur.,.

S3-4_ Supplementary information to Section 3.4

These tables document some of the quantitative projections of projected climate change impacts that are to be found in the literature cited in this report. They do not necessarily contain all of the quantitative projections that could be found in the literature, in particular where a single publication contains a large number of projections.

Table S1 – 3.4.2 Freshwater resources

See Excel file : « Table_SI-3.4.2.xls »

Table S2 – 3.4.3 Terrestrial and wetland ecosystems

See Excel file : « Table_SI-3.4.3.xls »

Table S3- 3.4.4 Ocean Systems

See Excel file : « Table_SI-3.4.4.xls »

Table S4 – 3.4.5 – Coastal and low-lying areas

See Excel file : « Table_SI-3.4.5.xls »

Table S5 – 3.4.6. Food security and food production systems

See Excel file : « Table_SI-3.4.6.xls »

S3-4-2_Supplementary information to Section 3.4.2

3.4.2 Freshwater resources (quantity and quality)

3.4.2.1 Water availability

In this section, Arnell and Lloyd-Hughes (2014) assess water scarcity based on the simple indicatior of average annual runoff per capita called water resources stress and define that watershed is exposed to such stress if watershed average annual runoff is less than 1000 m^3 cap^{-1} yr^{-1}. The same condition is applied to identify chronic supply-side water scarcity within a given spatial unit in the study of Gerten et al. (2013) that refer to Falkenmark and Widstrand (1992) whose index is called Withdrawal to Water Resouces (WWR) ratio. With WWR, Hanasaki et al. (2013) indicate a chronic water shortage if water withdrawal exceeds 40% of the water resources in a region. A quantitative metric of freshwater stress is defined in terms future projections of population and aridity, where freshwater stress index is caluculated as a population change index multiplied by an aridity change index Karnauskas et al. (2018). Schewe et al. (2014) apply two water scarcity classes: annual blue water availability below 500 m^3 per cabita, namely absolute water scarcity, and below 1,000 m^3 per capita that is referred to as chronic water scarcity.

3.4.2.2 Extreme hydrological events (floods and droughts)

Alfieri et al. (2017) assume population who have any positive flood depth is affected by flood to estimate the potential population affected by overlaying population density and flood hazard maps. Arnell et al. (2018) define exposure to river flooding by the average annual number of people living in major floodplains affected by floods grater than the baseline 30-year flood. Arnell and Lloyd-Hughes (2014) use an indicator in which the number of flood-prone people living in areas where the frequency of the baseline (1960–1990) 20-year flood either doubles (occurs more frequently than one in 10 years) or halves (occurs more rarely than one in 40 years) although these thresholds are arbitrary. Kinoshita et al. (2018) estimate fatalities due to flooding by multiplying exposure (population prone to flooding, defined in the study as gridded population) by vulnerability and numerically calculate fllod hazard as the extent and depth of flood, while estimating potential affected exposure by superimposing the modeled hazard on the population data. In the study, Kinoshita et al. (2018) consider exposure as gidded population whereas historical vulnerability is defined as a ratio of the observed flood consequences and potentially affected exposure at a national level in equation.

Definiton of drought. In the study of Arnell et al. (2018), drought is presented by the standardized runoff index called SRI, which is calculated from monthly runoff simulated with the MacPDM.09 global hydrological model described in Gosling and Arnell (2010), and define the occurrence of a drought that when the SRI is less than –1.5 and as for drought frequency for a given time series of monthly runoff, it is determined by counting the number of months with SRI less than –1.5. Liu et al. (2018) quantify the changes in drought characteristics, adopting Palmer Drought Severity Index (PDSI) that describes the balance between water supply (precipitation) and atmospheric evaporative demand required the precipitation estimated under climatically appropriate for existing conditions, which is described by Zhang et al. (2016) Wells et al. (2004) and Zhang et al. (2016). Liu et al. (2018) other study suggest that PDSI is commonly applicable as an indication of meteorological drought and a hydrological drought for a multiyear time series. Liu et al. (2018) assume a severe drought event when the monthly PDSI is < -3, and identify a severe drought year if a severe drought occurs for at least a month in a year, while quantifying population affected by severe drought per grid-cell as (population * annual frequency of severe drought).

3.4.2.3 Groundwater

*Definiton of groundwater recharge.*Portmann et al. (2013) assess groundwater with groundwater recharge (GWR), which is assumed to curbed by a maximum groundwater recharge rate per a day.

GWR occurs if daily precipitation exceeds 12.5 mm d^{-1} in case of medium to coarse grained soils (Portmann et al., 2013). In some regions, groundwater is often intensively used to supplement the excess demand, often leading to groundwater depletion, besides, climate change adds further pressure on water resources and exaggerates human water demands due to increasing temperatures over agricultural lands (Wada et al. 2017).

3.4.2.4 Water quality

Water temperature directly affects water quality, and the most chemical and bacteriological processes are accelerated according to the temperature rise (Watts et al. 2015). Hosseini et al. (2017) summarize that the main impact on water quality due to climate change is attributed to changing air temperature and hydrology, and particularly ambient air temperature directly affect water temperature that is projected to increase due to global warming. Watts et al. (2015) describe that water quality is affected by many factors, including water temperature, hydrological regime, nutrient status and mobilization of toxic substances as well as point source, diffuse discharge and acidification potential, referring to (Whitehead et al. 2009). Patiño et al. (2014) reveal that changes in water quality can influence the spread of harmful aquatic species, referring to the fact that toxic algae are lethal to some aquatic animals and has posed considerable ecological and economic impacts on freshwater and marine ecosystems. Bonte and Zwolsman (2010) state that salinisation due to rising sea levels as well as poor land management and excessive groundwater extractions is putting a strain on freshwater resources availability around the world. Attributing changes in river water quality to specific factors are difficult since multiple factors act at different temporal and spatial scales, and it often requires examining long-term series of continuous data (Aguilera et al. 2015).

References

Aguilera, R., R. Marcé, and S. Sabater, 2015: Detection and attribution of global change effects on river nutrient dynamics in a large Mediterranean basin. Biogeosciences, 12, 4085–4098, doi:10.5194/bg-12-4085-2015.

Alfieri, L., B. Bisselink, F. Dottori, G. Naumann, A. de Roo, P. Salamon, K. Wyser, and L. Feyen, 2017: Global projections of river flood risk in a warmer world. Earth's Futur., 5, 171–182, doi:10.1002/2016EF000485.

Arnell, N. W., and B. Lloyd-Hughes, 2014: The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. Clim. Change, 122, 127–140, doi:10.1007/s10584-013-0948-4.

Arnell, N. W., J. A. Lowe, B. Lloyd-Hughes, and T. J. Osborn, 2018: The impacts avoided with a 1.5°C climate target: a global and regional assessment. Clim. Change, 147, 61–76, doi:10.1007/s10584-017-2115-9.

Bonte, M., and J. J. G. Zwolsman, 2010: Climate change induced salinisation of artificial lakes in the Netherlands and consequences for drinking water production. Water Res., 44, 4411–4424, doi:10.1016/j.watres.2010.06.004.

Gerten, D., and Coauthors, 2013: Asynchronous exposure to global warming: freshwater resources and terrestrial ecosystems. Environ. Res. Lett., 8, 034032, doi:10.1088/1748-9326/8/3/034032.

Hanasaki, N., and Coauthors, 2013: A global water scarcity assessment under Shared Socio-economic Pathways - Part 2: Water availability and scarcity. Hydrol. Earth Syst. Sci., 17, 2393–2413, doi:10.5194/hess-17-2393-2013.

Hosseini, N., J. Johnston, and K.-E. Lindenschmidt, 2017: Impacts of Climate Change on the Water Quality of a Regulated Prairie River. Water, 9, 199, doi:10.3390/w9030199.

Karnauskas, K. B., C.-F. Schleussner, J. P. Donnelly, K. J. Anchukaitis, K. Archukaitis, and K. J. Anchukaitis, 2018: Freshwater Stress on Small Island Developing States: Population Projections and Aridity Changes at 1.5°C and 2°C. Reg. Environ. Chang., 1–10, doi:https://doi.org/10.1007/s10113-018-1331-9.

Kinoshita, Y., M. Tanoue, S. Watanabe, and Y. Hirabayashi, 2018: Quantifying the effect of autonomous adaptation to global river flood projections: Application to future flood risk assessments. Environ. Res. Lett., 13, doi:10.1088/1748-9326/aa9401.

Liu, W., F. Sun, W. H. Lim, J. Zhang, H. Wang, H. Shiogama, and Y. Zhang, 2018: Global drought and severe drought-affected populations in 1.5 and 2&amp;thinsp;&amp;deg;C warmer worlds. Earth Syst. Dyn., 9, 267–283, doi:10.5194/esd-9-267-2018.

Patiño, R., D. Dawson, and M. M. Vanlandeghem, 2014: Retrospective Analysis of Associations between Water Quality and Toxic Blooms of Golden Alga (Prymnesium parvum) in Texas Reservoirs: Implications for Understanding Dispersal Mechanisms and Impacts of Climate Change. Harmful Algae, 33, 1–11, doi:10.1016/j.hal.2013.12.006.

Portmann, F. T., P. Döll, S. Eisner, and M. Flörke, 2013: Impact of climate change on renewable groundwater resources: assessing the benefits of avoided greenhouse gas emissions using selected CMIP5 climate projections. Environ. Res. Lett., 8, 024023, doi:10.1088/1748-9326/8/2/024023.

Schewe, J., and Coauthors, 2014: Multimodel assessment of water scarcity under climate change. Proc. Natl. Acad. Sci. U. S. A., 111, 3245–3250, doi:10.1073/pnas.0709640104.

Wada, Y., and Coauthors, 2017: Human–water interface in hydrological modelling: current status and future directions. Earth Syst. Sci, 215194, 4169–4193, doi:10.5194/hess-21-4169-2017.

Watts, G., and Coauthors, 2015: Climate change and water in the UK – past changes and future prospects. Prog. Phys. Geogr., 39, 6–28, doi:10.1177/0309133314542957.

Zhang, F., J. Tong, B. Su, J. Huang, and X. Zhu, 2016: Simulation and projection of climate change in the south Asian River basin by CMIP5 multi-model ensembles. J. Trop. Meteorol., 32, 734–742.

S3-4-4_Supplementary information to Section 3.4.4

Update of Expert assessment by Gattuso et al. (2015).

J.-P. Gattuso, A. Magnan, R. Billé, W. W. L. Cheung, E. L. Howes, F. Joos, D. Allemand, L. Bopp, S. R. Cooley, C. M. Eakin, O. Hoegh-Guldberg, R. P. Kelly, H.-O. Pörtner, A. D. Rogers, J. M. Baxter, D. Laffoley, D. Osborn, A. Rankovic, J. Rochette, U. R. Sumaila, S. Treyer, C. Turley

Published 3 July 2015, Science 349, aac4722 (2015)

DOI: 10.1126/science.aac4722

Risk assessment update: November 18, 2017 (by relevant expert team plus lead authors of Chapter 3) Special report on the Implications of 1.5°C).

This Section S3-4-4 includes:

Supplementary Text

Table S1

Full Reference List

Background information and rationale of expert judgment on the risk of impact due to CO_2 levels by 2100.

This supplementary material provides the background information and rationale for the construction of the burning embers diagrams used in Figure 3.17 to represent the risk of impacts from CO2 levels (by 2100) for keystone marine and coastal organisms and ecosystem services.

This is the expert judgment by the group on the overall risk - balancing negative, neutral and positive impacts across species and regions using current literature.

Table S6: The temperature at which transitions in the level of risk occur in response to climate change, from expert judgement by Gattuso et al. (2015) and updated in March 2018 for following three years of scientific literature. [White: no detectible risks from climate change; Yellow: Moderate levels of risk; Red: High level of risk; and Purple: Very high level of risk].
Note: these data were used to build the burning embers for representative marine organisms, ecosystems and sectors.
Note: red numbers are where the update has resulted in conclusions different to that of Gattuso et al. (2015).

		Average global sea surface temperature (SST)		
Component	**Colour transition**		**2015**	**2018**
Seagrasses (mid latitude)	White to Yellow	Begin	0.5	0.5
		End	0.8	0.8
	Yellow to Red	Begin	1.5	1.5

		Average global sea surface temperature (SST)		
Component	**Colour transition**		**2015**	**2018**
		End	1.8	1.8
	Red to Purple	Begin	2.2	2.2
		End	3	3
Mangroves	White to Yellow	Begin	1.8	1.3
		End	3	1.5 (2.5)*
	Yellow to Red	Begin	3	2.5
		End	3.2	2.7
	Red to Purple	Begin	N/A	NA
		End	N/A	NA
Warm water corals	White to Yellow	Begin	0.3	0.2
		End	0.4	0.4
	Yellow to Red	Begin	0.5	0.4
		End	0.8	0.6
	Red to Purple	Begin	0.8	0.6
		End	1.5	1.2
Pteropods (high latitude)	White to Yellow	Begin	0.7	0.7
		End	0.8	0.8
	Yellow to Red	Begin	0.8	0.8
		End	1.5	1.5
	Red to Purple	Begin	1.5	1.5
		End	2	2
Bivalves (mid latitude)	White to Yellow	Begin	0.4	0.4
		End	0.6	0.6
	Yellow to Red	Begin	0.9	0.9
		End	1.1	1.1
	Red to Purple	Begin	1.3	1.3
		End	1.5	1.5
Krill (high latitude)	White to Yellow	Begin	0.7	0.7
		End	0.9	0.9
	Yellow to Red	Begin	1	1
		End	1.6	1.6
	Red to Purple	Begin	1.8	1.8
		End	3.2	3.2

		Average global sea surface temperature (SST)		
Component	**Colour transition**		**2015**	**2018**
Finfish	White to Yellow	Begin	0.5	0.5
		End	0.7	0.7
	Yellow to Red	Begin	1.1	1.1
		End	1.3	1.3
	Red to Purple	Begin	1.4	1.4
		End	1.6	1.6
Open-ocean carbon uptake	White to Yellow	Begin	1	1
		End	1.5	1.5
	Yellow to Red	Begin	2	2
		End	3.2	3.2
	Red to Purple	Begin	N/A	N/A
		End	N/A	N/A
Coastal Protection	White to Yellow	Begin	0.5	0.5
		End	0.8	0.8
	Yellow to Red	Begin	1.5	1.5
		End	1.8	1.8
	Red to Purple	Begin	2.2	2.2
		End	3.2	3.2
Recreational services from coral reefs	White to Yellow	Begin	0.6	0.6
		End	0.8	0.8
	Yellow to Red	Begin	1	1
		End	1.5	1.5
	Red to Purple	Begin	2	2
		End	3.2	3.2
Bivalve fisheries and aquaculture (mid-latitude)	White to Yellow	Begin	1.1	1.1
		End	1.3	1.3
	Yellow to Red	Begin	1.7	1.7
		End	1.9	1.9
	Red to Purple	Begin	2.8	2.8
		End	3.2	3.2
Fin fisheries (low latitude)	White to Yellow	Begin	0.7	0.5
		End	0.9	0.7
	Yellow to Red	Begin	1	0.9

		Average global sea surface temperature (SST)		
Component	**Colour transition**		**2015**	**2018**
		End	1.2	1.1
	Red to Purple	Begin	2	2
		End	2.5	2.5
Fin fisheries (high latitude)	White to Yellow	Begin	0.7	0.7
		End	0.9	0.9
	Yellow to Red	Begin	2.2	2.2
		End	3.2	3.2
	Red to Purple	Begin	N/A	N/A
		End	N/A	N/A

Note: **Mangrove value differs from Table value but is consistent with main text.*

Expert assessment: Original assessment by Gattuso et al. (2015) using the IPCC Fifth Assessment Report (AR5) and literature published up to 2014. This current assessment updated the original assessment using literature from 2015 to early 2018. References for the current and past assessments are listed at the end of this document. This is Supplementary on-line material for the special report on the implications of 1.5oC warming.

Seagrasses (mid latitude)

Update: Recent literature supports the consensus reached by Gattuso et al., (2015) with increasing ocean temperatures a major threat, with the potential loss of key species such as *Posidonia oceanica* in the Mediterranean by mid-century (Jordà et al. 2012). Recent work has shown that increasing temperatures is a major threat to the shoot density (Guerrero-Meseguer et al. 2017) and quality of the seagrass *Zostera marina* (Repolho et al. 2017). Other studies in related systems reveal sub-chronic changes to the quality of seagrass shoots and leaves (Unsworth et al. 2014) and have speculated on the impact that these changes might have on coastal food webs (York et al. 2016). Several studies have speculated on the impact of rising seas, storms and flooding on seagrass productivity (Rasheed et al. 2014; Telesca et al. 2015; Pergent et al. 2015; Ondiviela et al. 2014). The consistency of the literature for the last two years with that examined since the AR5 suggest that the current risk levels for seagrasses proposed by Gattuso et al. (2015) are appropriate.

Therefore, seagrasses are already showing responses to climate change hence the expert consensus that the transition from undetectable to medium risks occurs between 0.5 and 0.8°C. Given the clear sensitivity of seagrass communities to rising sea temperatures, and other aspects of climate change such as sea level rise, storms and flooding, these risks transition from medium to high from 1.5°C to 1.8°C, and from high to very high over the interval from 2.2°C to 3°C.

Expert assessment by Gattuso et al. (2015; SOM):

Seagrasses, important habitats in coastal waters around the world, will be affected by climate change through a number of routes including direct effects of temperature on growth rates (Nejrup and Pedersen 2008; Höffle et al. 2011), occurrence of disease (Burge et al. 2013), mortality and physiology, changes in light levels arising from sea level changes, changes in exposure to wave action (Short and Neckles 1999), sometimes mediated through effects on adjacent ecosystems (Saunders et al. 2014), and also by changes in the frequency and magnitude of extreme weather events. There will be changes in the distribution of seagrass communities locally and regionally. Here we take the example of temperate seagrasses including *Posidonia oceanica* from the Mediterranean, *Zostera* spp from the USA, Europe, and Australia, because the information on the effects of ocean warming and acidification for these species from several field studies is robust. Results indicate that temperate seagrass meadows have already been negatively impacted by rising sea surface temperatures (Marbà and Duarte 2010). Models based on observations of natural populations indicate that at temperature increases of 1.5°C – 3°C mortality of shoots of seagrasses will be such that populations will be unsustainable and meadows will decline to the point where their ecological functions as a habitat will cease (reduction to 10% of present density of a healthy meadow; Marbà and Duarte 2010; Jordà et al. 2012; Carr et al. 2012; York et al. 2013).

The confidence level is very high under Representative Concentration Pathway (RCP)2.6 because of strong agreement in the literature. Confidence declines to high under RCP8.5 due to some uncertainty surrounding regional differences. For example, it has been suggested that the balance of effects on seagrass populations in the North East Atlantic could tip to positive due to the hypothetical opening of ecological niches with the decline of more sensitive species, and potential reduction of carbon limitation by elevated CO_2 which may help to ameliorate negative effects of other environmental drivers, such as warming, known to impact seagrass growth and survival (Brodie et al. 2014).

Mangroves

Update: Recent literature is consistent with previous conclusions regarding the complex changes facing mangroves, together with increasing concern regarding the interaction between climate change (e.g., elevated air and water temperatures, drought, sea level rise) and local factors (deforestation, damming of catchments and reduced sediment and freshwater) as outlined below (Feller et al. 2017; Alongi 2015). Decreases in the supply of sediments to deltas and coastal areas is impeding the ability of most mangroves (69% of sites) to keep pace with sea level rise through shoreward migration (Lovelock et al. 2015). At the same time, recent extremes associated with El Nino (e.g., extreme low sea level events, Duke et al., 2017; Lovelock et al., 2017). Shoreward migration is also challenged by the increasing amounts of coastal infrastructure preventing the relocation of mangroves (Saunders et al. 2014; Di Nitto et al. 2014). In some areas, mangroves are increasing in distribution (Godoy and De Lacerda 2015). The total loss projected for mangrove loss (10–15%) under a 0.6 m sea level rise continue to be dwarfed by the loss of mangroves to deforestation (1-2% per annum).

Given the scale of the die-back of mangroves in Australia's Gulf of Carpentaria (2015-2016), however, plus evidence that similar conditions to those of 2015-2016 (extreme heat and low tides), and the projection of greater El Niño-Southern Oscillation (ENSO) variability, (Risser and Wehner 2017; Widlansky et al. 2015), the risks from climate change for mangroves were judged to be higher than assessed by AR5, and subsequently by Gattuso et al. (2015), leading to the transitions having greater risk of occurring (Figure 3.17). Formal attribution of recent extreme events on mangroves to climate change, however, is at an early stage *(medium agreement, limited data).*

Expert assessment by Gattuso et al. (2015; SOM):

Mangroves are critically important coastal habitat for numerous species. Mangrove responses to increasing atmospheric CO_2 are complex, with some species thriving while others decline or exhibit little or no change (Alongi 2015). Temperature increase alone is likely to result in faster growth, reproduction, photosynthesis, and respiration, changes in community composition, diversity, and an expansion of latitudinal limits up to a certain point (Tittensor et al. 2010). Mangroves have already been observed to retreat with sea level rise (McKee et al. 2012). In many areas mangroves can adapt to sea level rise by landward migration, but these shifts threaten other coastal habitats such as salt marshes, which have other important biogeochemical and ecological roles. It is in areas with steep coastal inclines or coastal human infrastructure limiting landward migration that mangroves are most at risk. Climate change may lead to a maximum global loss of 10 to 15% of mangrove forest for a sea level rise of 0.6 m (high end of IPCC projections in AR4), but must be considered of secondary importance compared with current annual rates of deforestation of 1–2% (Alongi 2008). A large reservoir of below-ground nutrients, rapid rates of nutrient flux microbial decomposition, complex and highly efficient biotic controls, self- design and redundancy of keystone species, and numerous feedbacks, all contribute to mangrove resilience to various types of disturbance.

Mangrove response is species-specific and interacts with temperature, salinity, nutrient availability and patterns of precipitation. Many of these parameters are also subject to regional and local variation, as well as to human-induced pressures which changes over the coming decades are difficult to assess. Thus, the confidence level decreases from high under RCP2.6 to low under RCP8.5.

Warm-water corals

Update: Exceptionally warm conditions of 2015-2017 drove an unprecedented global mass coral bleaching and mortality event which affected coral reefs in a large number of countries (information still being gathered, Normile, 2016). In the case of Australia, 50% of shallow-water reef-building corals across the Great Barrier Reef died in unprecedented back-to-back bleaching events (Hughes et al. 2017). Elevated sea temperatures and record mortality was recorded from the Central to the Far northern sectors of the Great Barrier Reef. Similar impacts occurred in a range of regions including the Indian Ocean, Western Pacific, Hawaii and Caribbean oceans (Normile 2016) . The set of events has increased risk with current conditions being of high risk, and even low levels of future climate change having series implications for coral reefs. There continues to be a high to very high level of confidence as to where the transitions between risk levels for climate change impacts lie.

The unprecedented thermal stress along many tropical coastlines over the past three years (2015-2017) has led to extraordinary changes to coral reefs across the planet (as described above). The advent of back-to-back bleaching events, which were projected to occur around midcentury, appear to have already begun to occur as demonstrated by impacts on warm water corals and hence coral reefs. While corals were already stressed from climate change, and are in decline in many parts of the world, the scale and impact of recent events suggest that risk levels for the transitions between risk categories need to be adjusted to represent the current status of corals and coral reefs. For this reason, expert consultation since 2015 concluded that the transition from undetectable to moderate risk has already occurred (0.2°C to 0.4°C). Similarly, the transition from *moderate* to high levels of risks for warm water corals occurred approximately from 0.5°C to 0.6°C. In line with these changes, the transition from *high* to *very high* levels of risk appears associated with increases in GMST from 0.7°C to 1.3°C above the pre-industrial period.

Expert assessment by Gattuso et al. (2015; SOM):

Warm-water corals form reefs that harbor great biodiversity and protect the coasts of low lying land masses. There are very high levels of confidence that impacts were undetectable up until the early 1980s, when coral reefs in the Caribbean and eastern Pacific exhibited mass coral bleaching, as well as temperature-related disease outbreaks in the Caribbean Sea (Glynn 1984). Given a conservative lag time of 10 years between the atmospheric concentration of CO_2 and changes in sea surface temperature, the atmospheric CO_2 level of 325 ppm reached in the early 1970s was sufficient to initiate widespread coral bleaching and decline of coral health worldwide (Veron et al. 2009). As the 1980s unfolded, visible impacts of increasing sea surface temperature were seen in a widening number of areas, with the first global event in 1997-1998 and the loss of 16% of coral reefs (*high confidence*; C. R. Wilkinson 2000). Further increases in atmospheric carbon dioxide and sea surface temperature have increased the risk to corals (high confidence), with multiple widespread bleaching events, including loss of a large fraction of living corals in the Caribbean in 2005 (Eakin et al. 2010) and a subsequent global bleaching in 2010 (e.g., Moore et al. 2012), and current conditions suggesting the development of a third global event in 2015–2016 (C.M. Eakin, unpublished observation). If CO_2 levels continue to increase, there is a very high risk that coral reefs would be negatively affected by doubled pre-industrial CO_2 through impacts of both warming-induced bleaching and ocean acidification (high confidence), supported by a wide array of modeling (e.g., (Hoegh-Guldberg et al. 2014, Logan et al. 2014, Hoegh-Guldberg 1999, Donner et al. 2005, van Hooidonk et al. 2014), experimental (e.g., Dove et al. 2013), and field studies (Silverman et al. 2014, De'ath et al. 2012). This leads to a very high level of confidence under RCP2.6 and a high level of confidence under RCP8.5.

Pteropods (high latitude)

Update: Literature from the last two years is largely consistent with the expert assessment by Gattuso et al. (2015). There is increasing evidence of declining aragonite saturation in the open ocean with the detection of impacts that are most pronounced closest to the surface and with the severe biological impacts occurring within inshore regions. In this regard, pteropod shell dissolution has increased by 19-26% in both nearshore and offshore waters since the Pre-industrial period (Feely et al. 2016). Impacts of ocean acidification are also cumulative with other stresses such as elevated sea temperature and hypoxia (Bednaršek et al. 2016). These changes are consistent with observations of large portions of the shelf waters associated with the Washington-Oregon-California coast being strongly corrosive, with 53% of onshore and 24% of offshore pteropod individuals showing severe damage from dissolution (Bednaršek et al., 2014). Several researchers propose that pteropod condition be used as a biological indicator which they argue will become increasingly important as society attempts to understand the characteristics and rate of change in ocean acidification impacts on marine organisms and ecosystems (Manno et al. 2017; Bednaršek et al. 2017). The last two years of research has increased confidence in our understanding of the impact of ocean acidification on pteropods under field conditions. The question of the genetic adaptation of pteropods to increasing ocean acidification remains unresolved although the observation of increasing damage to pteropods from field measurements argues against this being a significant factor in the future.

As described here and by Gattuso et al. (2015), pteropods are clearly being impacted by climate change and ocean acidification, especially in polar regions. Therefore, the transition from undetectable to medium levels of stress has been judged to occur between 0.7°C and 0.8°C. The transition from medium to high levels of risk of impact on these important organisms was judged to occur from 0.8°C to 1.5°C, with the transition from high to very high occurring from 1.5°C to 2°C.

Expert assessment by Gattuso et al. (2015; SOM):

Pteropods are key links in ocean food webs between microscopic and larger organisms, including fish, birds and whales. Ocean acidification at levels anticipated under RCP8.5 leads to a decrease in pteropod shell production (Comeau et al. 2009, 2010; Lischka et al. 2011), an increase in shell degradation (Lischka and Riebesell 2012; Comeau et al. 2012), a decrease in swimming activity when ocean acidification is combined with freshening (Mannoa et al. 2012), and an increase in mortality that is enhanced at temperature changes smaller than those projected for RCP8.5 (Lischka et al. 2011; Lischka and Riebesell 2012). Shell dissolution has already been observed in high latitude populations (Bednaršek et al. 2012). Aragonite saturation (Ωa) levels below 1.4 results in shell dissolution with severe shell dissolution between 0.8 and 1 (Bednaršek and Ohman 2015). Despite high agreement amongst published findings, uncertainty remains surrounding the potential to adapt to environmental drivers because long-term laboratory experiments with pteropods are notoriously difficult. Hence the confidence level is *medium* under RCP2.6. However, confidence increases to very high under RCP8.5 because it is almost certain that genetic adaptation to such large and rapid changes in pH and temperature will not be possible.

Bivalves (mid latitude)

Update: Literature has rapidly expanded since 2015 with a large number of studies showing impacts of ocean warming and acidification on wide range of life history stages of bivalve molluscs (e.g., Asplund et al., 2014; Castillo et al., 2017; Lemasson et al., 2017; Mackenzie et al., 2014; Ong et al., 2017; Rodrigues et al., 2015; Shi et al., 2016; Velez et al., 2016; Waldbusser et al., 2014; Wang et al., 2016; Zhao et al., 2017; Zittier et al., 2015). Impacts on adult bivalves include decreased growth, increased respiration, and reduced calcification with larval stages tending to have an increase in developmental abnormalities and elevated mortality after exposure (Ong et al. 2017; Zhao et al. 2017; Wang et al. 2016; Lemasson et al. 2017). Many recent studies have also identified interactions between factors such as increased temperature and ocean acidification, with salinity perturbations as well as decreases in oxygen concentrations (Parker et al. 2017; Velez et al. 2016; Lemasson et al. 2017). Changes in metabolism with increasing ocean acidification has been detected in a number of transcriptome studies, suggesting a complex and wide-ranging response by bivalves to increasing CO_2 and temperature (Li et al. 2016a,b). Observations of reduced immunity which may have implications for disease management (Castillo et al. 2017). These changes are likely to impact the ecology of oysters, and may be important when it comes to the maintenance of oyster reefs, which provide important ecological structure for other species. Bivalves, for example, are more susceptible to the impacts of temperature and salinity if they have been exposed to high levels of CO_2, leading to the suggestion that there will be a narrowing of the physiological range and hence distribution of oyster species such as *Saccostrea glomerata* (Parker et al. 2017). Confidence level is adjusted to high given the convergence of recent literature. These studies continue to report growing impacts as opposed to a reduction under rapid genetic adaptation by bivalve molluscs. The overall levels of risk are retained - reflecting the moderate risk that already exists, and the potential for transformation into high very high levels of risk with relatively small amounts of further climate change.

Recent literature reinforces the conclusions of Gattuso et al. (2015) and confirms the transition of risk from low to moderate for the bivalves associated with mid-latitude environments is occurring between 0.4°C and 0.6°C. The transition for these organisms from moderate to high levels of risk occurs at 0.9°C and 1.1°C. Subsequent transition from high to very high was judged to occur between 1.3°C and 1.5°C.

Expert assessment by Gattuso et al. (2015; SOM):

Both cultured and wild bivalves are an important food source worldwide. Temperate bivalve shellfish, such as oysters, clams, mussels and scallops, have already been negatively impacted by ocean acidification. In the Northwest United States, Pacific oyster larval mortality has been associated with upwelling of natural CO_2-rich waters acidified by additional fossil fuel CO_2 (*high confidence*; Barton et al. 2012). Ocean acidification acts synergistically with deoxygenation (Gobler et al. 2014) and warming (Mackenzie et al. 2014a; Kroeker et al. 2013) to heighten physiological stress (Wittmann and Pörtner 2013) on bivalve shellfish (*high confidence*), suggesting that future ocean conditions that include warming, deoxygenation, and acidification will be particularly difficult for members of this taxon. Archaeological/geological and modeling studies show range shifts of bivalves in response to prior and projected warming (Raybaud et al. 2015) and acidification (Lam et al. 2014). Model projections also anticipate decreases in mollusk body size under continued harvesting as conditions change farther from the present (Cooley et al. 2015). Impacts are expected to be high to very high when CO_2 concentrations exceed those expected for 2100 in the RCP2.6 and 4.5 levels (*medium confidence*; Lam et al. 2014; S. R. Cooley, J. E. Rheuban, D. R. Hart, V. Luu, D. M. Glover, J. A. Hare 2015). The confidence level is medium both under RCP2.6 and RCP8.5 primarily due to the possibility of bivalves adapting over generations (Pespeni et al. 2013), or for specific species to outcompete other wild species in future conditions (e.g., A. W. Miller, A. C. Reynolds, C. Sobrino 2009).

Krill (high latitude)

Update: Sea ice continues to retreat at high rates in both polar oceans with both the Artic and Antarctica being among the fastest warming regions on the planet (Turner et al. 2017; Notz and Stroeve 2016). In Antarctic waters, a decrease in sea ice represents a loss of critical habitat for krill (David et al. 2017). Projected changes of this habitat through increasing temperature and acidification could have major impacts on food, reproduction and development, and hence the abundance of this key organism for Antarctic food webs. Differences appear to be a consequence of regional dynamics in factors such as regional variation in ice, productivity, and predation rates, and an array of other factors (Steinberg et al. 2015). Other factors such as interactions with factors such as ocean acidification and the shoaling of the aragonite saturation horizon are likely to play key roles. (Kawaguchi et al. 2013; Piñones and Fedorov 2016). While factors such as ocean acidification and the loss of sea ice (due to increasing temperature) are unambiguous in their effects, there continues to be considerable uncertainty around the details of how krill populations are likely to respond to factors such as changing productivity, storms, and food webs.

While there are considerable gaps in our knowledge about the impacts of climate change on krill, there is consensus that direct climate impacts are beginning to be detected at average global sea surface temperatures of around 0.7°C and that transition to medium stress occurs at around about 0.9°C. With a low level of confidence and hence much uncertainty, expert consensus concludes that transition from medium to high levels of risk of impact occurred between 1.0°C and 1.6°C. Subsequent transitions from high to very high levels of risk are judged to lie somewhere between 1.8°C and 3.2°C although levels of confidence are low at this time.

Expert assessment by Gattuso et al. (2015; SOM):

Krill (euphausid crustaceans) is a critical link in the food web at higher latitudes, supporting mammals and birds among many other species. Distributional changes and decreases in krill abundance have already been observed associated with temperature increase (Atkinson et al. 2004). The effect of changes in the extent of sea ice is considered to be an indirect effect of temperature. Temperature effects are predicted to be regional (Hill et al. 2013). If the extent of sea ice is maintained, populations in cooler waters may experience positive effects in response to small increases in temperature. In contrast, populations in warmer areas may experience some negative temperature effects by 2100 under RCP2.6. Since all life stages are associated with sea ice, decreases in krill stocks are projected to occur concurrently with the loss of sea ice habitat, potentially outweighing possible positive impacts (H. Flores, A. Atkinson, S. Kawaguchi, B. A. Krafft, G. Milinevsky, S. Nicol, C. Reiss et al. 2012). Increases in sea surface temperature of 1˚C –2˚C have significant impacts on krill. From Figure 4 in Flores et al. (H. Flores, A. Atkinson, S. Kawaguchi, B. A. Krafft, G. Milinevsky, S. Nicol, C. Reiss et al. 2012) severe disruptions of the life cycle are expected at a level of 2°C sea surface temperature rise and 500 µatm pCO_2. Therefore, high impact on populations would be reached approximately at the CO_2 level projected for 2100 by RCP4.5. Conditions in 2100 under the RCP2.6 scenario would be around the upper limit of the high-risk range. Negative effects of ocean acidification on reproduction, larval and early life stages have been observed above 1,250 µatm pCO_2, a value that is likely to be reached in parts of the Southern Ocean by 2100 under RCP8.5 (Kawaguchi et al. 2013). Figure 1 in H. Flores, A. Atkinson, S. Kawaguchi, B. A. Krafft, G. Milinevsky, S. Nicol, C. Reiss et al. (2012) shows that the area with strongest sea ice decline partly overlaps with areas of high krill density (from the Peninsula to the South Orkneys). There is also a significant warming trend in this area which may force populations southwards into less productive regions. Substantial decline in the viability of major krill populations in the Southern Ocean may occur within the next 100 years (Kawaguchi et al. 2013), which could have catastrophic consequences for dependent marine mammals and birds. The genetic homogeneity of krill suggests that rapid adaptation through natural selection of more tolerant genotypes is unlikely (Bortolotto et al. 2011).

Finfish

Update: Impacts and responses identified in 2015 regarding the relative risk of climate change to finfish have strengthened. In this regard, there is a growing number of studies indicating that different stages of development may also be made more complex by fish having different stages of the life-cycle in different habitats, which may each be influenced by climate change in different ways and to different extents, as well as evidence of differing sensitivities to change between different stages (Ong et al. 2017, 2015; Esbaugh 2017). Increasing numbers of fish species have been identified as relocating to higher latitudes, with tropical species being found increasingly in temperate zones ('tropicalization', Horta E Costa et al., 2014; Verges et al., 2014; Vergés et al., 2016)) and temperate species being found in some polar regions ('Borealization', Fossheim et al., 2015). Concern has been raised that greater numbers of extinctions will occur in the tropics as species relocate (García Molinos et al. 2015; Burrows et al. 2014; Poloczanska et al. 2016). Changing conditions in polar regions are particularly risky due to the rapid rates of warming (Turner et al. 2017; Notz and Stroeve 2016). One of the consequences of this is that an increasing number of fish species are expanding their distributional ranges into the Arctic, being followed by large, migratory fish predators. The borealization of fish communities in the Arctic is leading to a reorganization of species and ecological processes which is not well understood (Fossheim et al. 2015).

There is considerable evidence that changes in the distribution of finfish are, and have been, occurring over the last few decades. Evidence of the movement of tropical species to higher latitudes is unambiguous as is the shift in many pelagic species of finfish. Consequently, the distribution and abundance of finfish is already occurring, and based on the updated expert consensus of Gattuso et al. (2015), appears to have transition from undetectable to medium levels of risk at average global sea surface temperatures of 0.5°C and 0.7°C. There is little evidence that these changes are slowing and therefore risks are estimated as transitioning from medium to high levels of risk at 1.1°C to 1.3°C, and from high to very high levels of risk at 1.4°C to 1.6°C.

Expert assessment by Gattuso et al. (2015; SOM):

Marine fishes are important predators and prey in ocean ecosystems, contributing substantially to coastal economies, food security and livelihood. Warming-induced shifts in the abundance, geographic distribution, migration patterns, and phenology of marine species, including fishes, were reported and projected with very high confidence in the IPCC AR5 (Pörtner et al. 2014). Empirical and theoretical evidence of range shifts in response to temperature gradients are reported across various taxa and many geographical locations (Bates et al. 2014; Poloczanska et al. 2013; Couce et al. 2013), with observations suggesting that range shifts correspond with the rate and directionality of climate shifts or 'climate velocity' across landscapes (Pinsky et al. 2013). Observed range shifts associated with ocean warming may result in hybridization between native and invasive species through overlapping ranges, leading to reduced fitness and thus potentially increasing the risks of genetic extinction and reducing the adaptability to environmental changes (Muhlfeld et al. 2014; Potts et al. 2014). Some taxa are incapable of keeping pace with climate velocities, as observed with benthic invertebrates in the North Sea (Hiddink et al. 2015). The tropicalization of temperate marine ecosystems through poleward range shifts of tropical fish grazers increases the grazing rate of temperate macroalgae as seen in Japan and the Mediterranean (Verges et al. 2014). Such trophic impacts resulting from climate-induced range shifts are expected to affect ecosystem structure and dynamic in temperate reefs (Verges et al. 2014). Projected future changes in temperature and other physical and chemical oceanographic factors are expected to affect the distribution and abundance of marine fishes, as elaborated by species distribution models with rate of shift at present day rate under the RCP8.5 scenario (Cheung et al. 2009). Limiting emissions to RCP2.6 is projected to reduce the average rate of range shift by 65% by mid-21st century (Jones and Cheung 2015). Shifts in distribution of some species may be limited by the bathymetry or geographic boundaries, potentially resulting in high risk of local extinction particularly under high CO_2 emissions scenarios (Ben Rais Lasram et al. 2010). While evidence suggests that adult fishes can survive high levels of CO_2, behavioral studies have found significant changes in species' responses under levels of CO_2 elevated above those of the present day level (Munday et al. 2014). Long-term persistence of these phenomena remains unknown. Based on the above, fishes already experience medium risk of impacts at present day (*high confidence*). Risk increases from medium to high by end of 21st century when emissions change from RCP2.6 to RCP4.5 and become very high under RCP8.5, highlighting the potential non-reversibility of the potential impacts. Some evidence for direct and indirect impacts of ocean acidification on finfish is available but varies substantially between species. Also, understanding about the scope of evolutionary adaptation for marine fishes to climate change and ocean acidification are limited, although it is unlikely that majority of the species can fully adapt to expected changes in ocean properties without any impacts on their biology and ecology. Overall, we have robust evidence and high agreement (thus *high confidence*) from experimental data, field observations and mathematical modelling in detecting and attributing impacts for finfish in the present day and under RCP2.6. The uncertainty about the sensitivity to ocean acidification and scope for evolutionary adaptation leads to medium confidence levels for their risk under high emissions scenarios.

Open ocean carbon uptake

Update: Several recent studies have shown a decreasing CO_2 flux into the Pacific and Atlantic Oceans, southern ocean, and ocean in general (Iida et al. 2015). Concern over changes to the circulation of the ocean (e.g., Atlantic Meridional Overturning Circulation, AMOC) has grown since 2015, with the observation of cooling surface areas of the Atlantic (Rahmstorf et al. 2015).

Recent literature is consistent with the expert assessment of Gattuso et al. (2015) with risks of impact from changing ocean carbon uptake being barely detectable today but transitioning to medium risk between 1°C and 1.5°C. Risks transition from medium to high levels of risk between 2°C and 3.2°C. Higher levels of risk such as a rapid change in the circulation of the MOC are speculative at this point.

Expert assessment by Gattuso et al. (2015; SOM):

The uptake of anthropogenic carbon by the ocean in the industrial period and in the future is a service that is predominantly provided by physico-chemical processes (Prentice and J. T. Houghton et al. 2001). The sensitivity of ocean carbon uptake to increasing cumulative CO_2 emissions, including effects of changing ocean chemistry, temperature, circulation and biology, is assessed along the following lines of quantitative evidence: (i) the fraction of total cumulative anthropogenic emissions taken up by the ocean over the industrial period and the 21st century in CMIP5 Earth System Model projections for the four RPCs (27); (ii) the fraction of additional (marginal) emissions remaining airborne or taken up by the ocean for background atmospheric CO_2 following the four RCPs (Joos et al. 2013). In addition, the risk of large-scale reorganization of ocean circulation, such as a collapse of the North Atlantic overturning circulation and associated reductions in allowable carbon emissions towards CO_2 stabilization, is increasing with the magnitude and rate of CO_2 emissions, in particular beyond the year 2100. Confidence level is *high* for both RCP2.6 and RCP8.5 because the underlying physical and chemical process are well known.

Coastal protection

Update: Sea level rise and intensifying storms are placing increasing stress on coastal environments and communities. Coastal protection by ecosystems as well as man-made infrastructure are important in terms of mitigating risks ranging from the physical destruction of ecosystems and human infrastructure to the salinization of coastal water supplies and direct impacts on human safety (Bosello and De Cian 2014). Risks are particularly high for low-lying areas, such as carbonate atoll islands in the tropical Pacific where land for food and dwelling and water are limited, and effects of a rising sea plus intensifying storms create circumstances may make many of these island systems uninhabitable within decades (Storlazzi et al. 2015). Even in advantaged countries such as the United States, these factors place millions at serious risk from even modest changes in inundation, with over 4 million US based people at serious risk in response to a 90 cm sea level rise by 2100 (Hauer et al. 2016).

Both natural and human coastal protection have the potential to reduce the impacts (Fu and Song 2017). Coral reefs, for example, provide effective protection by dissipating around 97% of wave energy, with 86% of the energy being dissipated by reef crests alone (Ferrario et al. 2014). Natural ecosystems, when healthy, also have the ability to repair themselves after being damaged, which sets them apart from coastal hardening and other human responses that require constant maintenance (Barbier 2015; Elliff and Silva 2017). Recognising and restoring coastal ecosystems such as coral reefs, mangroves and coastal vegetation in general may be more cost-effective than human remedies in terms of seawalls and coastal hardening, where costs of creating and maintaining structures may not always be cost-effective (Temmerman et al. 2013).

The last two years have seen an increase in the number of studies identifying the importance of coastal ecosystems as important to the protection of people and property along coastlines against sea level rise and storms. Analysis of the role of natural habitats in the protection people and infrastructure in Florida, New York and California, for example, has delivered a key insight into the significance of the problems and opportunities for the United States (Arkema et al. 2013). Some ecosystems which are important to coastal protection can keep pace with sea level rise, but only if other factors such as harvesting (i.e., of oysters; Rodriguez et al., 2014) or sediment supply (i.e., to mangroves, Lovelock et al., 2015) are managed. Several studies have pointed to the opportunity to reduce risks promoting more holistic approaches to mitigating damage from sea level rise and storms by developing integrated coastal plans that ensure that human infrastructure enables the shoreward relocation of coastal vegetation such as mangroves and salt marsh. The latter enhancing coastal protection as well as having other important ecological functions such as habitat for fish and the sources of a range of other resources (Mills et al. 2016; Lovelock et al. 2015; Di Nitto et al. 2014).

Recent studies have increasingly stressed the coastal protection needs to be considered in the context of new ways of managing coastal land, including protecting and managing coastal ecosystems as they also undergo shifts in their distribution and abundance (André et al. 2016). These shifts in thinking require new tools in terms of legal and financial instruments, as well as integrated planning that involves not only human communities and infrastructure, but also ecosystem responses. In this regard, the interactions between climate change, sea level rise and coastal disasters are being increasingly informed by models (Bosello and De Cian 2014) with a widening appreciation of the role of natural ecosystems as an alternative to hardened coastal structures (Cooper et al. 2016).

Increase evidence of a rapid decay in ecosystems such as coral reefs and mangroves has increased the confidence surrounding conclusions that risks in coastal areas are increasing. Escalation of coastal impacts arising from Super Storm Sandy and Typhoon Haiyan (Villamayor et al. 2016; Long et al. 2016) have improved understanding of the future of coastal areas in terms of impacts, response and mitigation (Shults and Galea 2017; Rosenzweig and Solecki 2014).

Recent assessments of the last couple of years of literature confirm the expert judgement of Gattuso et al. (2015), although are emphasised by growing evidence that heat stress, ocean acidification, and intensifying storms are increasing the breakdown of natural coastal barriers that otherwise provide important protection for coastal communities, ecosystems and infrastructure. While there is growing evidence of these changes in the frequency and intensity of climate change, no changes in levels of risk from Gattuso et al. (2015) or perceived. Risk of impacts with respect to coastal protection transition from undetectable to medium at 0.5°C and 0.8°C, with the transition from medium to high levels of risk occurring from 1.5°C to 1.8°C. Further transition of impact risks from the loss of coastal protection has been judged to occur between 2.2°C and 3.2°C.

Expert assessment by Gattuso et al. (2015; SOM):

Estimating the sensitivity of natural coastal protection to climate change requires to combine sensitivity across different ecosystems, especially coral reefs, mangrove forests and seagrass beds. Other ecosystems provide coastal protection, including salt marshes, macroalgae, oyster and mussel beds, and also beaches, dunes and barrier islands (stabilized by organisms; Spalding et al. 2014; Defeo et al. 2009) but there is less understanding of the level of protection conferred by these other organisms and habitats (Spalding et al. 2014). Although studies indicate some of these systems are already impacted by the effects of rising CO_2, or suggest they will be in the near future, levels of sensitivity are not well established, are highly variable, and in some cases their overall influence on coastal protection may be uncertain (i.e., species are replaced by functional equivalents in this context; K. B. Gedan 2009).

We reason that some coastal protection has already been lost—a result of impacts on coral reefs, seagrasses and other ecosystems from sea temperature rise. In the case of corals, this began in the late 1970s. Recent papers demonstrate collapse in three-dimensional structure of reefs in the Caribbean (Alvarez-Filip et al. 2009) and the Seychelles (Sheppard et al. 2005), the second phase of which appears to be climate-related. Other studies show that some areas have not recovered from the 1997-1998 and 2010 bleaching events and that some reefs have collapsed there (e.g., parts of the Seychelles). There is thus little doubt that the coastal protection function of some reefs has already been reduced. A decreasing protection may also be the case for seagrasses, although such effects have not been measured. It should also be noted that other human impacts have already largely destroyed, or are progressively destroying some of these ecosystems, through direct action (e.g., 85% oyster reefs lost globally and 1-2% of mangrove forests cut down per annum; Beck et al. 2011). It therefore appears that some impact on coastal protection has already occurred but we lack data to extrapolate globally, hence the confidence level is *low* in the present day.

Confidence in the loss of coastal protection decreases with increasing CO_2 emissions because coastal protection is conferred by a range of habitats and the co-dependency or interactions between them make projections difficult. For example, protection to seagrass beds conferred by coral reefs or the replacement of salt marsh with mangrove forest (Saunders et al. 2014; Alongi 2015). Additionally, human-driven pressure on these ecosystems is inherently difficult to forecast decades from now due to the possible implementation of new policies. Interacting effects of different symptoms of climate change such as increased temperature, decreasing pH, salinity, nutrient availability, patterns of precipitation and occurrence of pathogens will all influence the physiological response of individual species and ecosystems and thus further reduce the predictability of responses at higher emissions.

Recreational services from coral reefs

Update: Tourism is one of the largest industries globally. A significant part of the global tourist industry is associated with tropical coastal regions and islands (Spalding et al. 2017). Coastal tourism can be a dominant money earner in terms of foreign exchange for many countries, particularly Small Island Developing States (SIDS; Weatherdon et al., 2016). The direct relationship between increased global temperatures, elevated thermal stress, and the loss of coral reefs (3.4.4.10; Box 3.4) has raised concern about the risks of climate change for local economies and industries based on coral reefs.

Risks to the recreational services of coral reefs from climate change are considered here. The recent heavy loss of coral reefs from tourist locations worldwide has prompted interest in the relationship between increasing sea temperatures, declining coral reef ecosystems, and tourist revenue (Normile 2016). About 30% of the world’s coral support tourism which generates close to $36 billion USD on an annual basis (Spalding et al. 2017). Tourist expenditure, in this case, represents economic activity which supports jobs, revenue for business and taxes. Climate change in turn can influence the quality of the tourist experience through such aspects through changing weather patterns, physical impacts such as storms, and coastal erosion, as well as the effects of extremes on biodiversity within a region. Recent impacts in the Caribbean in 2017 highlight the impacts of climate change related risks associated with coastal tourism, with the prospect that many businesses will take years to recover from impacts such as hurricanes Harvey, Irma and Maria (Gewin 2017; Shults and Galea 2017)

A number of projects have attempted to estimate the impact (via economic valuation) of losing key coral reef ecosystems such as the Great Barrier Reef (Oxford Economics 2009; Spalding et al. 2017). A recent study by Deloitte_Access_Economics. (2017) revealed that the Great Barrier Reef contributed $6.4 billion AUD and 64,000 jobs annually to the Australian economy in 2015–16. In terms of its social, economic and iconic value to Australia, the Great Barrier Reef is worth $56 billion AUD. The extreme temperatures of 2015–2017 removed 50% of the reef-building corals on the Great Barrier Reef (Hughes et al. 2017), there is considerable concern about the growing risk of climate change to the Great Barrier Reef, not only for its value biologically, but also as part of a series of economic risks at local, state and national levels.

Our understanding of the potential impacts of climate change on tourism within small island and low-lying coastal areas in tropical and subtropical is made less certain by the flexibility and creativity of people. For example, the downturn of coral reefs in countries that are dependent on coral reef tourism doesn’t necessarily mean a decline in Gross Domestic Product (GDP), given that some countries have many other options for attracting international revenue. As well, our understanding of future tourist expectations and desires are uncertain at this point.

Additional literature over the past couple of years confirm the risk from climate change to the recreational services that are derived from coral reefs, and which are important for a large number of coastal communities throughout the tropics. A transition in the risk of impacts to recreational services from coral reefs occurs between 0.6°C and 0.8°C, with a further transition from medium to high levels of risk between 1.0°C and 1.5°C. Very high levels of risk occur between 2.0°C and higher as the frequency and intensity of extreme events (i.e. storm events, coastal inundation, and/or droughts, depending on the region) become increasingly difficult to manage for coastal tourism like that associated with coral reefs. Note, the risks to corals are higher than those to the recreational services that corals provide to coastal communities. This highlights the fact that many communities today have lost coral but still are able to operate using recreational services from other sources. This difference disappears as one goes to higher levels of risk as the options for supporting recreational activities from the remnants of coral reefs are seriously reduced.

Expert assessment by Gattuso et al. (2015; SOM):

The impacts of CO_2 and sea surface temperature on the condition of coral reefs ultimately affect the flow of ecosystem goods and services to human communities and businesses. There is an interesting lag between the degradation of corals and coral reefs and a detectable effect on human users. For this reason, the risk of impacts on human recreation and tourism begins significantly later than ecosystem changes are detected by marine scientists. As of 2015, atmospheric CO_2 concentration is 400 ppm and average sea surface temperature is 0.8°C above that of the pre-industrial period. Mass bleaching and mortality events have degraded coral populations and this has negatively impacted the recreational choices of a few, but not most, clients (*high confidence*; Hoegh-Guldberg et al. 2007). This impact on tourists' choice is expected to reach moderate to high-levels as CO_2 approaches 450 ppm, at which point reefs begin net erosion and sea level, coral cover, storms, and other environmental risks become significant considerations in destination attractiveness (*medium confidence*). By 600 ppm, the breakdown of the structure of most reefs becomes obvious, other changes such as reduced coral cover and increased sea level and storm damage mean that significant coastal recreation and tourism becomes difficult in most circumstances and many operations may be discarded (Hoegh-Guldberg et al. 2007). This will have a very high impact on recreational services (*medium confidence*). Confidence levels under RCP2.6 and RCP8.5 are *medium* because predicting tourists' expectations several decades from now remains relatively uncertain.

Bivalve fisheries and aquaculture (mid latitude)

Update: Aquaculture is one of the fastest growing food sectors and is becoming increasingly essential to meeting the demand for protein for the global population (FAO 2016). Studies published over the period 2015-2017 showed a steady increase in the risks associated with bivalve fisheries and aquaculture at mid-latitude locations coincident with increases in temperature, ocean acidification, introduced species, disease and other associated risks (Clements and Chopin 2017; Clements et al. 2017; Lacoue-Labarthe et al. 2016; Parker et al. 2017). These have been met with a range of adaptation responses by bivalve fishing and aquaculture industries (Callaway et al. 2012; Weatherdon et al. 2016).

Risks are also likely to increase as a result of sea level rise and intensifying storms which pose a risk to hatcheries and other infrastructure (Callaway et al. 2012; Weatherdon et al. 2016). Some of the least predictable yet potentially most important risks are associated with the invasion of diseases, parasites and pathogens, which may be mitigated to a certain extent by active intervention by humans. Many of these have reduced the risks from these factors although costs have increased in at least some industries.

The risk of impact from ocean warming and acidification to bivalve aquaculture and fisheries is increasing - although not enough to warrant redefinition of the size and transition of risks from climate change.Therefore, literature since 2015 is consistent with the conclusion of how the risk of impact changes with greater levels of climate change. Risk to these important industries increases from nondetectable to medium at 1.1°C and 1.3°C, with the transition from medium to high levels of risk occurring from 1.7°C to 1.9°C. The transition from high to very high levels of risk is projected to between 2.8°C and 3.2°C.

Expert assessment by Gattuso et al. (2015; SOM):

Ecosystem services provided by temperate bivalves include marine harvests (both from capture fisheries and aquaculture), water quality maintenance, and coastal stabilization. Of these, marine harvests are easiest to quantify, and have been the subject of several assessments. Confidence is high that ocean acidification has already jeopardized marine harvest revenues in the Northwest United States (Washington State Blue Ribbon Panel on Ocean Acidification 2012). Although the affected hatcheries have taken steps to enhance monitoring, alter hatchery water intake and treatment, and diversify hatchery locations (Barton et al. 2015), these adaptations will only delay the onset of ocean acidification-related problems (high confidence). Wild harvest populations are fully exposed to ocean acidification and warming, and societal adaptations like these are not applicable. Services provided by bivalves will continue even if populations migrate, decrease in size, or individuals become smaller, so effects are somewhat more delayed than those on shellfish themselves. In 2100, impacts are expected to be moderate under RCP2.6 and very high under RCP8.5. The level of confidence declines as a function of increasing CO_2 emissions due to the uncertainty about the extent of local adaptation: medium under RCP2.6 and low under RCP8.5.

Fin fisheries (low latitude)

Update: Low latitude fin fisheries, or small-scale fisheries, provide food for millions of people along tropical coastlines and hence play an important role in the food security of a large number of countries (McClanahan et al. 2015; Pauly and Charles 2015). In many cases, populations are heavily dependent on these sources of protein given the lack of alternatives (Cinner et al. 2016, 2012; Pendleton et al. 2016). The climate related stresses affecting fin fish (see Section 'Finfish' above), however, are producing a number of challenges for small scale fisheries based on these species (e.g., (Pauly and Charles 2015; Bell et al. 2017; Kittinger 2013).

Recent literature (2015–2017) has continued to outline growing threats from the rapid shifts in the biogeography of key species (García Molinos et al. 2015; Poloczanska et al. 2013; Burrows et al. 2014; Poloczanska et al. 2016) and the ongoing rapid degradation of key habitats such as coral reefs, seagrass and mangroves (see Sections above on 'Sea grasses (mid latitude)', 'Mangroves' and 'Pteropods', as well as Chapter 3, Box 3.4). As these changes have accelerated, so have the risks to the food and livelihoods associated with small-scale fisheries (Cheung et al. 2010). These risks have compounded with non-climate stresses (e.g., pollution, overfishing, unsustainable coastal development) to drive many small-scale fisheries well below the sustainable harvesting levels required to keep these resources functioning as a source of food (McClanahan et al. 2015, 2009; Pendleton et al. 2016). As a result, projections of climate change and the growth in human populations increasingly predict shortages of fish protein for many regions (e.g., Pacific, e.g., Bell et al., 2013, 2017; Indian Ocean, e.g., McClanahan et al., 2015). Mitigation of these risks involved marine spatial planning, fisheries repair, sustainable aquaculture, and the development of alternative livelihoods (Song and Chuenpagdee 2015; Kittinger 2013; McClanahan et al. 2015; Weatherdon et al. 2016). Threats to small-scale fisheries have also come from the increasing incidence of alien (nuisance) species as well as an increasing incidence of disease, although the literature on these threats is at a low level of development and understanding (Kittinger et al. 2013; Weatherdon et al. 2016).

As assessed by Gattuso et al. (2015), risks of impacts on small-scale fisheries are medium today, but are expected to reach very high levels under scenarios extending beyond RCP2.6. The research literature plus the growing evidence that many countries will have trouble adapting to these changes places confidence a high level as to the risks of climate change on low latitude in fisheries. These effects are more sensitive, hence the higher risks at lower levels of temperature change.

Small-scale fisheries are highly dependent on healthy coastal ecosystems. With the growing evidence of impacts described above, the loss of habitat for small-scale fisheries is intensifying the risks of impact from climate change. For this reason, expert consensus has judged that risks have become greater since the assessment of Gattuso et al. (2015). Therefore, the transition from undetectable to medium levels of risk is projected to occur between 0.5°C and 0.7°C, with the transition from medium to high levels of risk occurring between 0.9°C and 1.1°C. The transition from high to very high levels of risk of impact as being judged to occur between 2.0°C and 2.5°C.

Expert assessment by Gattuso et al. (2015; SOM):

Evidence of climate change altering species composition of tropical marine fisheries is already apparent globally (Cheung et al. 2013). Simulations suggest that, as a result of range shifts and decrease in abundance of fish stocks, fisheries catch is likely to decline in tropical regions (Barange et al. 2014, Cheung et al. 2010). Projections also suggest that marine taxa in tropical regions are likely to lose critical habitat (e.g., coral reefs), leading to a decrease in fisheries productivity (Bell et al. 2013). Because of the magnitude of impacts, capacity for the fisheries to reduce such risks by protection, repair or adaptation is expected to be low (Pörtner et al. 2014). Thus, these impacts increase with increasing CO_2 emissions. Risk of impacts is close to medium level in present day, and increases to high and very high when CO_2 concentration reaches the levels expected in 2100 under RCP4.5 and RCP8.5, respectively.

The scope of adaptation for low latitude fin fisheries is narrow because of the high level of impacts on ecosystems and fisheries resources, lack of new fishing opportunities from species range shifts to compensate for the impacts, and relatively lower social-economic capacity of many countries to adapt changes. Thus, confidence level is high on projected impacts on low latitude fin fisheries.

Fin fisheries (mid and high latitude)

Update: While risks and reality of decline are high for low latitude fin fisheries, projections for mid to high latitude fisheries include increases in fishery productivity in many cases (FAO 2016; Hollowed et al. 2013; Cheung et al. 2013; Lam et al. 2014). These changes are associated with the biogeographical shift of species towards higher latitudes (‘borealisation’, Fossheim et al., 2015) which brings benefits as well as challenges (e.g., increased risk of disease and invasive species). Factors underpinning the expansion of fisheries production to high latitude locations include warming and increase light and mixing due to retreating sea ice (Cheung et al. 2009). As a result of this, fisheries in the cold temperate regions of the North Pacific and North Atlantic are undergoing major increase primary productivity and consequently in the increased harvest of fish from Cod and Pollock fisheries (Hollowed and Sundby 2014). At more temperate locations, intensification of some upwelling systems is also boosting primary production and fisheries catch (Sydeman et al. 2014; Shepherd et al. 2017), although there are increasing threats from deoxygenation as excess biomass falls into the deep ocean, fueling higher metabolic rates and oxygen drawdown (Bakun et al. 2015; Sydeman et al. 2014).

Similar to the assessment by Gattuso et al. (2015), our confidence in understanding risks at higher levels of climate change and longer periods diminishes over time. The ability of fishing industries to adapt to changes is considerable although the economic costs of adapting can be high. Complex, changes in fin fisheries at high latitudes has a number of climate related risks associated with it (as described above and by Gattuso et al. (2015). In this case, risks of climate impacts on fin fisheries at high latitudes is projected to transition from undetectable to medium levels of risk at 0.7°C to 0.9°C. The shift from medium to high levels of risk is projected by the expert consensus to occur between 2.2°C and 3.2°C.

Expert assessment by Gattuso et al. (2015; SOM):

Evidence that climate change effects altering species composition in mid and high latitude fisheries can already be observed globally, with increasing dominance of warmer-water species since the 1970s (Cheung et al. 2013). Global-scale projections suggest substantial increases in potential fisheries catch in high latitude regions (Barange et al. 2014; Cheung et al. 2010) under RCP8.5 by mid- to end-21st century. However, ocean acidification increases uncertainty surrounding the potential fisheries gain because the Arctic is a hotspot of ocean acidification (Lam et al. 2014). Risks of impacts of warming, ocean acidification and deoxygenation on mid-latitude regions are variable (Cheung et al. 2013; Barange et al. 2014). Overall, existing fish stocks are expected to decrease in catch while new opportunities for fisheries may emerge from range expansion of warmer-water. Declines in catch have been projected for fisheries in the Northeast Pacific (Ainsworth et al. 2011), Northwest Atlantic (Guénette et al. 2014), and waters around the U.K. (Jones et al. 2014) by mid 21st century under SRES A1B and A2 scenarios (equivalent to RCP6.0 to 8.5). While it is uncertain whether small-scale fisheries will have the mobility to follow shifts in ranges of target species, those with access to multiple gears types may be able to adapt more easily to climate-related changes in stock composition. Societal adaptation to reduce the risk of impacts is expected to be relatively higher than tropical fisheries. Thus, medium risk is assigned from present day, and risk increases to high when CO_2 concentration is beyond level expected from RCP4.5.

Risk to fisheries at mid and high latitudes depends on how the fishers, fishing industries and fisheries management bodies respond and adapt to changes in species composition and distribution. Prediction of the scope of such adaptive response is uncertain particularly under greater changes in fisheries resources. Thus, the confidence level is *high* under RCP2.6 and low under RCP8.5

References

Ainsworth, C. H., J. F. Samhouri, D. S. Busch, W. W. L. Cheung, J. Dunne, and T. A. Okey, 2011: Potential impacts of climate change on Northeast Pacific marine foodwebs and fisheries. ICES J. Mar. Sci., 68, 1217–1229.

Alongi, D. M., 2008: Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. Estuar. Coast. Shelf Sci., 76, 1–13, doi:10.1016/j.ecss.2007.08.024.

——, 2015: The Impact of Climate Change on Mangrove Forests. Curr. Clim. Chang. Reports, 1, 30–39, doi:10.1007/s40641-015-0002-x.

Alvarez-Filip, L., N. K. Dulvy, J. A. Gill, I. M. Cote, and A. R. Watkinson, 2009: Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. Proc. R. Soc. B Biol. Sci., 276, 3019–3025, doi:10.1098/rspb.2009.0339.

André, C., D. Boulet, H. Rey-Valette, and B. Rulleau, 2016: Protection by hard defence structures or relocation of assets exposed to coastal risks: Contributions and drawbacks of cost-benefit analysis for long-term adaptation choices to climate change. Ocean Coast. Manag., 134, 173–182, doi:10.1016/j.ocecoaman.2016.10.003.

Arkema, K. K., and Coauthors, 2013: Coastal habitats shield people and property from sea-level rise and storms. Nat. Clim. Chang., 3, 913–918, doi:10.1038/nclimate1944.

Asplund, M. E., S. P. Baden, S. Russ, R. P. Ellis, N. Gong, and B. E. Hernroth, 2014: Ocean acidification and host-pathogen interactions: Blue mussels, Mytilus edulis, encountering Vibrio tubiashii. Environ. Microbiol., 16, 1029–1039, doi:10.1111/1462-2920.12307.

Atkinson, A., V. Siegel, E. Pakhomov, and P. Rothery, 2004: Long-term decline in krill stock and increase in salps within the Southern Ocean. Nature, 432, 100–103, doi:10.1038/nature02996.

Bakun, A., B. A. Black, S. J. Bograd, M. García-Reyes, A. J. Miller, R. R. Rykaczewski, and W. J. Sydeman, 2015: Anticipated Effects of Climate Change on Coastal Upwelling Ecosystems. Curr. Clim. Chang. Reports, 1, 85–93, doi:10.1007/s40641-015-0008-4.

Barange, M., and Coauthors, 2014: Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nat. Clim. Chang., 4, 211–216, doi:10.1038/nclimate2119.

Barbier, E. B., 2015: Valuing the storm protection service of estuarine and coastal ecosystems. Ecosyst. Serv., 11, 32–38, doi:10.1016/j.ecoser.2014.06.010.

Barton, A., B. Hales, G. G. Waldbusser, C. Langdon, and R. A. Feely, 2012: The Pacific oyster, Crassostrea gigas, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. Limnol. Oceanogr., 57, 698–710, doi:10.4319/lo.2012.57.3.0698.

——, and Coauthors, 2015: Impacts of coastal acidification on the Pacific Northwest shellfish industry and adaptation strategies implemented in response. Oceanography, 28, 146–159, doi:10.5670/oceanog.2015.38.

Bates, A. E., and Coauthors, 2014: Defining and observing stages of climate-mediated range shifts in marine systems. Glob. Environ. Chang., 26, 27–38, doi:10.1016/j.gloenvcha.2014.03.009.

Beck, M. W., and Coauthors, 2011: Oyster Reefs at Risk and Recommendations for Conservation, Restoration, and Management. Bioscience, 61, 107–116, doi:10.1525/bio.2011.61.2.5.

Bednaršek, N., and M. D. Ohman, 2015: Changes in pteropod distributions and shell dissolution across a frontal system in the California Current System. Mar. Ecol. Prog. Ser., 523, 93–103, doi:10.3354/meps11199.

——, and Coauthors, 2012: Extensive dissolution of live pteropods in the Southern Ocean. Nat. Geosci., 5, 881–885, doi:10.1038/ngeo1635.

——, R. A. Feely, J. C. P. Reum, B. Peterson, J. Menkel, S. R. Alin, and B. Hales, 2014: Limacina helicina shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. Proc. R. Soc. B Biol. Sci., 281, 20140123–20140123, doi:10.1098/rspb.2014.0123.

Bednaršek, N., C. J. Harvey, I. C. Kaplan, R. A. Feely, and J. Možina, 2016: Pteropods on the edge: Cumulative effects of ocean acidification, warming, and deoxygenation. Prog. Oceanogr., 145, 1–24, doi:10.1016/j.pocean.2016.04.002.

Bednaršek, N., T. Klinger, C. J. Harvey, S. Weisberg, R. M. McCabe, R. A. Feely, J. Newton, and N. Tolimieri, 2017: New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management. Ecol. Indic., 76, 240–244, doi:10.1016/j.ecolind.2017.01.025.

Bell, J. D., and Coauthors, 2013: Mixed responses of tropical Pacific fisheries and aquaculture to climate change. Nat. Clim. Chang., 3, 591–599, doi:10.1038/nclimate1838.

Bell, J. D., and Coauthors, 2017: Adaptations to maintain the contributions of small-scale fisheries to

food security in the Pacific Islands. Mar. Policy, doi:10.1016/j.marpol.2017.05.019.
Bortolotto, E., A. Bucklin, M. Mezzavilla, L. Zane, and T. Patarnello, 2011: Gone with the currents: lack of genetic differentiation at the circum-continental scale in the Antarctic krill Euphausia superba. BMC Genet., 12, 32, doi:10.1186/1471-2156-12-32.

Bosello, F., and E. De Cian, 2014: Climate change, sea level rise, and coastal disasters. A review of modeling practices. Energy Econ., 46, 593–605, doi:10.1016/j.eneco.2013.09.002.
Brodie, J., and Coauthors, 2014: The future of the northeast Atlantic benthic flora in a high CO2 world. Ecol. Evol., 4, 2787–2798, doi:10.1002/ece3.1105.
Burge, C. A., C. J. S. Kim, J. M. Lyles, and C. D. Harvell, 2013: Special issue Oceans and Humans Health: The ecology of marine opportunists. Microb. Ecol., 65, 869–879, doi:10.1007/s00248-013-0190-7.
Burrows, M. T., and Coauthors, 2014: Geographical limits to species-range shifts are suggested by climate velocity. Nature, 507, 492–495, doi:10.1038/nature12976.
C. R. Wilkinson, 2000: Status of Coral Reefs of the World: 2000. Aust. Inst. Mar. Sci. Townsville, Aust., 363.
Callaway, R., and Coauthors, 2012: Review of climate change impacts on marine aquaculture in the UK and Ireland. Aquat. Conserv. Mar. Freshw. Ecosyst., 22, 389–421, doi:10.1002/aqc.2247.
Carr, J. A., P. D'Odorico, K. J. McGlathery, and P. L. Wiberg, 2012: Modeling the effects of climate change on eelgrass stability and resilience: Future scenarios and leading indicators of collapse. Mar. Ecol. Prog. Ser., 448, 289–301.
Castillo, N., L. M. Saavedra, C. A. Vargas, C. Gallardo-Escárate, and C. Détrée, 2017: Ocean acidification and pathogen exposure modulate the immune response of the edible mussel Mytilus chilensis. Fish Shellfish Immunol., 70, 149–155, doi:10.1016/j.fsi.2017.08.047.
Cheung, W. W. L., V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. Watson, and D. Pauly, 2009: Projecting global marine biodiversity impacts under climate change scenarios. Fish Fish., 10, 235–251, doi:10.1111/j.1467-2979.2008.00315.x.
Cheung, W. W. L., V. W. Y. Lam, J. L. Sarmiento, K. Kearney, R. Watson, D. Zeller, and D. Pauly, 2010: Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob. Chang. Biol., 16, 24–35, doi:10.1111/j.1365-2486.2009.01995.x.
——, R. Watson, and D. Pauly, 2013: Signature of ocean warming in global fisheries catch. Nature, 497, 365–368, doi:10.1038/nature12156.
Cinner, J. E., and Coauthors, 2012: Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. Glob. Environ. Chang., 22, 12–20, doi:10.1016/j.gloenvcha.2011.09.018.
Cinner, J. E., and Coauthors, 2016: A framework for understanding climate change impacts on coral reef social–ecological systems. Reg. Environ. Chang., 16, 1133–1146, doi:10.1007/s10113-015-0832-z.
Clements, J. C., and T. Chopin, 2017: Ocean acidification and marine aquaculture in North America: Potential impacts and mitigation strategies. Rev. Aquac., 9, 326341, doi:10.1111/raq.12140.
Clements, J. C., D. Bourque, J. McLaughlin, M. Stephenson, and L. A. Comeau, 2017: Extreme ocean acidification reduces the susceptibility of eastern oyster shells to a polydorid parasite. J. Fish Dis., 40, 1573–1585, doi:10.1111/jfd.12626.
Comeau, S., G. Gorsky, R. Jeffree, J.-L. Teyssié, and J.-P. Gattuso, 2009: Impact of ocean acidification on a key Arctic pelagic mollusc (Limacina helicina). Biogeosciences, 6, 1877–1882, doi:10.5194/bg-6-1877-2009.
Comeau, S., R. Jeffree, J.-L. Teyssié, and J.-P. Gattuso, 2010: Response of the Arctic pteropod Limacina helicina to projected future environmental conditions. PLoS One, 5, doi:10.1371/journal.pone.0011362.
Comeau, S., S. Alliouane, and J.-P. Gattuso, 2012: Effects of ocean acidification on overwintering juvenile Arctic pteropods Limacina helicina. Ecol. Prog. Ser., 456, 279–284, doi:10.3354/meps09696.
Cooley, S. R., J. E. Rheuban, D. R. Hart, V. Luu, D. M. Glover, J. A. Hare, and S. C. Doney, 2015: An Integrated Assessment Model for Helping the United States Sea Scallop (Placopecten magellanicus) Fishery Plan Ahead for Ocean Acidification and Warming. PLoS One, 10,

e0124145, doi:10.1371/journal.pone.0124145.

Cooper, J. A. G., M. C. O'Connor, and S. McIvor, 2016: Coastal defences versus coastal ecosystems: A regional appraisal. Mar. Policy, doi:10.1016/j.marpol.2016.02.021.

Couce, E., A. Ridgwell, and E. J. Hendy, 2013: Future habitat suitability for coral reef ecosystems under global warming and ocean acidification. Glob. Chang. Biol., 19, 3592–3606, doi:10.1111/gcb.12335.

David, C., F. L. Schaafsma, J. A. van Franeker, B. Lange, A. Brandt, and H. Flores, 2017: Community structure of under-ice fauna in relation to winter sea-ice habitat properties from the Weddell Sea. Polar Biol., 40, 247–261, doi:10.1007/s00300-016-1948-4.

De'ath, G., K. E. Fabricius, H. Sweatman, and M. Puotinen, 2012: The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proc. Natl. Acad. Sci. U. S. A., 109, 17995–17999, doi:10.1073/pnas.1208909109.

Defeo, O., A. McLachlan, D. S. Schoeman, T. A. Schlacher, J. Dugan, A. Jones, M. Lastra, and F. Scapini, 2009: Threats to sandy beach ecosystems: A review. Estuar. Coast. Shelf Sci., 81, 1–12, doi:10.1016/j.ecss.2008.09.022.

Donner, S., W. J. Skirving, C. M. Little, M. Oppenheimer, and O. Hoegh-Gulberg, 2005: Global assessment of coral bleaching and required rates of adaptation under climate change. Glob. Chang. Biol., 11, 2251–2265, doi:10.1111/j.1365-2486.2005.01073.x.

Dove, S. G., D. I. Kline, O. Pantos, F. E. Angly, G. W. Tyson, and O. Hoegh-Guldberg, 2013: Future reef decalcification under a business-as-usual CO2 emission scenario. Proc. Natl. Acad. Sci. U. S. A., 110, 15342–15347, doi:10.1073/pnas.1302701110.

Duke, N. C., and Coauthors, 2017: Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: A severe ecosystem response, coincidental with an unusually extreme weather event. Mar. Freshw. Res., 68, 1816–1829, doi:10.1071/MF16322.

Eakin, C. M., and Coauthors, 2010: Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005. PLoS One, 5, e13969, doi:10.1371/journal.pone.0013969.

Elliff, C. I., and I. R. Silva, 2017: Coral reefs as the first line of defense: Shoreline protection in face of climate change. Mar. Environ. Res., 127, 148–154, doi:10.1016/j.marenvres.2017.03.007.

Esbaugh, A. J., 2017: Physiological implications of ocean acidification for marine fish: emerging patterns and new insights. J. Comp. Physiol. B, 188, 1–13, doi:10.1007/s00360-017-1105-6.

FAO, 2016: The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all. Rome, Italy, 200 pp.

Feely, R. A., and Coauthors, 2016: Chemical and biological impacts of ocean acidification along the west coast of North America. Estuar. Coast. Shelf Sci., 183, 260–270, doi:10.1016/j.ecss.2016.08.043.

Feller, I. C., D. A. Friess, K. W. Krauss, and R. R. Lewis, 2017: The state of the world's mangroves in the 21st century under climate change. Hydrobiologia, 803, doi:10.1007/s10750-017-3331-z.

Ferrario, F., M. W. Beck, C. D. Storlazzi, F. Micheli, C. C. Shepard, and L. Airoldi, 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. Nat. Commun., 5, 3794, doi:10.1038/ncomms4794.

Fossheim, M., R. Primicerio, E. Johannesen, R. B. Ingvaldsen, M. M. Aschan, and A. V. Dolgov, 2015: Recent warming leads to a rapid borealization of fish communities in the Arctic. Nat. Clim. Chang., 5, 673–677, doi:10.1038/nclimate2647.

Fu, X., and J. Song, 2017: Assessing the economic costs of sea level rise and benefits of coastal protection: A spatiotemporal approach. Sustain., 9, doi:10.3390/su9081495.

García Molinos, J., and Coauthors, 2015: Climate velocity and the future global redistribution of marine biodiversity. Nat. Clim. Chang., 6, 83–88, doi:10.1038/nclimate2769.

Gattuso, J.-P., and Coauthors, 2015: Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. Science (80-.)., 349, aac4722, doi:10.1126/science.aac4722.

Gedan, K. B., and M. D. Bertness, 2009: Experimental warming causes rapid loss of plant diversity in New England salt marshes. Ecol. Lett., 12, 842–848, doi:10.1111/j.1461-0248.2009.01337.x.

Gewin, V., 2017: Scientists hit hard by powerful hurricanes in 2017 share tips for weathering future disasters. Nature, 551, 401–403.

Glynn, P. W., 1984: Widespread coral mortality and the 1982-83 El Niño warming event. Environ.

Conserv., 11, 133–146, doi:10.1017/S0376892900013825.

Gobler, C. J., E. L. DePasquale, A. W. Griffith, and H. Baumann, 2014: Hypoxia and Acidification Have Additive and Synergistic Negative Effects on the Growth, Survival, and Metamorphosis of Early Life Stage Bivalves. PLoS One, 9, e83648, doi:10.1371/journal.pone.0083648.

Godoy, M. D. P., and L. D. De Lacerda, 2015: Mangroves Response to Climate Change: A Review of Recent Findings on Mangrove Extension and Distribution. An Acad Bras CiencAnnals Brazilian Acad. Sci., 87, 651–667, doi:10.1590/0001-3765201520150055.

Guénette, S., J. N. Araújo, and A. Bundy, 2014: Exploring the potential effects of climate change on the Western Scotian Shelf ecosystem, Canada. J. Mar. Syst., 134, 89–100, doi:10.1016/j.jmarsys.2014.03.001.

Guerrero-Meseguer, L., A. Marín, and C. Sanz-Lázaro, 2017: Future heat waves due to climate change threaten the survival of P. oceanica seedlings. Environ. Pollut., 230, 40–45, doi:10.1016/j.envpol.2017.06.039.

H. Flores, A. Atkinson, S. Kawaguchi, B. A. Krafft, G. Milinevsky, S. Nicol, C. Reiss, G., J. A. Tarling, R. Werner, E. Bravo Rebolledo, V. Cirelli, J. Cuzin-Roudy, S. Fielding, B. A. van Franeker, J. J. Groeneveld, M. Haraldsson, A. Lombana, E. Marschoff, M. Meyer, E. A. Pakhomov, A. P. Van de Putte, E. Rombolá, K. Schmidt, V. Siegel, and T. W. Teschke, H. Tonkes, J. Y. Toullec, P. N. Trathan, N. Tremblay, 2012: Impact of climate change on Antarctic krill. Mar. Ecol. Prog. Ser., 458, 1–19, doi:10.3354/meps09831.

Hauer, M. E., J. M. Evans, and D. R. Mishra, 2016: Millions projected to be at risk from sea-level rise in the continental United States. Nat. Clim. Chang., 6, 691–695, doi:10.1038/nclimate2961.

Hiddink, J. G., M. T. Burrows, and J. García Molinos, 2015: Temperature tracking by North Sea benthic invertebrates in response to climate change. Glob. Chang. Biol., 21, 117–129, doi:10.1111/gcb.12726.

Hill, S. L., T. Phillips, and A. Atkinson, 2013: Potential Climate Change Effects on the Habitat of Antarctic Krill in the Weddell Quadrant of the Southern Ocean. PLoS One, 8, doi:10.1371/journal.pone.0072246.

Hoegh-Guldberg, O., 1999: Climate change, coral bleaching and the future of the world's coral reefs. Mar. Freshw. Res., 50, 839, doi:10.1071/MF99078.

Hoegh-Guldberg, O., and Coauthors, 2007: Coral Reefs Under Rapid Climate Change and Ocean Acidification. Science (80-.)., 318, 1737–1742.

——, R. Cai, E. S. S. Poloczanska, P. G. G. Brewer, S. Sundby, K. Hilmi, V. J. J. Fabry, and S. Jung, 2014: The Ocean. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change, V.R. Barros et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, United Kingdom and New York, NY, USA, 1655–1731.

Höffle, H., M. S. Thomsen, and M. Holmer, 2011: High mortality of Zostera marina under high temperature regimes but minor effects of the invasive macroalgae Gracilaria vermiculophylla. doi: Estuar. Coast. Shelf Sci., 92, 35–46, doi:10.1016/j.ecss.2010.12.017e.

Hollowed, A. B., and S. Sundby, 2014: Change is coming to the northern oceans. Science (80-.)., 344, 1084–1085, doi:10.1126/science.1251166.

Hollowed, A. B., and Coauthors, 2013: Projected impacts of climate change on marine fish and fisheries. ICES J. Mar. Sci., 70, 1023–1037, doi:10.1093/icesjms/fst081.

van Hooidonk, R., J. A. Maynard, D. Manzello, and S. Planes, 2014: Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. Glob. Chang. Biol., 20, 103–112, doi:10.1111/gcb.12394.

Horta E Costa, B., J. Assis, G. Franco, K. Erzini, M. Henriques, E. J. Gon??alves, and J. E. Caselle, 2014: Tropicalization of fish assemblages in temperate biogeographic transition zones. Mar. Ecol. Prog. Ser., 504, 241–252, doi:10.3354/meps10749.

Hughes, T. P., and Coauthors, 2017: Global warming and recurrent mass bleaching of corals. Nature, 543, 373–377, doi:10.1038/nature21707.

Iida, Y., A. Kojima, Y. Takatani, T. Nakano, H. Sugimoto, T. Midorikawa, and M. Ishii, 2015: Trends in pCO2 and sea–air CO2 flux over the global open oceans for the last two decades. J. Oceanogr., 71, 637–661, doi:10.1007/s10872-015-0306-4.

Jones, M. C., and W. W. L. Cheung, 2015: Multi-model ensemble projections of climate change effects on global marine biodiversity. ICES J. Mar. Sci., 72, 741–752, doi:10.1093/icesjms/fsu172.

Jones, M. C., S. R. Dye, J. K. Pinnegar, R. Warren, and W. W. Cheung, 2014: Using scenarios to project the changing profitability of fisheries under climate change. Fish Fish., doi:10.1111/faf.12081.

Joos, F., and Coauthors, 2013: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. Atmos. Chem. Phys., 13, 2793–2825, doi:10.5194/acp-13-2793-2013.

Jordà, G., N. Marbà, and C. M. Duarte, 2012: Mediterranean seagrass vulnerable to regional climate warming. Nat. Clim. Chang., 2, 821–824, doi:10.1038/nclimate1533.

Kawaguchi, S., and Coauthors, 2013: Risk maps for Antarctic krill under projected Southern Ocean acidification. Nat. Clim. Chang., 3, 843–847, doi:10.1038/nclimate1937.

Kittinger, J. N., 2013: Human Dimensions of Small-Scale and Traditional Fisheries in the Asia-Pacific Region. Pacific Sci., 67, 315–325, doi:10.2984/67.3.1.

——, and Coauthors, 2013: Emerging frontiers in social-ecological systems research for sustainability of small-scale fisheries. Curr. Opin. Environ. Sustain., 5, 352–357, doi:10.1016/j.cosust.2013.06.008.

Kroeker, K. J., R. L. Kordas, R. Crim, I. E. Hendriks, L. Ramajo, G. S. Singh, C. M. Duarte, and J. P. Gattuso, 2013: Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. Glob. Chang. Biol., 19, 1884–1896, doi:10.1111/gcb.12179.

Lacoue-Labarthe, T., and Coauthors, 2016: Impacts of ocean acidification in a warming Mediterranean Sea: An overview. Reg. Stud. Mar. Sci., 5, 1–11, doi:10.1016/j.rsma.2015.12.005.

Lam, V. W. Y., W. W. L. Cheung, and U. R. Sumaila, 2014: Marine capture fisheries in the Arctic: Winners or losers under climate change and ocean acidification? Fish Fish., 17, 335–357, doi:10.1111/faf.12106.

Lemasson, A. J., S. Fletcher, J. M. Hall-Spencer, and A. M. Knights, 2017: Linking the biological impacts of ocean acidification on oysters to changes in ecosystem services: A review. J. Exp. Mar. Bio. Ecol., 492, 49–62, doi:10.1016/j.jembe.2017.01.019.

Li, S., J. Huang, C. Liu, Y. Liu, G. Zheng, L. Xie, and R. Zhang, 2016a: Interactive Effects of Seawater Acidification and Elevated Temperature on the Transcriptome and Biomineralization in the Pearl Oyster Pinctada fucata. Environ. Sci. Technol., 50, 1157–1165, doi:10.1021/acs.est.5b05107.

——, C. Liu, J. Huang, Y. Liu, S. Zhang, G. Zheng, L. Xie, and R. Zhang, 2016b: Transcriptome and biomineralization responses of the pearl oyster Pinctada fucata to elevated CO2 and temperature. Sci. Rep., 6, 18943, doi:10.1038/srep18943.

Lischka, S., and U. Riebesell, 2012: Synergistic effects of ocean acidification and warming on overwintering pteropods in the Arctic. Glob. Chang. Biol., 18, 3517–3528, doi:10.1111/gcb.12020.

Lischka, S., J. Büdenbender, T. Boxhammer, and U. Riebesell, 2011: Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod Limacina helicina: mortality, shell degradation, and shell growth. Biogeosciences, 8, 919–932, doi:10.5194/bg-8-919-2011.

Logan, C. A., J. P. Dunne, C. M. Eakin, and S. D. Donner, 2014: Incorporating adaptive responses into future projections of coral bleaching. Glob. Chang. Biol., 20, 125–139, doi:10.1111/gcb.12390.

Long, J., C. Giri, J. Primavera, and M. Trivedi, 2016: Damage and recovery assessment of the Philippines' mangroves following Super Typhoon Haiyan. Mar. Pollut. Bull., 109, 734–743, doi:10.1016/j.marpolbul.2016.06.080.

Lovelock, C. E., and Coauthors, 2015: The vulnerability of Indo-Pacific mangrove forests to sea-level rise. Nature, 526, 559–563, doi:10.1038/nature15538.

——, I. C. Feller, R. Reef, S. Hickey, and M. C. Ball, 2017: Mangrove dieback during fluctuating sea levels. Sci. Rep., 7, 1680, doi:10.1038/s41598-017-01927-6.

Mackenzie, C. L., S. A. Lynch, S. C. Culloty, and S. K. Malham, 2014a: Future oceanic warming and acidification alter immune response and disease status in a commercial shellfish species, Mytilus edulis L. PLoS One, 9, doi:10.1371/journal.pone.0099712.

——, G. A. Ormondroyd, S. F. Curling, R. J. Ball, N. M. Whiteley, and S. K. Malham, 2014b: Ocean warming, more than acidification, reduces shell strength in a commercial shellfish species during food limitation. PLoS One, 9, doi:10.1371/journal.pone.0086764.

Manno, C., and Coauthors, 2017: Shelled pteropods in peril: Assessing vulnerability in a high CO2 ocean. Earth-Science Rev., 169, 132–145, doi:10.1016/j.earscirev.2017.04.005.

Mannoa, C., N. Morataa, and R. Primiceriob, 2012: Limacina retroversa’s response to combined effects of ocean acidification and sea water freshening. Estuar. Coast. Shelf Sci., 113, 163–171, doi:10.1016/j.ecss.2012.07.019.

Marbà, N., and C. M. Duarte, 2010: Mediterranean warming triggers seagrass (Posidonia oceanica) shoot mortality. Glob. Chang. Biol., 16, 2366–2375, doi:10.1111/j.1365- 2486.2009.02130.x.

McClanahan, T. R., J. C. Castilla, A. T. White, and O. Defeo, 2009: Healing small-scale fisheries by facilitating complex socio-ecological systems. Rev. Fish Biol. Fish., 19, 33–47, doi:10.1007/s11160-008-9088-8.

McClanahan, T. R., E. H. Allison, and J. E. Cinner, 2015: Managing fisheries for human and food security. Fish Fish., 16, 78–103, doi:10.1111/faf.12045.

McKee, K., K. Rogers, and N. Saintilan, 2012: Response of salt marsh and mangrove wetlands to changes in atmospheric CO2, climate, and sea level. Glob. Chang. Funct. Distrib. Wetl., 63–96.

Miller, A. W., A. C. Reynolds, C. Sobrino, and G. F. Riedel, 2009: Shellfish face uncertain future in high CO2 world: Influence of acidification on oyster larvae calcification and growth in estuaries. PLoS One, 4, doi:10.1371/journal.pone.0005661.

Moore, J. A. Y., and Coauthors, 2012: Unprecedented mass bleaching and loss of coral across 12° of latitude in Western Australia in 2010-11. PLoS One, 7, doi:10.1371/journal.pone.0051807.

Muhlfeld, C. C., and Coauthors, 2014: Invasive hybridization in a threatened species is accelerated by climate change. Nat. Clim. Chang., 4, 620–624, doi:10.1038/nclimate2252.

Munday, P. L., A. J. Cheal, D. L. Dixson, J. L. Rummer, and K. E. Fabricius, 2014: Behavioural impairment in reef fishes caused by ocean acidification at CO2 seeps. Nat. Clim. Chang., 4, 487–492, doi:10.1038/nclimate2195.

Nejrup, L. B., and M. F. Pedersen, 2008: Effects of salinity and water temperature on the ecological performance of the Zostera marina. Aquat. Bot., 88, 239–246, doi:10.1016/j.aquabot.2007.10.006.

Di Nitto, D., G. Neukermans, N. Koedam, H. Defever, F. Pattyn, J. G. Kairo, and F. Dahdouh-Guebas, 2014: Mangroves facing climate change: Landward migration potential in response to projected scenarios of sea level rise. Biogeosciences, 11, 857–871, doi:10.5194/bg-11-857-2014.

Normile, D., 2016: El Niño’s warmth devastating reefs worldwide. Science, 352, 15–16, doi:10.1126/science.352.6281.15.

Notz, D., and J. Stroeve, 2016: Observed Arctic sea-ice loss directly follows anthropogenic CO 2 emission. Science (80-.)., 354, 747–750, doi:10.1126/science.aag2345.

O’Mahony, J., R. Simes, D. Redhill, K. Heaton, C. Atkinson, E. Hayward, and M. Nguyen, 2017: At What Price? The Economic, Social and Icon Value of the Great Barrier Reef. Brisbane, Australia, 92 pp.

Ondiviela, B., I. J. Losada, J. L. Lara, M. Maza, C. Galván, T. J. Bouma, and J. van Belzen, 2014: The role of seagrasses in coastal protection in a changing climate. Coast. Eng., 87, 158–168, doi:10.1016/j.coastaleng.2013.11.005.

Ong, E. Z., M. Briffa, T. Moens, and C. Van Colen, 2017: Physiological responses to ocean acidification and warming synergistically reduce condition of the common cockle Cerastoderma edule. Mar. Environ. Res., 130, 38–47, doi:10.1016/j.marenvres.2017.07.001.

Ong, J. J. L., A. Nicholas Rountrey, J. Jane Meeuwig, S. John Newman, J. Zinke, and M. Gregory Meekan, 2015: Contrasting environmental drivers of adult and juvenile growth in a marine fish: implications for the effects of climate change. Sci. Rep., 5, 10859, doi:10.1038/srep10859.

Oxford Economics, 2009: Valuing the Effects of Great Barrier Reef Bleaching. Great Barrier Reef Foundation, Newstead, QLD, Australia, 102 pp.

Parker, L. M., E. Scanes, W. A. O’Connor, R. A. Coleman, M. Byrne, H. O. Pörtner, and P. M. Ross, 2017: Ocean acidification narrows the acute thermal and salinity tolerance of the Sydney rock oyster Saccostrea glomerata. Mar. Pollut. Bull., 122, 263–271, doi:10.1016/j.marpolbul.2017.06.052.

Pauly, D., and A. Charles, 2015: Counting on small-scale fisheries. Science (80-.)., 347, 242–243, doi:10.1126/science.347.6219.242-b.

Pendleton, L., and Coauthors, 2016: Coral reefs and people in a high-CO2 world: Where can science make a difference to people? PLoS One, 11, 1–21, doi:10.1371/journal.pone.0164699.

Pergent, G., C. Pergent-Martini, A. Bein, M. Dedeken, P. Oberti, A. Orsini, J. F. Santucci, and F. Short, 2015: Dynamic of Posidonia oceanica seagrass meadows in the northwestern Mediterranean: Could climate change be to blame? Comptes Rendus - Biol., 338, 484–493, doi:10.1016/j.crvi.2015.04.011.

Pespeni, M. H., and Coauthors, 2013: Evolutionary change during experimental ocean acidification. Proc. Natl. Acad. Sci., 110, 6937–6942, doi:10.1073/pnas.1220673110.

Piñones, A., and A. V. Fedorov, 2016: Projected changes of Antarctic krill habitat by the end of the 21st century. Geophys. Res. Lett., 43, 8580–8589, doi:10.1002/2016GL069656.

Pinsky, M. L., B. Worm, M. J. Fogarty, J. L. Sarmiento, and S. A. Levin, 2013: Marine Taxa Track Local Climate Velocities. Science (80-.)., 341, 1239–1242, doi:10.1126/science.1239352.

Poloczanska, E. S., and Coauthors, 2013: Global imprint of climate change on marine life. Nat. Clim. Chang., 3, 919–925, doi:10.1038/nclimate1958.

——, and Coauthors, 2016: Responses of Marine Organisms to Climate Change across Oceans. Front. Mar. Sci., 3, 62, doi:10.3389/fmars.2016.00062.

Pörtner, H. O., D. M. Karl, P. W. Boyd, W. W. L. Cheung, S. E. Lluch-Cota, Y. Nojiri, D. N. Schmidt, and P. O. Zavialov, 2014: Ocean Systems. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, C.B. Field et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 411–484.

Potts, W. M., and Coauthors, 2014: Ocean warming, a rapid distributional shift, and the hybridization of a coastal fish species. Glob. Chang. Biol., 20, 2765–2777, doi:10.1111/gcb.12612.

Prentice, C., and E. J. T. Houghton et al., 2001: “The carbon cycle and atmospheric carbon dioxide” in Climate Change 2001: the Scientific Basis. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, 183–237.

Rahmstorf, S., J. E. Box, G. Feulner, M. E. Mann, A. Robinson, S. Rutherford, and E. J. Schaffernicht, 2015: Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nat. Clim. Chang., 5, 475–480, doi:10.1038/nclimate2554.

Ben Rais Lasram, F., F. Guilhaumon, C. Albouy, S. Somot, W. Thuiller, and D. Mouillot, 2010: The Mediterranean Sea as a ‘cul-de-sac’ for endemic fishes facing climate change. Glob. Chang. Biol., 16, 3233–3245, doi:10.1111/j.1365-2486.2010.02224.x.

Rasheed, M. A., S. A. McKenna, A. B. Carter, and R. G. Coles, 2014: Contrasting recovery of shallow and deep water seagrass communities following climate associated losses in tropical north Queensland, Australia. Mar. Pollut. Bull., 83, 491–499, doi:10.1016/j.marpolbul.2014.02.013.

Raybaud, V., G. Beaugrand, J.-M. Dewarumez, and C. Luczak, 2015: Climate-induced range shifts of the American jackknife clam Ensis directus in Europe. Biol. Invasions, 17, 725–741, doi:10.1007/s10530-014-0764-4.

Repolho, T., and Coauthors, 2017: Seagrass ecophysiological performance under ocean warming and acidification. Sci. Rep., 7, 41443, doi:10.1038/srep41443.

Risser, M. D., and M. F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. Geophys. Res. Lett., n/a--n/a, doi:10.1002/2017GL075888.

Rodrigues, L. C., J. C. J. M. Van Den Bergh, F. Massa, J. A. Theodorou, P. Ziveri, and F. Gazeau, 2015: Sensitivity of Mediterranean Bivalve Mollusc Aquaculture to Climate Change, Ocean Acidification, and Other Environmental Pressures: Findings from a Producer Survey. J. Shellfish Res., 34, 1161–1176, doi:10.2983/035.034.0341.

Rodriguez, A. B., and Coauthors, 2014: Oyster reefs can outpace sea-level rise. Nat. Clim. Chang., 4, 493–497, doi:10.1038/nclimate2216.

Rosenzweig, C., and W. Solecki, 2014: Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. Glob. Environ. Chang., 28, 395–408, doi:10.1016/j.gloenvcha.2014.05.003.

Saunders, M. I., and Coauthors, 2014: Interdependency of tropical marine ecosystems in response to climate change. Nat. Clim. Chang., 4, 724–729, doi:10.1038/NCLIMATE2274.

Shepherd, J. G., P. G. Brewer, A. Oschlies, and A. J. Watson, 2017: Ocean ventilation and deoxygenation in a warming world: introduction and overview. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., 375, 20170240, doi:10.1098/rsta.2017.0240.

Sheppard, C., D. J. Dixon, M. Gourlay, A. Sheppard, and R. Payet, 2005: Coral mortality increases wave energy reaching shores protected by reef flats: Examples from the Seychelles. Estuar. Coast. Shelf Sci., 64, 223–234, doi:10.1016/j.ecss.2005.02.016.

Shi, W., X. Zhao, Y. Han, Z. Che, X. Chai, and G. Liu, 2016: Ocean acidification increases cadmium accumulation in marine bivalves: a potential threat to seafood safety. Sci. Rep., 6, 20197, doi:10.1038/srep20197.

Short, F. T., and H. A. Neckles, 1999: The effects of global climate change on seagrasses. Aquat. Bot., 63, 169–196, doi:10.1016/S0304-3770(98)00117-X.

Shults, J. M., and S. Galea, 2017: Preparing for the Next Harvey, Irma, or Maria — Addressing Research Gaps. Perspective, 363, 1–3, doi:10.1056/NEJMp1002530.

Silverman, J., and Coauthors, 2014: Community calcification in Lizard Island, Great Barrier Reef: A 33year perspective. Geochim. Cosmochim. Acta, 144, 72–81, doi:https://doi.org/10.1016/j.gca.2014.09.011.

Song, A. M., and R. Chuenpagdee, 2015: Interactive Governance for Fisheries. Interact. Gov. Small-Scale Fish., 5, 435–456, doi:10.1007/978-3-319-17034-3.

Spalding, M. D., S. Ruffo, C. Lacambra, I. Meliane, L. Z. Hale, C. C. Shepard, and M. W. Beck, 2014: The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. Ocean Coast. Manag., 90, 50–57, doi:10.1016/j.ocecoaman.2013.09.007.

——, L. Burke, S. A. Wood, J. Ashpole, J. Hutchison, and P. zu Ermgassen, 2017: Mapping the global value and distribution of coral reef tourism. Mar. Policy, 82, 104–113, doi:10.1016/j.marpol.2017.05.014.

Steinberg, D. K., and Coauthors, 2015: Long-term (1993-2013) changes in macrozooplankton off the western antarctic peninsula. Deep. Res. Part I Oceanogr. Res. Pap., 101, 54–70, doi:10.1016/j.dsr.2015.02.009.

Storlazzi, C. D., E. P. L. Elias, and P. Berkowitz, 2015: Many Atolls May be Uninhabitable Within Decades Due to Climate Change. Sci. Rep., 5, 14546, doi:10.1038/srep14546.

Sydeman, W. J., M. Garcia-Reyes, D. S. Schoeman, R. R. Rykaczewski, S. A. Thompson, B. A. Black, and S. J. Bograd, 2014: Climate change and wind intensification in coastal upwelling ecosystems. Science (80-.)., 345, 77–80, doi:10.1126/science.1251635.

Telesca, L., and Coauthors, 2015: Seagrass meadows (Posidonia oceanica) distribution and trajectories of change. Sci. Rep., 5, 12505, doi:10.1038/srep12505.

Temmerman, S., P. Meire, T. J. Bouma, P. M. J. Herman, T. Ysebaert, and H. J. De Vriend, 2013: Ecosystem-based coastal defence in the face of global change. Nature, 504, 79–83, doi:10.1038/nature12859.

Tittensor, D. P., C. Mora, W. Jetz, H. K. Lotze, D. Ricard, E. V. Berghe, and B. Worm, 2010: Global patterns and predictors of marine biodiversity across taxa. Nature, 466, 1098–1101, doi:10.1038/nature09329.

Turner, J., T. Phillips, G. J. Marshall, J. S. Hosking, J. O. Pope, T. J. Bracegirdle, and P. Deb, 2017: Unprecedented springtime retreat of Antarctic sea ice in 2016. Geophys. Res. Lett., 44, 6868–6875, doi:10.1002/2017GL073656.

Unsworth, R. K. F., M. van Keulen, and R. G. Coles, 2014: Seagrass meadows in a globally changing environment. Mar. Pollut. Bull., 83, 383–386, doi:10.1016/j.marpolbul.2014.02.026.

Velez, C., E. Figueira, A. M. V. M. Soares, and R. Freitas, 2016: Combined effects of seawater acidification and salinity changes in Ruditapes philippinarum. Aquat. Toxicol., 176, 141–150, doi:10.1016/j.aquatox.2016.04.016.

Verges, A., and Coauthors, 2014: The tropicalization of temperate marine ecosystems: climate-mediated changes in herbivory and community phase shifts. Proc. R. Soc. B Biol. Sci., 281, 20140846–20140846, doi:10.1098/rspb.2014.0846.

Vergés, A., and Coauthors, 2016: Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. Proc. Natl. Acad. Sci., 113, 13791–13796, doi:10.1073/pnas.1610725113.

Veron, J. E., and Coauthors, 2009: The coral reef crisis: The critical importance of <350 ppm CO2. Mar. Pollut. Bull., 58, 1428–1436, doi:10.1016/j.marpolbul.2009.09.009.

Villamayor, B. M. R., R. N. Rollon, M. S. Samson, G. M. G. Albano, and J. H. Primavera, 2016: Impact of Haiyan on Philippine mangroves: Implications to the fate of the widespread monospecific Rhizophora plantations against strong typhoons. Ocean Coast. Manag., 132, 1–14, doi:10.1016/j.ocecoaman.2016.07.011.

Waldbusser, G. G., and Coauthors, 2014: Saturation-state sensitivity of marine bivalve larvae to ocean acidification. Nat. Clim. Chang., 5, 273–280, doi:10.1038/nclimate2479.

Wang, Q., and Coauthors, 2016: Effects of ocean acidification on immune responses of the Pacific oyster Crassostrea gigas. Fish Shellfish Immunol., 49, 24–33, doi:10.1016/j.fsi.2015.12.025.

Washington State Blue Ribbon Panel on Ocean Acidification, 2012: Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response. Washington Department of Ecology, Olympia, WA, USA,.

Weatherdon, L. V., A. K. Magnan, A. D. Rogers, U. R. Sumaila, and W. W. L. Cheung, 2016: Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. Front. Mar. Sci., 3, 48, doi:10.3389/fmars.2016.00048.

Widlansky, M. J., A. Timmermann, and W. Cai, 2015: Future extreme sea level seesaws in the tropical Pacific. Sci. Adv., 1, doi:10.1126/sciadv.1500560.

Wittmann, A. C., and H.-O. Pörtner, 2013: Sensitivities of extant animal taxa to ocean acidification. Nat. Clim. Chang., 3, 995–1001, doi:10.1038/nclimate1982.

York, P. H., R. K. Gruber, R. Hill, P. J. Ralph, D. J. Booth, and P. I. Macreadie, 2013: Physiological and morphological responses of the temperate seagrass Zostera muelleri to multiple stressors: Investigating the interactive effects of light and temperature. PLoS One, 8, doi:10.1371/journal.pone.0076377.

York, P. H., and Coauthors, 2016: Identifying knowledge gaps in seagrass research and management: An Australian perspective. Mar. Environ. Res., 1–10, doi:10.1016/j.marenvres.2016.06.006.

Zhao, X., W. Shi, Y. Han, S. Liu, C. Guo, W. Fu, X. Chai, and G. Liu, 2017: Ocean acidification adversely influences metabolism, extracellular pH and calcification of an economically important marine bivalve, Tegillarca granosa. Mar. Environ. Res., 125, 82–89, doi:10.1016/j.marenvres.2017.01.007.

Zittier, Z. M. C., C. Bock, G. Lannig, and H. O. Pörtner, 2015: Impact of ocean acidification on thermal tolerance and acid-base regulation of Mytilus edulis (L.) from the North Sea. J. Exp. Mar. Bio. Ecol., 473, 16–25, doi:10.1016/j.jembe.2015.08.001.

S3-4-13 Supplementary information to Section 3.4

Temperature-related morbidity and mortality

Detection and attribution studies show heat-related mortality in some locations has increased because of climate change (Ebi et al. 2017), alongside evidence of acclimatization and adaptation reducing mortality, particularly in high-income countries (Arbuthnott et al. 2016; Chung et al. 2017; de' Donato et al. 2015; Bobb et al. 2014; Lee et al. 2014) with future adaptation trends uncertain.

The projected risks of heat-related morbidity and mortality are generally higher under warming of 2°C than 1.5°C, with projections of greater exposure to high ambient temperatures and increased morbidity and mortality (Section 3.4.7). This indicates a transition in risk between 1.5°C and 2°C. The extent of the increase will depend on adaptation (until mid-century) and on adaptation and mitigation later in the century (Smith et al. 2014). Under 1.5°C, most risks associated with exposure to heat could be reduced through adaptation. Risks under warming of 2°C will depend on the timing of when temperature targets are met and on development choices, such as modifying urban infrastructure to reduce heat islands. The longer the delay in reaching 2°C, and the more resilient and sustainable the development pathway, the lower the expected health risks (Sellers and Ebi 2017).

Heat-related mortality	White to Yellow	Begin	0
		End	1
	Yellow to Red	Begin	1
		End	3
	Red to Purple	Begin	no transition to purple
		End	no transition to purple

Tourism

Changing weather patterns, extreme weather and climate events, and sea level rise are affecting global tourism investments, environment and cultural destination assets, operational and transportation costs, and tourist demand patterns (Section 3.4.9.1). Assets being affected include biodiversity, beaches, coral reefs, glaciers, and other environmental and cultural assets. 'Last chance' tourism markets are developing based on observed impacts on environmental and cultural heritage.

Based on limited analyses, risks to the tourism sector are higher at 2°C than at 1.5°C, with greater impacts on climate-sensitive sun, beach, and snow sports tourism markets. The degradation or loss of coral reef systems will increase the risks for coastal tourism, particularly in sub-tropical and tropical regions.

Tourism	White to Yellow	Begin	0
		End	1.5
	Yellow to Red	Begin	1.5
		End	3
	Red to Purple	Begin	no transition to purple
		End	no transition to purple

Coastal Flooding

Sea level rise (SLR) and coastal flooding have been observed or projected to be defined by all but two (iv, viii) of the overarching key risks identified by O'Neill et al. (2017). Even without climate change, flooding occurs. Hence it is important to determine the contribution climate change has made to this. Furthermore, the severity and extent of coastal flooding is highly dependent on the rate and timing of SLR based on emissions (and therefore commitment to SLR) (Section 13.4 in Church et al. 2013 AR5; this Report, Chapter 3, Section 3.3.9), plus the ability to adapt (Wong et al. 2014 AR5, Section 5.4. and 3.4.5.7).

SLR has been occurring naturally for hundreds of years (Church et al. 2013 AR5, Section 13.2; Kopp et al. 2016). It has and will be enhanced by man-made climate change, whilst acknowledging rates of decadal change due to natural conditions (e.g., White et al. 2005). Early signs of SLR departing from Holocene rates are reported since approximately 1900 (Jevrejeva et al. 2014; Dangendorf et al. 2015; Kopp et al. 2016), analogous to temperatures approximately 0.1°C above pre-industrial levels. It is very likely that global mean SLR was 1.7 [1.5–1.9] mm yr^{-1} between 1901 and 2010, but from 1993 to 2010, the rate was very likely higher at 3.2 [2.8 to 3.6] mm yr^{-1} (Church et al. 2013 AR5, Section 13.2.2.1 and Section 13.2.2.2). Climate-change induced SLR has been detectable and attributable for a few decades (Slangen et al. 2016; Kjeldsen et al. 2015; Rignot et al. 2011; Nerem et al. 2018), occurring around 0.3°C rise above pre-industrial levels.

The ability to adapt to changing sea-levels is variable between natural and human systems (Nicholls et al. 2007 AR4, Sections 6.4 and 6.6; Wong et al. 2014 AR5, Section 5.4). Adaptation may happen more effectively or be more advanced in some nations or communities more than others (Section 3.4.5.7; Araos et al. 2016; Ford et al. 2015). Whilst acknowledging that sensitive environments experience the adverse effects of climate change induced SLR today, analysis suggests that impacts could be more widespread in sensitive systems and ongoing at 1.7°C of temperature rise with respect to pre-industrial, even when considering adaptation measures.

Coastal flooding	White to Yellow	Begin	0.1
		End	0.3
	Yellow to Red	Begin	0.3
		End	1.7
	Red to Purple	Begin	1.7
		End	2.5

Fluvial Flooding

It is reported that flood frequency has increased while there was limited evidence of a decrease in flood magnitude in some region (Section 3.3.5.1). Tanoue et al. (2016) detect the increase of frequency and magnitude of flood that is attribute to climate change, and find that growing exposure of people and assets to flood according to the increase of population and economy exacerbate flood damage. Therefore, it is concluded that the current status, compared to the pre-industrial level, should be moderate.

In general, fluvial flooding at 1.5°C is projected to be higher than at 2°C, and at both levels of warming, projected changes in the magnitude and frequency of flood create regionally differentiated risks (Section 3.4.2).

The study of Alfieri et al. (2017) clearly points out a positive correlation between global warming and global flood risk. The projected number of the global population exposed to flood risk becomes quadratically increase as the temperature rises from 1.5°C to 4°C, in which the population is 100% increase at 1.5°C, 170% at 2°C and 580% at 4.0°C relative to the baseline period (1976–2005) (Alfieri et al. 2017). Relative changes in population affected (economic damage) at 2°C warming are projected to exceed 200% in 20 (19) countries, concluded that the transition to high risk should be at 2°C warming.

Warming of 4°C from pre-industrial level is projected to be a threefold increase of the proportion of the global population who are exposed to a 20th century 100-year fluvial flood compared to the warming of 1.6°C, while the 4.0°C warming is 14 times as high as present-day exposure (Hirabayashi et al. 2013).

The above-mentioned assessments assume the population is constant, although the variation between socio-economic differences is greater than the variation between the extent of the global warming, resulting in the change in the magnitude of the flood risks, however these changes are not considered in this context.

Meanwhile, Kinoshita et al. (2018) indicate that potential economic loss can be halved by autonomous adaptation. However, few studies assess quantitative mitigation by adaptation, therefore transition to very high risk (red to purple) is not applicable.

Fluvial Flooding	White to Yellow	Begin	0
		End	0.6
	Yellow to Red	Begin	0.6
		End	2
	Red to Purple	Begin	N/A
		End	N/A

Crop Yields

Scientific literature shows that climate change resulted in changes in the production levels of the main agricultural crops. Crop yields showed contrasting patterns depending on cultivar, geographical area and response to CO_2 fertilization effect, resulting in a transition from no risk (white) to moderate risk (yellow) below recent temperatures.

The projected risks for several cropping systems are generally higher under warming of 2°C than of 1.5°C (Section 3.4.6), with different impacts depending on geographical area. The most significant crop yield declines are found in West Africa, Southeast Asia, and Central and South America (Section 3.4.6), whilst less-pronounced yield reductions are expected for northern latitudes. Globally, this indicates a different adaptation capacity among the several cropping systems, thus suggesting a transition in risk from moderate (yellow) to high risk (red) between 1.5ºC and 2.5°C.

Crop Yields	White to Yellow	Begin	0,5
		End	0,8
	Yellow to Red	Begin	1,5
		End	2,5
	Red to Purple	Begin	N/A
		End	N/A

Arctic

High-latitude tundra and boreal forest are particularly at risk, and woody shrubs are already encroaching into the tundra (*high confidence*, Section 3.4.3). These impacts had already been detected at recent temperatures (0.7ºC) hence locating transition from undetected to moderate risk between 0ºC and 0.7ºC, but further impacts have been detected more recently and risks increase further with warming (3.4.2).

It is *very likely* that there will be least one sea-ice-free Arctic summer per decade at 2°C, while this is one per century at 1.5°C. (*high confidence*) (Sections 3.3.8, 3.4.4.7). Further warming is projected to cause greater effects in a 2°C world than a 1.5°C world, for example, limiting warming to 1.5°C would prevent the loss of an estimated permafrost area of 2 million km^2 over future centuries compared to 2°C (*high confidence)* (Sections 3.3.2, 3.4.3, 3.5.5). A transition from high (red) to very high (purple) risk is therefore located between 1.5ºC and 2ºC.

Arctic	White to Yellow	Begin	0
		End	0,7
	Yellow to Red	Begin	0,7
		End	1,5
	Red to Purple	Begin	1,5
		End	2

Terrestrial Ecosystems

Detection and attribution studies show that impacts of climate change on terrestrial ecosystems have been taking place in the last few decades, indicating a transition from no risk (white) to moderate risk (yellow) below recent temperatures.

The projected risks to unique and threatened terrestrial ecosystems are generally higher under warming of 2°C than 1.5°C (Section 3.4.3). Globally, effects on terrestrial biodiversity escalate significantly between these two levels of warming. Key examples of this include much more extensive shifts of biomes (major ecosystem types) and a doubling or tripling of the number of plants, animals or insects losing over half of their climatically determined geographic ranges (Section 3.4.3). This indicates a transition in risk from moderate (yellow) to high risk (red) between 1.5°C and 2°C, however since some systems and species are unable to adapt to levels of warming below 2°C, the transition to high risk is located below 2°C. By 3°C, biome shifts and species range losses escalate to very high levels and the systems have very little capacity to adapt (3.4.3).

Terrestrial Ecosystems	White to Yellow	Begin	0.3
		End	0.5
	Yellow to Red	Begin	1.5
		End	1.8
	Red to Purple	Begin	2.0
		End	3.0

Mangroves

Recent literature is consistent with previous conclusions regarding the complex changes facing mangroves, together with increasing concern regarding the interaction between climate change (e.g., elevated air and water temperatures, drought, sea level rise) and local factors (deforestation, damming of catchments and reduced sediment and freshwater) as outlined below (Feller et al. 2017; Alongi 2015). Decreases in the supply of sediments to deltas and coastal areas is impeding the ability of most mangroves (69% of sites) to keep pace with sea level rise through shoreward migration (Lovelock et al. 2015). At the same time, recent extremes associated with El Niño (e.g., extreme low sea level events, Duke et al., 2017; Lovelock et al., 2017). Shoreward migration is also challenged by the increasing amounts of coastal infrastructure preventing the relocation of mangroves (Saunders et al. 2014; Di Nitto et al. 2014). In some areas, mangroves are increasing in distribution (Godoy and De Lacerda 2015). The total loss projected for mangrove loss (10–15%) under a 0.6 m sea level rise continue to be dwarfed by the loss of mangroves to deforestation (1–2% per annum).

Given the scale of the die-back of mangroves in Australia’s Gulf of Carpentaria (2015-2016), however, plus evidence that similar conditions to those of 2015-2016 (extreme heat and low tides), and the projection of greater El Niño-Southern Oscillation (ENSO) variability, (Risser and Wehner 2017; Widlansky et al. 2015), the risks from climate change for mangroves were judged to be higher than assessed by AR5, and subsequently by Gattuso et al. (2015), leading to the transitions having greater risk of occurring (Figure 3.17). Formal attribution of recent extreme events on mangroves to climate change, however is at an early stage *(medium agreement, limited data).*

See accompanying assessment by (Gattuso et al. 2015) in **Annex 3.1** S3-4-4_Supplementary information to Section 3.4.4.

Mangroves	White to Yellow	Begin	1.3
		End	1.5 (2.5)*
	Yellow to Red	Begin	2.5
		End	2.7
	Red to Purple	Begin	NA
		End	NA

Warm water corals

Exceptionally warm conditions of 2015–2017 drove an unprecedented global mass coral bleaching and mortality event which affected coral reefs in a large number of countries (information still being gathered, Normile, 2016). In the case of Australia, 50% of shallow-water reef-building corals across the Great Barrier Reef died in unprecedented back-to-back bleaching events (Hughes et al. 2017). Elevated sea temperatures and record mortality was recorded from the Central to the Far northern sectors of the Great Barrier Reef. Similar impacts occurred in a range of regions including the Indian Ocean, Western Pacific, Hawaii and Caribbean oceans (Normile 2016) . The set of events has increased risk with current conditions being of high risk, and even low levels of future climate change being largely catastrophic for coral reefs. There continues to be a very high level of confidence as to the impacts under RCP2.6, as well as a high confidence for those under RCP8.5.

The unprecedented thermal stress along many tropical coastlines over the past three years (2015-2017) has led to extraordinary changes to coral reefs across the planet (as described above). The advent of back-to-back bleaching events, which were projected to occur around midcentury, appear to have already begun to occur as demonstrated by impacts on warm water corals and hence coral reefs. While corals were already stressed from climate change, and are in decline in many parts of the world, the scale and impact of recent events suggest that risk levels for the transitions between risk categories need to be adjusted to represent the current status of corals and coral reefs. For this reason, expert consultation since 2015 concluded that the transition from undetectable to moderate risk has already occurred (0.2°C to 0.4°C). Similarly, the transition from *moderate* to high levels of risks for warm water corals occurred approximately from 0.5°C to 0.6°C. In line with these changes, the transition from *high* to *very high* levels of risk appears associated with increases in GMST from 0.7°C to 1.3°C above the pre-industrial period.

See accompanying assessment by (Gattuso et al. 2015) in Annex 3.1 S3-4-4_Supplementary information to Section 3.4.4.

Warm water corals	White to Yellow	Begin	0.2
		End	0.4
	Yellow to Red	Begin	0.5
		End	0.6
	Red to Purple	Begin	0.7
		End	1.3

Small-scale fin fisheries (low latitude)

Low latitude fin fisheries, or small-scale fisheries, provide food for millions of people along tropical coastlines and hence play an important role in the food security of a large number of countries (McClanahan et al. 2015; Pauly and Charles 2015). In many cases, populations are heavily dependent on these sources of protein given the lack of alternatives (Cinner et al. 2016, 2012; Pendleton et al. 2016). The climate related stresses affecting fin fish (see Section S3.4.4, subsection on ‘Fin fish’), however, are producing a number of challenges for small scale fisheries based on these species (e.g., (Pauly and Charles 2015; Bell et al. 2017; Kittinger 2013).

Recent literature (2015–2017) has continued to outline growing threats from the rapid shifts in the biogeography of key species (García Molinos et al. 2015; Poloczanska et al. 2013; Burrows et al. 2014; Poloczanska et al. 2016) and the ongoing rapid degradation of key habitats such as coral reefs, seagrass and mangroves (see Section 3.4.4, subsections on ‘Seagrasses’, ‘Mangroves’ and ‘Pteropods’ and Chapter 3, Box 3.4). As these changes have accelerated, so have the risks to the food and livelihoods associated with small-scale fisheries (Cheung et al. 2010). These risks have compounded with non-climate stresses (e.g., pollution, overfishing, unsustainable coastal development) to drive many small-scale fisheries well below the sustainable harvesting levels required to keep these resources functioning as a source of food (McClanahan et al. 2015, 2009; Pendleton et al. 2016). As a result, projections of climate change and the growth in human populations increasingly predict shortages of fish protein for many regions (e.g., Pacific, e.g., Bell et al., 2013, 2017; Indian Ocean, e.g., McClanahan et al., 2015). Mitigation of these risks involved marine spatial planning, fisheries repair, sustainable aquaculture, and the development of alternative livelihoods (Song and Chuenpagdee 2015; Kittinger 2013; McClanahan et al. 2015; Weatherdon et al. 2016). Threats to small-scale fisheries have also come from the increasing incidence of alien (nuisance) species as well as an increasing incidence of disease, although the literature on these threats is at a low level of development and understanding (Kittinger et al. 2013; Weatherdon et al. 2016).

As assessed by Gattuso et al. (2015), risks of impacts on small-scale fisheries are medium today, but are expected to reach very high levels under scenarios extending beyond RCP2.6. The research literature plus the growing evidence that many countries will have trouble adapting to these changes places confidence a high level as to the risks of climate change on low latitude in fisheries. These effects are more sensitive, hence the higher risks at lower levels of temperature change.

Small-scale fisheries are highly dependent on healthy coastal ecosystems. With the growing evidence of impacts described above, the loss of habitat for small-scale fisheries is intensifying the risks of impact from climate change. For this reason, expert consensus has judged that risks have become greater since the assessment of Gattuso et al. (2015). Therefore, the transition from undetectable to medium levels of risk is projected to occur between 0.5°C and 0.7°C, with the transition from medium to high levels of risk occurring between 0.9°C and 1.1°C. The transition from high to very high levels of risk of impact as being judged to occur between 2°C and 2.5°C.

See accompanying assessment by (Gattuso et al. 2015) in Annex 3.1 S3-4-4_Supplementary information to Section 3.4.4.

Small scale fin fisheries (low latitude)	White to Yellow	Begin	0.5
		End	0.7
	Yellow to Red	Begin	0.9
		End	1.1
	Red to Purple	Begin	2
		End	2.5

References

Alfieri, L., B. Bisselink, F. Dottori, G. Naumann, A. de Roo, P. Salamon, K. Wyser, and L. Feyen, 2017: Global projections of river flood risk in a warmer world. Earth's Futur., 5, 171–182, doi:10.1002/2016EF000485.

Alongi, D. M., 2015: The Impact of Climate Change on Mangrove Forests. Curr. Clim. Chang. Reports, 1, 30–39, doi:10.1007/s40641-015-0002-x.

Araos, M., L. Berrang-Ford, J. D. Ford, S. E. Austin, R. Biesbroek, and A. Lesnikowski, 2016: Climate change adaptation planning in large cities: A systematic global assessment. Environ. Sci. Policy, 66, 375–382, doi:10.1016/j.envsci.2016.06.009.

Arbuthnott, K., S. Hajat, C. Heaviside, and S. Vardoulakis, 2016: Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. Environ. Heal., 15, S33, doi:10.1186/s12940-016-0102-7.

Bell, J. D., and Coauthors, 2013: Mixed responses of tropical Pacific fisheries and aquaculture to climate change. Nat. Clim. Chang., 3, 591–599, doi:10.1038/nclimate1838.

Bell, J. D., and Coauthors, 2017: Adaptations to maintain the contributions of small-scale fisheries to food security in the Pacific Islands. Mar. Policy, doi:10.1016/j.marpol.2017.05.019.

Bobb, J. F., R. D. Peng, M. L. Bell, and F. Dominici, 2014: Heat-Related Mortality and Adaptation to Heat in the United States. Environ. Health Perspect., doi:10.1289/ehp.1307392.

Burrows, M. T., and Coauthors, 2014: Geographical limits to species-range shifts are suggested by climate velocity. Nature, 507, 492–495, doi:10.1038/nature12976.

CHEUNG, W. W. L., V. W. Y. LAM, J. L. SARMIENTO, K. KEARNEY, R. WATSON, D. ZELLER, and D. PAULY, 2010: Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob. Chang. Biol., 16, 24–35, doi:10.1111/j.1365-2486.2009.01995.x.

Chung, E. S., H.-K. Cheong, J.-H. Park, J.-H. Kim, and H. Han, 2017: Current and Projected Burden of Disease From High Ambient Temperature in Korea. Epidemiology, 28, S98–S105.

Church, J. a., and Coauthors, 2013: Sea level change. Clim. Chang. 2013 Phys. Sci. Basis. Contrib. Work. Gr. I to Fifth Assess. Rep. Intergov. Panel Clim. Chang., 1137–1216, doi:10.1017/CB09781107415315.026.

Cinner, J. E., and Coauthors, 2012: Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. Glob. Environ. Chang., 22, 12–20, doi:10.1016/j.gloenvcha.2011.09.018.

Cinner, J. E., and Coauthors, 2016: A framework for understanding climate change impacts on coral reef social–ecological systems. Reg. Environ. Chang., 16, 1133–1146, doi:10.1007/s10113-015-0832-z.

Dangendorf, S., M. Marcos, A. Müller, E. Zorita, R. Riva, K. Berk, and J. Jensen, 2015: Detecting anthropogenic footprints in sea level rise. Nat. Commun., 6, 7849.

de' Donato, F. K., and Coauthors, 2015: Changes in the Effect of Heat on Mortality in the Last 20 Years in Nine European Cities. Results from the PHASE Project. Int. J. Environ. Res. Public Health, 12, 15567–15583, doi:10.3390/ijerph121215006.

Duke, N. C., and Coauthors, 2017: Large-scale dieback of mangroves in Australia's Gulf of Carpentaria: A severe ecosystem response, coincidental with an unusually extreme weather event. Mar. Freshw. Res., 68, 1816–1829, doi:10.1071/MF16322.

Ebi, K., N. Ogden, J. Semenza, and A. Woodward, 2017: Detecting and Attributing Health Burdens to Climate Change. Environ. Health Perspect., 125, 085004, doi:10.1289/EHP1509.

Feller, I. C., D. A. Friess, K. W. Krauss, and R. R. Lewis, 2017: The state of the world's mangroves in the 21st century under climate change. Hydrobiologia, 803, doi:10.1007/s10750-017-3331-z.

Ford, J. D., G. McDowell, and T. Pearce, 2015: The adaptation challenge in the Arctic. Nat. Clim. Chang., 5, 1046–1053, doi:10.1038/nclimate2723.

García Molinos, J., and Coauthors, 2015: Climate velocity and the future global redistribution of marine biodiversity. Nat. Clim. Chang., 6, 83–88, doi:10.1038/nclimate2769.

Gattuso, J.-P., and Coauthors, 2015: Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios. Science (80-.)., 349, aac4722, doi:10.1126/science.aac4722.

Godoy, M. D. P., and L. D. De Lacerda, 2015: Mangroves Response to Climate Change: A Review of Recent Findings on Mangrove Extension and Distribution. An Acad Bras CiencAnnals Brazilian Acad. Sci., 87, 651–667, doi:10.1590/0001-3765201520150055.

Hirabayashi, Y., R. Mahendran, S. Koirala, L. Konoshima, D. Yamazaki, S. Watanabe, H. Kim, and S. Kanae, 2013: Global flood risk under climate change. Nat. Clim. Chang., 3, 816–821, doi:10.1038/nclimate1911.

Hughes, T. P., and Coauthors, 2017: Global warming and recurrent mass bleaching of corals. Nature, 543, 373–377, doi:10.1038/nature21707.

Jevrejeva, S., J. C. Moore, A. Grinsted, A. P. Matthews, and G. Spada, 2014: Trends and acceleration in global and regional sea levels since 1807. Glob. Planet. Change, 113, 11–22, doi:https://doi.org/10.1016/j.gloplacha.2013.12.004.

Kinoshita, Y., M. Tanoue, S. Watanabe, and Y. Hirabayashi, 2018: Quantifying the effect of autonomous adaptation to global river flood projections: Application to future flood risk assessments. Environ. Res. Lett., 13, doi:10.1088/1748-9326/aa9401.

Kittinger, J. N., 2013: Human Dimensions of Small-Scale and Traditional Fisheries in the Asia-Pacific Region. Pacific Sci., 67, 315–325, doi:10.2984/67.3.1.

——, and Coauthors, 2013: Emerging frontiers in social-ecological systems research for sustainability of small-scale fisheries. Curr. Opin. Environ. Sustain., 5, 352–357, doi:10.1016/j.cosust.2013.06.008.

Kjeldsen, K. K., and Coauthors, 2015: Spatial and temporal distribution of mass loss from the Greenland Ice Sheet since AD 1900. Nature, 528, 396.

Kopp, R., and Coauthors, 2016: Temperature-driven global sea-level variability in the Common Era. Proc. Natl. Acad. Sci., 113, 1434–1441.

Lee, M., F. Nordio, A. Zanobetti, P. Kinney, R. Vautard, and J. Schwartz, 2014: Acclimatization across space and time in the effects of temperature on mortality: a time-series analysis. Environ. Heal., 13, 89, doi:10.1186/1476-069X-13-89.

Lovelock, C. E., and Coauthors, 2015: The vulnerability of Indo-Pacific mangrove forests to sea-level rise. Nature, 526, 559–563, doi:10.1038/nature15538.

——, I. C. Feller, R. Reef, S. Hickey, and M. C. Ball, 2017: Mangrove dieback during fluctuating sea levels. Sci. Rep., 7, 1680, doi:10.1038/s41598-017-01927-6.

McClanahan, T., E. H. Allison, and J. E. Cinner, 2015: Managing fisheries for human and food security. Fish Fish., 16, 78–103, doi:10.1111/faf.12045.

McClanahan, T. R., J. C. Castilla, A. T. White, and O. Defeo, 2009: Healing small-scale fisheries by facilitating complex socio-ecological systems. Rev. Fish Biol. Fish., 19, 33–47, doi:10.1007/s11160-008-9088-8.

Nerem, R. S., B. D. Beckley, J. T. Fasullo, B. D. Hamlington, D. Masters, and G. T. Mitchum, 2018: Climate-change-driven accelerated sea-level rise detected in the altimeter era. Proc. Natl. Acad. Sci., 115, 2022–2025, doi:10.1073/pnas.1717312115.

Nicholls, R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden, and C. . Woodroffe, 2007: Coastal systems and low-lying areas. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. Van der Linden, and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 315–356.

Di Nitto, D., G. Neukermans, N. Koedam, H. Defever, F. Pattyn, J. G. Kairo, and F. Dahdouh-Guebas, 2014: Mangroves facing climate change: Landward migration potential in response to projected scenarios of sea level rise. Biogeosciences, 11, 857–871, doi:10.5194/bg-11-857-2014.

Normile, D., 2016: El Niño’s warmth devastating reefs worldwide. Science, 352, 15–16, doi:10.1126/science.352.6281.15.

O’Neill, B. C., and Coauthors, 2017: IPCC Reasons for Concern regarding climate change risks. Nat. Clim. Chang., 7, 28–37, doi:10.1038/nclimate3179.

Pauly, D., and A. Charles, 2015: Counting on small-scale fisheries. Science (80-.)., 347, 242–243, doi:10.1126/science.347.6219.242-b.

Pendleton, L., and Coauthors, 2016: Coral reefs and people in a high-CO2 world: Where can science make a difference to people? PLoS One, 11, 1–21, doi:10.1371/journal.pone.0164699.

Poloczanska, E. S., and Coauthors, 2013: Global imprint of climate change on marine life. Nat. Clim. Chang., 3, 919–925, doi:10.1038/nclimate1958.

——, and Coauthors, 2016: Responses of Marine Organisms to Climate Change across Oceans. Front. Mar. Sci., 3, 62, doi:10.3389/fmars.2016.00062.

Rignot, E., I. Velicogna, van den Broeke M. R., A. Monaghan, and J. T. M. Lenaerts, 2011: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. Geophys. Res. Lett., 38, doi:10.1029/2011GL046583.

Risser, M. D., and M. F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. Geophys. Res. Lett., n/a--n/a, doi:10.1002/2017GL075888.

Saunders, M. I., and Coauthors, 2014: Interdependency of tropical marine ecosystems in response to climate change. Nat. Clim. Chang., 4, 724–729, doi:10.1038/NCLIMATE2274.

Sellers, S., and K. L. Ebi, 2017: Climate Change and Health under the Shared Socioeconomic Pathway Framework. Int. J. Environ. Res. Public Health, 15, 3, doi:10.3390/ijerph15010003.

Slangen, A. B. A., J. A. Church, C. Agosta, X. Fettweis, B. Marzeion, and K. Richter, 2016: Anthropogenic forcing dominates global mean sea-level rise since 1970. Nat. Clim. Chang., 6, 701–705, doi:10.1038/nclimate2991.

Smith, K. R., and Coauthors, 2014: Human Health: Impacts, Adaptation, and Co-Benefits. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK and New York, NY, USA, 709–754.

Song, A. M., and R. Chuenpagdee, 2015: Interactive Governance for Fisheries. Interact. Gov. Small-Scale Fish., 5, 435–456, doi:10.1007/978-3-319-17034-3.

Tanoue, M., Y. Hirabayashi, H. Ikeuchi, E. Gakidou, and T. Oki, 2016: Global-scale river flood vulnerability in the last 50 years. Sci. Rep., 6, 36021, doi:10.1038/srep36021.

Weatherdon, L. V., A. K. Magnan, A. D. Rogers, U. R. Sumaila, and W. W. L. Cheung, 2016: Observed and Projected Impacts of Climate Change on Marine Fisheries, Aquaculture, Coastal Tourism, and Human Health: An Update. Front. Mar. Sci., 3, 48, doi:10.3389/fmars.2016.00048.

White, N., J. Church, and J. Gregory, 2005: Coastal and global averaged sea level rise for 1950 to 2000. Geophys. Res. Lett., 32, doi:10.1029/2004GL021391.

Widlansky, M. J., A. Timmermann, and W. Cai, 2015: Future extreme sea level seesaws in the tropical Pacific. Sci. Adv., 1, doi:10.1126/sciadv.1500560.

Wong, P. P., I. J. Losada, J.-P. Gattuso, J. Hinkel, A. Khattabi, K. L. McInnes, Y. Saito, and A. Sallenger, 2014: Coastal Systems and Low-Lying Areas. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, C.B. Field et al., Eds., Cambridge University Press, Cambridge, UK and New York, NY, USA, 361–409.

SI_S3-4-7_Supplementary information to Section 3.4.7 Human health

Table S6. Decades when 1.5°C, 2°C, and higher degrees of warming are reached for multi-climate model means

Generation	Scenario	Decade 1.5°C reached	Decade 2°C reached	dT 2080-2099	dT 2090-2099
SRES	B1	2039-2048	2065-2074	2.18	2.27
SRES	A1b	2029-2038	2045-2054	3.00	3.21
SRES	A2	2032-2041	2048-2057	3.39	3.83
RCP	2.6	2047-2056	a	1.48	1.49
RCP	4.5	2031-2040	2055-2064	2.32	2.37
RCP	6.0	2036-2045	2058-2067	2.63	2.86
RCP	8.5	2026-2035	2040-2049	3.90	4.39

[a]2°C not reached

Table S7. Projected temperature-related risks at 1.5°C and 2°C. *Abbreviations: DALY: Disability adjusted life year; RCP: Representative Concentration Pathway; SSP: Shared Socioeconomic Pathway, GMST: Global Mean Surface Temperature*

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Global and 21 regions	Heat-related mortality in adults over 65 years of age	1961–1990	BCM2.0, EGMAM1, EGMAM2, EGMAM3, CM4vl	A1B	2030, 2050		In 2030, 92,207 additional heat-related deaths without adaptation (ensemble mean) and 28,055 with adaptation under BCM2	In 2050, 255,486 additional heat-related deaths without adaptation and 73,936 with adaptation under BCM2 scenario; the	Population growth and aging; improved health in elderly due to economic development; three levels of adaptation (none, partial, and full)	(Hales et al. 2014)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
							scenario; the Asia Pacific, Asia, North Africa / Middle East, Sub-Saharan Africa, Europe, and north America at higher risk.	same regions are at higher risk.		
Global	Extremely hot summers over land areas (>3 standard deviations anomalies)	1861–1880	26 models from CMIP5	RCP2.6, RCP4.5, RCP8.5	to 2100	Probability of an extremely hot summer (>3 standard deviations) in 1996–2005 (compared with 1951–1980) is 4.3%	Probability of an extremely hot summer is approximately 25.5% and probability of an exceedingly hot summer (>5 standard deviations) is approximately 7.1% above pre-industrial	Extremely hot summers are projected to occur over nearly 40% of the land area		(Wang et al. 2015)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Global	Population exposure to hot days and heatwaves	1961–1990	21 CMIP5 GCMs	Temperature change based on pattern scaling	Up to 2100	Increasing exposure to heatwaves already evident	The frequency of heatwave days increases dramatically as global mean temperature increases, although the extent of increase varies by region. Increases are greatest in tropical and sub-tropical regions where the standard deviation of warm season daily maximum temperature is least, and therefore, a smaller increase in	Overall, exposure to heatwaves is reduced by more than 75% in all models in each region if GMSTs do not increase to 2°C; the avoided impacts vary by region.		(Arnell et al. 2018)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
							temperature leads to a larger increase in heat wave frequency.			
Japan, Korea, Taiwan, USA, Spain, France, Italy	Heat-related mortality for 65+ age group	1961–1990	BCM2	A1B	2030, 2050		In 2030, heat-related excess deaths increased over baselines in all countries, with the increase dependent on the level of adaptation	In 2050, heat-related excess deaths are higher than for 2030, with the increase dependent on the level of adaptation	Three adaptation assumptions: 0, 50, and 100%	(Honda et al. 2014)
Australia (five largest cities) and UK	Temperature-related mortality	1993–2006	UKCP09 from HadCM3; OzClim 2011	A1B, B1, A1FI	2020s, 2050s, 2080s	For England and Wales, the estimated % change in mortality associated with heat exposure is 2.5% (95% CI: 1.9–3.1) per 1°C rise in	In the 2020s, heat-related deaths increase from 1,503 at baseline to 1,511 with a constant population and 1,785 with the projected	In the 2050s, heat-related deaths further increase to 2,866 with a constant population and to 4,012 with the projected population.	Projected population change	(Vardoulakis et al. 2014)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
						temperature above the heat threshold (93rd percentile of daily mean temperature). In Australian cities, the estimated overall % change in mortality is 2.1% (95% CI: 1.3, 2.9).	population. In Australia, the numbers of projected deaths are 362 and 475, respectively, with a baseline of 214 deaths.	In Australia, the numbers of projected deaths are 615 and 970, respectively		
Australia	Temperature-related morbidity and mortality; days per year above 35°C	1971–2000	CSIRO	2030 A1B low and high; 2070 A1FI low and high	2030, 2070	4–6 dangerously hot days per year for un-acclimatized individuals	Sydney - from 3.5 days at baseline to 4.1–5.1 days in 2030; Melbourne - from 9 days at baseline to 11–13 days in 2030	Sydney – 6–12 days and Melbourne – 15–26 days in 2070		(Hanna et al. 2011)
Brisbane, Sydney, and Melbourne Australia	Temperature-related mortality	1988–2009	62 GCMs, with spatial downscaling and bias	A2, A1B, B1	2050s, 2090s		In 2030, net temperature-related mortality	In 2050, there are further net temperature		(Guo et al. 2016)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
			correction				(heat/ cold) increases in Brisbane under all scenarios, increases in Sydney under A2, and declines in Melbourne under all scenarios	related mortality (heat/cold) increases in Brisbane under all scenarios, increases in Sydney under A2 and A1B, and further declines in Melbourne under all scenarios		
Brisbane Australia	Years of life lost due to temperature extremes (hot and cold)	1996–2003		Added 1–4°C to observed daily temperature to project for 2050	2000, 2050	In 2000, 3,077 temperature-related years of life lost for men, with 616 years of life lost due to hot temperatures and 2,461 years of life lost due to cold. The	For 1°C above baseline, years of life lost increase by 1,014 (840 to 1,178) for hot temperatures and decrease by 1,112 (–1,337 to –871) for cold temperatures	For 2°C above baseline, years of life lost increase by 2,450 (2,049 to 2,845,) for hot temperatures and decrease by 2,069, (–2,484 to –1,624) for cold		(Huang et al. 2012)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
						numbers for women are 3,495 (total), 903(hot), and 2,592 (cold).		temperatures		
Quebec, Canada	Heat-related mortality	1981–1999	Ouranos Consortium; SDSM downscaled HADCM3	A2 and B2 (projected impacts the same)	2020 (2010–2039), 2050 (2040–2069), 2080 (2070–2099)		2% increase in summer mortality in 2020	4–6% increase in summer mortality in 2050		(Doyon et al. 2008)
USA, 209 cities	Heat- and cold-related mortality	1990 (1976–2005)	Bias corrected (BCCA) GFDL-CM3, MIROC5	RCP6.0	2030 (2016–2045), 2050 (2036–2065), 2100 (2086–2100)		In 2030, a net increase in premature deaths, with decreases in temperature-related winter mortality and increases in summer mortality; the magnitude varied by region and city with an overall increase of 11,646 heat-	In 2050, a further increase in premature deaths, with decreases in temperature-related winter mortality and increases in summer mortality; the magnitude varied by region and city with an overall increase of	Held population constant at 2010 levels; mortality associated with high temperatures decreased between 1973–1977 and 2003–2006	(Schwartz et al. 2015)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
							related deaths.	15,229 heat-related deaths.		
Washington State, USA	Heat-related mortality	1970–1999	PCM1, HadCM	Average of PCM1-B1 and HadCM-A1B; humidex baseline; number & duration of heatwaves calculated	2025, 2045, 2085		Under moderate warming in 2025, 96 excess deaths in Seattle area.	Under moderate warming in 2045, 156 excess deaths in Seattle area.	Holding population constant at 2025 projections	(Jackson et al. 2010)
Boston, New York, Philadelphia, USA	Heat-related mortality	1971–2000	CMIP5 bias corrected (BCSD)	RCP4.5, RCP8.5	2010–2039, 2040–2069, 2070–2099	Baseline heat-related mortality is 2.9–4.5 / 100,000 across the three cities	In the 2020s under both RCPs, heat-related mortality increased to 5.9–10 / 100,000	In the 2050s, heat-related mortality increased to 8.8–14.3 / 100,000 under RCP4.5 and to 11.7 to 18.9 / 100,000 under RCP8.5	Population constant at 2000	(Petkova et al. 2017)
Europe	Heat-related mortality	1971–2000	SMHI RCA4/HadGEM2 ES r1	RCP4.5; RCP8.5	2035–2064; 2071–209		2035–2064 excess heat mortality to	2071–2099 excess heat mortality to		(Kendrovski et al. 2017)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
			(MOHC)				be 30,867 and 45,930	be 46,690 and 117,333 attributable deaths/year		
Europe; London, UK and Paris, France	Heat-related mortality	Present climate	Half a degree Additional warming, Prognosis and Projected Impacts (HAPPI)	Climate stabilization at 1.5° and 2°C		Model of 2003 heat event resulted in about 735 excess deaths for Paris and about 315 for London	Compared with 2°C stabilization, mortality event is 2.4 times less likely in London and 1.6 times less likely in Paris	22% increase in mortality in Paris and 15% increase in mortality in London, compared with 1.5°C stabilization		(Mitchell 2018)
UK	Temperature-related mortality	1993–2006	9 regional model variants of HadRm3-PPE-UK, dynamically downscaled	A1B	2000–2009, 2020–2029, 2050–2059, 2080–2089	At baseline, 1,974 annual heat-related and 41,408 cold-related deaths	In the 2020s, in the absence of adaptation, heat-related deaths would increase to 3,281 and cold-related deaths to increase to 42,842	In the 2050s, the absence of adaptation, heat-related deaths projected to increase 257% by the 2050s to 7,040 and cold-related mortality to decline about 2%	Population projections to 2081	(Hajat et al. 2014)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Netherlands	Temperature-related mortality	1981–2010	KNMI' 14; G-scenario is a global temperature increase of 1°C and W-scenario an increase of 2°C		2050 (2035–2065)	At baseline, the attributable fraction for heat is 1.15% and for cold is 8.9%; or 1511 deaths from heat and 11,727 deaths from cold	Without adaptation, under the G scenario, the attributable fraction for heat is 1.7–1.9% (3,329–3,752 deaths) and for cold is 7.5–7.9% (15,020-15,733 deaths). Adaptation decreases the numbers of deaths, depending on the scenario.	Without adaptation, under the W scenario, the attributable fraction for heat is 2.2–2.5% (4,380-5,061 deaths) and for cold is 6.6–6.8% (13,149-13,699 deaths). Adaptation decreases the numbers of deaths, depending on the scenario.	Three adaptation scenarios, assuming a shift in the optimum temperature, changes in temperature sensitivity, or both; population growth and declining mortality risk per age group	(Huynen and Martens 2015)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Korea	Burden of disease from high ambient temperatures	2011	CMIP5	RCP4.5; RCP8.5	2030; 2050	DALY for all-cause mortality in 2011 was 0.49 (DALY/1000) DALY for cardio-and cerebrovascular disease was 1.24 DALY/1000	In 2030 DALY for all-cause mortality, 0.71 (DALY/1000) DALY for cardio-and cerebrovascular disease is 1.63 (1.82) DALY/1000	In 2050, DALY for all-cause mortality, 0.77 (1.72) (DALY/1000) DALY for cardio-and cerebrovascular disease is 1.76 (3.66) DALY/1000		(Chung et al. 2017)
Beijing, China	Heat-related mortality	1970–1999	Downscaled and bias corrected (BCSD) 31 GCMs in WCRP CMIP5; monthly change factors applied to daily weather data to create a projection	RCP4.5, RCP8.5	2020s (2010–2039), 2050s (2040–2069), 2080s (2070–2099)	Approximately 730 additional annual heat-related deaths in 1980s	In the 2020s, under low population growth and RCP4.5 and RCP8.5, heat-related deaths projected to increase to 1,012 and 1,019, respectively. Numbers of deaths are higher with	In the 2050s under low population growth, and RCP4.5 and RCP8.5, heat-related deaths projected to increase to 1,411 and 1,845, respectively.	Adults 65+ years of age; no change plus low, medium, and high variants of population growth; future adaptation based on Petkova et al. 2014, plus shifted mortality 5%, 15%, 30%,	(Li et al. 2016c)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
							medium and high population growth.		50%	
Beijing, China	Cardiovascular and respiratory heat-related mortality	1971–2000	Access 1.0, CSIRO Mk3.6.0, GFDL-CM3, GISS E2R, INM-CM4	RCP4.5, RCP8.5	2020s, 2050s, 2080s	Baseline cardiovascular mortality 0.396 per 100,000; baseline respiratory mortality 0.085 per 100,000	Cardiovascular mortality could increase by an average percentage of 18.4% in the 2020s under RCP4.5 and by 16.6% under RCP8.5. Statistically significant increases are projected for respiratory mortality.	Cardiovascular mortality could increase by an average percentage of 47.8% and 69.0% in the, 2050s and 2080s under RCP4.5, and by 73.8% and 134% under RCP8.5. Similar increases are projected for respiratory mortality.		(Li et al. 2015)
Africa	Five thresholds for number of hot days per year when health	1961–2000	CCAM (CSIRO) forced by coupled GCMs: CSIRO,	A2	2011–2040, 2041–2070, 2071–2100	In 1961–1990, average number of hot days (maximum	In 2011–2040, annual average number of hot days (maximum	In 2041–2070, annual average number of hot days (maximum	Projected population in 2020 and 2025	(Garland et al. 2015)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
	could be affected, as measured by maximum apparent temperature		GFDL20, GFDL 21, MIROC, MPI, UKMO. CCAM was then downscaled. Biased corrected using CRU TS3.1 dataset			apparent temperature ≥ 27°C) ranged from 0 to 365, with high variability across regions.	apparent temperature ≥ 27°C) projected to increase by 0–30 in most parts of Africa, with a few regions projected to increase by 31–50.	apparent temperature ≥ 27°C) projected to increase by up to 296, with large changes projected in southern Africa and parts of northern Africa		

Table S8. Projected air quality-related health risks at 1.5°C and 2°C. *Abbreviations: DALY: Disability adjusted life year; RCP: Representative Concentration Pathway; SSP: Shared Socioeconomic Pathway ; CV : Cardio-Vascular*

Region	***Health outcome metric***	***Study baseline***	***Climate model(s) and air pollution models***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Global	PM 2.5 and O_3-related mortality	2000	ACCMIP model; CESM	RCP2.6; RCP4.5; RCP6.0; RCP8.5	2000; 2030; 2050; 2100	Global O_3 mortality 382,000 (121,000–728,000) deaths year -1; global mortality burden of PM2.5 1.70 (1.30–2.10) million deaths year^{-1}	PM2.5-related mortality peaks in 2030 (2.4–2.6 million deaths/year — except for RCP6.0)	O_3-related mortality peaks in 2050 (1.84–2.6 million deaths per year)	Population projected from 2010–2100	(Silva et al. 2016)
Global & Europe and France	PM2.5-related CV- and O_3-related respiratory mortality	2010	IPSL-cm5-MR, LDMz-INCA, CHIMERE	RCP4.5 (for Europe and France)	2010; 2030-2050	Global CV mortality 17,243,000	In 2030, in Europe PM2.5-related CV mortality decreases by 3.9% under CLE; and 7.9% under MFR. In 2030 O_3-related respiratory mortality decreases by 0.3% under MFR	In 2050, 4.5% decrease in PM2.5 related CV mortality under CLE and 8.2% MFR.	Population 2030–sensitivity analysis	(Likhvar et al. 2015)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s) and air pollution models*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
UK	O_3-related morbidity and mortality	2003	EMEP-WRF	A2, B2	2003, 2030	O_3-attributable mortality and morbidity in 2003: 11,500 deaths and 30,700 hospitalizations	With no threshold for O_3, increase of premature mortality and hospitalization of 28% (under B2 + CLE scenario) – greatest health effects; A2 premature morbidity and mortality projections: 22%. With 35 ppbv, 52% increase in mortality and morbidity (under B2+CLE)	Increases in temperatures by 5°C, projected O_3 mortality will increase from 4% (no O_3 threshold) to 30% (35 ppbv O_3 threshold)	Population projections increase, +5°C scenario	(Heal et al. 2013)
Poland	PM2.5 mortality	2000	ECHAM5-RegCM3, CAMx	A1B	1990s; 2040s; 2090s	39,800 premature deaths related to PM2.5 air pollution	0.4–1°C in 2040; 6% decrease in PM2.5 related mortality in 2040s	2–3°C in the 2090s; 7% decrease in PM25 related mortality in 2090s		(Tainio et al. 2013)

Region	*Health outcome metric*	*Study baseline*	*Climate model(s) and air pollution models*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
Korea	O_3 summer mortality	2001–2010	ICAMS	RCP2.6; RCP4.5; RCP6.0; RCP8.5	1996–2005; 2016–2025; 2046–2055		In the 2020s, summer mortality to increase by: 0.5%, 0.0%, 0.4%, and 0.4% due to temperature change. In the 2020s, due to O_3 concentration change, mortality to increase by 0.0%, and 0.5%	In the 2050s, summer mortality to increase by: 1.9%, 1.5%, 1.2% and 4.4% by temperature change. In the 2050s, due to O_3 concentration, mortality to increase by 0.2%, 0.4% and 0.6%	Current mortality trends expected to increase, temperature effects compared	(Lee et al. 2017)

Region	***Health outcome metric***	***Study baseline***	***Climate model(s) and air pollution models***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
U.S. (12 metropolitan areas)	O_3 inhalation exposures	2000	APEX, CESM, MIP5, WRF, CMAQ	RCP4.5; RCP6.; RCP8.5	1995-2005; 2025-2035	At least on exceeded/year	Comparing 2030 to 2000, almost universal trend with at least three exceedances (of DM8H exposure above the 60 ppb and 70 bbp thresholds)	Health implications Increase as population exposures to O_3 increases based on the degree of radiative forcing in 2100	Population projections using IPCC SRES and adapted for U.S.	(Dionisio et al. 2017)

Table S9. Projected vectorborne disease risks at 1.5°C and 2°C. *Abbreviations: DALY: Disability adjusted life year; RCP: Representative Concentration Pathway; SSP: Shared Socioeconomic Pathway*

Region	***Health outcome metric***	***Study baseline***	***Climate model(s)***	***Scenario***	***Time periods of interest***	***Impacts at study baseline***	***Projected impacts at 1.5°C***	***Projected impacts at 2°C***	***Other factors considered***	***Reference***
Malaria										
China	Malaria vectors *Anopheles dirus, A. minimus, A. lesteri, A. sinensis*	2005–2008	BCC-CSM1-1, CCCma_CanESM2, CSIRO-Mk3.6.0 from CMIP5	RCP2.6, RCP4.5, RCP8.5	2020–2049, 2040–2069		In the 2030s, environmentally suitable areas for *A. dirus* and *A. minimus* increase by an average of 49% and 16%, respectively	In the 2050s environmentally suitable areas for *A. dirus* and *A. minimus* decrease by 11% and 16%, respectively. An increase of 36% and 11%, in environmentally suitable area of *A. lesteri* and *A. sinensis*	Land use, urbanization	(Ren et al. 2016)
Northern China	Spatial distribution of malaria	2004–2010	GCMs from CMIP3	B1, A1B, A2	2020, 2030, 2040, 2050	Average malaria incidence 0.107% per annum in northern China	In 2020, malaria incidence increases 19–29%, and increases	In 2040, malaria incidence increases 33–119% and 69–182% in	Elevation, GDP, water density index held constant	(Song et al. 2016)

							43–73% in 2030, with increased spatial distribution	2050, with increased spatial distribution		
Sub-Saharan Africa	Malaria	2006–2016	21 CMIP5 models	RCP4.5, RCP8.5	2030, 2050, 2100		In 2030, under RCP8.5, many parts of western and central Africa will have no malaria, but significant malaria hotspots will be along the Sahel belt, eastern and southern parts of Africa.	Climate change will redistribute the spatial pattern of future malaria hotspots especially under RCP8.5.	Various environmental variables	(Semakula et al. 2017)
Aedes										
Global	Global niche models for autochthonous Chikungunya transmission	Current climate	CESM 1 bcg, FIO ESM, GISS e2-r, INM CM4 and MPI-ESM-lr	RCP4.5, RCP8.5	2021–2040; 2041–2060; 2061–2080	Current distribution of Chikungunya transmission	In 2021–2040, climatically suitable areas projected to increase in multiple regions,	In 2041–2060, greater geographic expansion		(Tjaden et al. 2017)

							including China, Sub-Saharan Africa, the United States, and continental Europe			
North America, United States	Climate suitability for *Aedes albopictus* vector for dengue, Chikungunya, and vectorborne zoonoses such as West Nile Virus (WNV), Eastern Equine Encephalitis virus, Rift Valley Fever virus, Cache Valley virus and LaCrosse virus	1981-2010	8 RCMs: CanRCM4, CRCM5, CRCM 4.2.3, HIRHAM5, RegCM3, ECPC, MM5I, WRF	RCP4.5, RCP8.5, A2	2020s (2011–2040), 2050s (2041–2070).	Index of precipitation and temperature suitability was highly accurate in discriminating suitable and non-suitable climate	In 2011–2040 under RCP4.5, climate suitability increases across US, with the magnitude and pattern dependent on parameter projected and RCM	In 2041–2070 under RCP4.5, areal extent larger than in earlier period; under RCP8.5, areal extent larger	Climatic indicators of *Ae. albopictus* survival; overwintering conditions (OW); OW combined with annual air temperature (OWAT); and an index of suitability	(Ogden et al. 2014a)

Mexico	Dengue	1985–2007	National Institute of Ecology; added projected changes to historic observations	A1B, A2, B1	2030, 2050, 2080	National: 1.001/100.000 cases annually Nuevo Leon: 1.683/100.000 cases annually Queretaro: 0.042/100.000 cases annually Veracruz: 2.630/100.000 cases annually	In 2030, dengue incidence increases 12–18%	In 2050, dengue incidence increases 22–31%.	At baseline, population, GDP, urbanization, access to piped water	(Colón-González et al. 2013)
Europe, Eurasia and the Mediterranean	Climatic suitability for Chikungunya outbreaks	1995-2007	COSMO-CLM, building on ECHAM5	A1B and B1	2011-2040, 2041–2070, 2071–2100	Currently, climatic suitability in southern Europe. The size of these regions will expand during the 21st century	In 2011–2040, increases in risk are projected for Western Europe in the first half of the 21st century	In 2041–2070, projected increased risks for central Europe.		(Fischer et al. 2013)
Europe	Potential establishment of *Ae.*	Current bioclimatic data	Regional climate model COSMO-	A1B, B1	2011–2040, 2041–2070, 2071–2100		In 2011–2040, higher	Between 2011–40 and 2041–		(Fischer et al. 2011)

	albopictus	derived from monthly temperature and rainfall values	CLM				values of climatic suitability for *Ae. albo pictus* increases in western and central Europe	2070, for southern Europe, only small changes in climatic suitability are projected. Increasing suitability at higher latitudes is projected for the end of the century.		
Europe	Dengue fever risk in 27 EU countries	1961–1990	COSMO-CLM (CCLM) forced with ECHAM5/MPIOM	A1B	2011–2040, 2041–2070, 2071–2100	Number of dengue cases are between 0 and 0.6 for most European areas, corresponding to an incidence of less than 2 per 100,000 inhabitants	In 2011–2040, increasing risk of dengue in southern parts of Europe	In 2041–2070, increased dengue risk in many parts of Europe, with higher risks towards the end of the century. Greatest increased risk around the Mediterrane	Socioeconomic variables, population density, degree of urbanization and log population	(Bouzid et al. 2014)

								an and Adriatic coasts and in northern Italy		
Tanzania	Distribution of infected *Aedes aegypti* co-occurrence with dengue epidemics risk	1950–2000	CMIP5		2020, 2050	Currently high habitat suitability for *Ae. aegypti* in relation to dengue epidemic, particularly near water bodies	Projected risk maps for 2020 show risk intensification in dengue epidemic risks areas, with regional differences	In 2050, greater risk intensification and regional differences		(Mweya et al. 2016)
West Nile Virus										
Europe, Eurasia, and the Mediterranean	Distribution of human WNV infection	Monthly temperature anomalies relative to 1980–1999, environmental variables for 2002–2013	NCAR CCSM3	A1B	2015-2050		In 2025, progressive expansion of areas with an elevated probability for WNV infections, particularly at the edges of the current transmission areas	In 2050, increases in areas with a higher probability of expansion	Prevalence of WNV infections in the blood donor population	(Semenza et al. 2016)

Lyme disease and other tick-borne diseases										
North America (mainly Ontario and Quebec, Canada, and Northeast and Midwest, U.S)	Capacity of Lyme disease vector (*Ixodes scapularis)* to reproduce under different environmental conditions	1971–2010	CRCM4.2.3, WRF, MM5I, CGCM3.1, CCSM3	A2	1971–2000, 2011–2040, 2041–2070	In 1971–2010, reproductive capacity increased in North America increased consistent with observations	In 2011–2040, mean reproductive capacity increased, with projected increases in the geographic range and number of ticks	In 2041–2070, further expansion and numbers of ticks projected. R_0 values for *I. scapularis* are projected to increase 1.5–2.3 times in Canada. In the U.S. values are expected to double.		(Ogden et al. 2014b)
Southeastern US, NY	Emergence of *I. scapularis*, leading to Lyme disease	1994–2012			2050	19 years of tick and small mammal data (mice, chipmunks)	In the 2020s, the number of cumulative degree-days enough to advance the	In the 2050s, the nymphal peak advances by 8–11 days, and the		(Levi et al. 2015)

							average nymphal peak by 4–6 days, and the mean larval peak by 5–8 days, based on 1.11–1.67°C increase in mean annual temperature	mean larval peak by 10–14 days, based on 2.22–3.06°C increase in mean annual temperature		
Other										
Venezuela	Chagas disease: number of people exposed to changes in the geographic range of five species of triatomine species	1950–2000	CSIRO3.0	A1B, B1	2020, 2060, 2080		In 2020 decreasing population vulnerability	In 2060, effects more pronounced, with less of a change under B1	MaxEnt model of climatic niche suitability	(Ceccarelli and Rabinovich 2015)
Colombia	Visceral leishmaniasis caused by the trypanosomatid	Present	CSIRO, Hadley	A2A, B2A	2020, 2050, 2080		In 2020, shift in the altitudinal distribution in the Caribbean	In 2050, even greater geographic area of potential occupancy,	MaxEnt model; three topographical variables	(González et al. 2014)

	parasite *Leishmania infantum*						Coast and increase in the geographic area of potential occupancy under optimistic scenarios	with a greater impact under A2.		

References

Arnell, N. W., J. A. Lowe, B. Lloyd-Hughes, and T. J. Osborn, 2018: The impacts avoided with a 1.5°C climate target: a global and regional assessment. Clim. Change, 147, 61–76, doi:10.1007/s10584-017-2115-9.

Bouzid, M., F. J. Colón-González, T. Lung, I. R. Lake, and P. R. Hunter, 2014: Climate change and the emergence of vector-borne diseases in Europe: case study of dengue fever. BMC Public Health, 14, 781, doi:10.1186/1471-2458-14-781.

Ceccarelli, S., and J. E. Rabinovich, 2015: Global Climate Change Effects on Venezuela's Vulnerability to Chagas Disease is Linked to the Geographic Distribution of Five Triatomine Species. J. Med. Entomol., 52, 1333–1343, doi:10.1093/jme/tjv119.

Chung, E. S., H.-K. Cheong, J.-H. Park, J.-H. Kim, and H. Han, 2017: Current and Projected Burden of Disease From High Ambient Temperature in Korea. Epidemiology, 28, S98–S105.

Colón-González, F. J., C. Fezzi, I. R. Lake, P. R. Hunter, and Y. Sukthana, 2013: The Effects of Weather and Climate Change on Dengue. PLoS Negl. Trop. Dis., 7, e2503, doi:10.1371/journal.pntd.0002503.

Dionisio, K. L., C. G. Nolte, T. L. Spero, S. Graham, N. Caraway, K. M. Foley, and K. K. Isaacs, 2017: Characterizing the impact of projected changes in climate and air quality on human exposures to ozone. J. Expo. Sci. Environ. Epidemiol., 27, 260, doi:10.1038/jes.2016.81.

Doyon, B., D. Belanger, and P. Gosselin, 2008: The potential impact of climate change on annual and seasonal mortality for three cities in Québec, Canada. Int. J. Health Geogr., 7, 23, doi:10.1186/1476-072x-7-23.

Fischer, D., S. M. Thomas, F. Niemitz, B. Reineking, and C. Beierkuhnlein, 2011: Projection of climatic suitability for Aedes albopictus Skuse (Culicidae) in Europe under climate change conditions. Glob. Planet. Change, 78, 54–64, doi:10.1016/j.gloplacha.2011.05.008.

——, S. M. Thomas, J. E. Suk, B. Sudre, A. Hess, N. B. Tjaden, C. Beierkuhnlein, and J. C. Semenza, 2013: Climate change effects on Chikungunya transmission in Europe: geospatial analysis of vector's climatic suitability and virus' temperature requirements. Int. J. Health Geogr., 12, 51, doi:10.1186/1476-072X-12-51.

Garland, R. M., M. Matooane, F. A. Engelbrecht, M. J. M. Bopape, W. A. Landman, M. Naidoo, J. van der Merwe, and C. Y. Wright, 2015: Regional Projections of Extreme Apparent Temperature Days in Africa and the Related Potential Risk to Human Health. Int. J. Environ. Res. Public Health, 12, 12577–12604, doi:10.3390/ijerph121012577.

González, C., A. Paz, and C. Ferro, 2014: Predicted altitudinal shifts and reduced spatial distribution of Leishmania infantum vector species under climate change scenarios in Colombia. Acta Trop., 129, 83–90, doi:10.1016/j.actatropica.2013.08.014.

Guo, Y., S. Li, D. L. Liu, D. Chen, G. Williams, and S. Tong, 2016: Projecting future temperature-related mortality in three largest Australian cities. Environ. Pollut., 208, 66–73, doi:10.1016/j.envpol.2015.09.041.

Hajat, S., S. Vardoulakis, C. Heaviside, and B. Eggen, 2014: Climate change effects on human health: Projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. J. Epidemiol. Community Health, 68, 641–648, doi:10.1136/jech-2013-202449.

Hales, S., S. Kovats, S. Lloyd, and D. Campbell-Lendrum, 2014: Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. S. Hales, S. Kovats, S. Lloyd, and D. Campbell-Lendrum, Eds. Geneva, Switzerland, 115 pp.

Hanna, E. G., T. Kjellstrom, C. Bennett, and K. Dear, 2011: Climate Change and Rising Heat: Population Health Implications for Working People in Australia. Asia-Pacific J. Public Heal., 23, 14s–26s, doi:10.1177/1010539510391457.

Heal, M. R., C. Heaviside, R. M. Doherty, M. Vieno, D. S. Stevenson, and S. Vardoulakis, 2013: Health burdens of surface ozone in the UK for a range of future scenarios. Environ. Int., 61, 36–44, doi:10.1016/j.envint.2013.09.010.

Honda, Y., and Coauthors, 2014: Heat-related mortality risk model for climate change impact projection. Environ. Health Prev. Med., 19, 56–63, doi:10.1007/s12199-013-0354-6.

Huang, C. R., A. G. Barnett, X. M. Wang, and S. L. Tong, 2012: The impact of temperature on years of life lost in Brisbane, Australia. Nat. Clim. Chang., 2, 265–270, doi:10.1038/Nclimate1369.

Huynen, M. M. T. E., and P. Martens, 2015: Climate Change Effects on Heat- and Cold-Related Mortality in the Netherlands: A Scenario-Based Integrated Environmental Health Impact Assessment. Int. J. Environ. Res. Public Health, 12, 13295–13320, doi:10.3390/ijerph121013295.

Jackson, J. E., and Coauthors, 2010: Public health impacts of climate change in Washington State: projected mortality risks due to heat events and air pollution. Clim. Change, 102, 159–186, doi:10.1007/s10584-010-9852-3.

Kendrovski, V., M. Baccini, G. Sanchez Martinez, T. Wolf, E. Paunovic, and B. Menne, 2017: Quantifying Projected Heat Mortality Impacts under 21st-Century Warming Conditions for Selected European Countries. Int. J. Environ. Res. Public Health, 14, 729, doi:10.3390/ijerph14070729.

Lee, J. Y., S. Hyun Lee, S.-C. Hong, and H. Kim, 2017: Projecting future summer mortality due to ambient ozone concentration and temperature changes. Atmos. Environ., 156, 88–94.

Levi, T., F. Keesing, K. Oggenfuss, and R. S. Ostfeld, 2015: Accelerated phenology of blacklegged ticks under climate warming. Philos. Trans. R. Soc. London B Biol. Sci., 370.

Li, T. T., J. Ban, R. M. Horton, D. A. Bader, G. L. Huang, Q. H. Sun, and P. L. Kinney, 2015: Heat-related mortality projections for cardiovascular and respiratory disease under the changing climate in Beijing, China. Sci. Rep., 5, doi:10.1038/srep11441.

——, R. M. Horton, D. A. Bader, M. G. Zhou, X. D. Liang, J. Ban, Q. H. Sun, and P. L. Kinney, 2016: Aging Will Amplify the Heat-related Mortality Risk under a Changing Climate: Projection for the Elderly in Beijing, China. Sci. Rep., 6, doi:10.1038/srep28161.

Likhvar, V., and Coauthors, 2015: A multi-scale health impact assessment of air pollution over the 21st century. Sci. Total Environ., 514, 439–449, doi:https://doi.org/10.1016/j.scitotenv.2015.02.002.

Mitchell, D., 2018: Extreme heat-related mortality avoided under Paris Agreement goals. Nat. Clim. Chang.,.

Mweya, C. N., S. I. Kimera, G. Stanley, G. Misinzo, L. E. G. Mboera, and N. Ntinginya, 2016: Climate Change Influences Potential Distribution of Infected Aedes aegypti Co-Occurrence with Dengue Epidemics Risk Areas in Tanzania. PLoS One, 11, e0162649, doi:10.1371/journal.pone.0162649.

Ogden, N. H., R. Milka, C. Caminade, and P. Gachon, 2014a: Recent and projected future climatic suitability of North America for the Asian tiger mosquito Aedes albopictus. Parasit. Vectors, 7, 532, doi:10.1186/s13071-014-0532-4.

——, M. Radojevic, X. Wu, V. R. Duvvuri, P. A. Leighton, and J. Wu, 2014b: Estimated effects of projected climate change on the basic reproductive number of the Lyme disease vector Ixodes scapularis. Environ. Health Perspect., 122, 631–638, doi:10.1289/ehp.1307799.

Petkova, E. P., J. K. Vink, R. M. Horton, A. Gasparrini, D. A. Bader, J. D. Francis, and P. L. Kinney, 2017: Towards More Comprehensive Projections of Urban Heat-Related Mortality: Estimates for New York City under Multiple Population, Adaptation, and Climate Scenarios. Environ. Health Perspect., 125, 47–55, doi:10.1289/Ehp166.

Ren, Z., and Coauthors, 2016: Predicting malaria vector distribution under climate change scenarios in China: Challenges for malaria elimination. Sci. Rep., 6, 20604, doi:10.1038/srep20604.

Schwartz, J. D., and Coauthors, 2015: Projections of temperature-attributable premature deaths in 209 US cities using a cluster-based Poisson approach. Environ. Heal., 14, 85, doi:ARTN 85 10.1186/s12940-015-0071-2.

Semakula, H. M., and Coauthors, 2017: Prediction of future malaria hotspots under climate change in sub-Saharan Africa. Clim. Change, 143, 415–428, doi:10.1007/s10584-017-1996-y.

Semenza, J. C., A. Tran, L. Espinosa, B. Sudre, D. Domanovic, and S. Paz, 2016: Climate change projections of West Nile virus infections in Europe: implications for blood safety practices. Environ. Heal., 15, S28, doi:10.1186/s12940-016-0105-4.

Silva, R. A., and Coauthors, 2016: The effect of future ambient air pollution on human premature mortality to 2100 using output from the ACCMIP model ensemble. Atmos. Chem. Phys., 16, 9847–9862, doi:10.5194/acp-16-9847-2016.

Song, Y., Y. Ge, J. Wang, Z. Ren, Y. Liao, and J. Peng, 2016: Spatial distribution estimation of malaria in northern China and its scenarios in 2020, 2030, 2040 and 2050. Malar. J., 15, 345, doi:10.1186/s12936-016-1395-2.

Tainio, M., K. Juda-Rezler, M. Reizer, A. Warchałowski, W. Trapp, and K. Skotak, 2013: Future climate and adverse health effects caused by fine particulate matter air pollution: case study for Poland. Reg. Environ. Chang., 13, 705–715, doi:10.1007/s10113-012-0366-6.

Tjaden, N. B., J. E. Suk, D. Fischer, S. M. Thomas, C. Beierkuhnlein, and J. C. Semenza, 2017: Modelling the effects of global climate change on Chikungunya transmission in the 21st century. Sci. Rep., 7, 3813, doi:10.1038/s41598-017-03566-3.

Vardoulakis, S., K. Dear, S. Hajat, C. Heaviside, B. Eggen, and A. J. McMichael, 2014: Comparative Assessment of the Effects of Climate Change on Heat-and

Cold-Related Mortality in the United Kingdom and Australia. Environ. Health Perspect., 122, 1285–1292, doi:10.1289/ehp.1307524.

Wang, L., J. B. Huang, Y. Luo, Y. Yao, and Z. C. Zhao, 2015: Changes in Extremely Hot Summers over the Global Land Area under Various Warming Targets. PLoS One, 10, doi:ARTN e0130660 10.1371/journal.pone.0130660.

SI_S3-4-7_Supplementary information to Key Economic Sectors

Table S10. Key Economic Sectors (Energy, Tourism, Transport, Water)

Projected Risks at 1.5°C and 2°C

Sector (sub sector)	*Region*	*Metric*	*Baselines*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
Energy (thermal and hydro plants; cooling demand)	Global	Cooling demand (absolute growth in annual cooling degree days (CDD)); hydroclimate risk to power production	1971−2000	5 GCMS GFDL-ESM2M; HadGEM2-ES; IPSL-CM5A-LR; MIROC-ESM-CHEM; NorESM1-M	RCP8.5 SSP1-3	1.5°C (2002−2048) 2.0°C (2014−2065)			Increased CCD, especially in tropical areas. Increased risk to thermal and hydro power plants in Europe, N. America, south and SE Asia, and SE Brazil		(Byers et al. 2018)
Energy (Wind)	Europe	Daily wind power output (transformed from daily near surface wind speeds)	2006−2015	HAPPI		1.5°C (2106−2115		Great potential for wind energy in Northern Europe, especially in the UK		Limited spatial resolution	(Hosking et al. 2018)
Energy (Electrici	US	Electric sector models:		MIT IGSM-CAM	REF CS3	2015−2050			Increase in electricity		(McFarland et al. 2015)

ty demand)		GCAM-USA ReEDS IPM			REF CS6 POL4.5 CS3 POL3.7 CS3 TEMP 3.7 CS3				demand by 1.6–6.5% in 2050		
Energy (demand)	Global	Economic and end-use energy model Energy service demands for space heating and cooling			RCP2.6 (2°C) RCP8.5 (4°C) RCP8.5 constant after 2020 (1.5°) SSP1 SSP2 SSP3	2050−2100		Economic loss of 0.31% in 2050 and 0.89% in 2100 globally	GDP negative impacts in 2100 are highest (median: -0.94%) under 4.0°C (RCP8.5) scenario compared with a GDP change (median: −0.05%) under 1.5°C scenario		(Park et al. 2018)
Energy (heating and cooling demand)	Global and Regional	Degree days above or below 18°C	1961−1990	21 CMIP5		2100		Cooling energy demand: 31% impacts avoided Heating energy demand: 27% impacts			(Arnell et al. 2018)

								avoided, relative to 2°C			
Energy (Hydropower)	US (Florida)	Conceptual rainfall-runoff (CRR) model: HYMOD MOPEX	1971‒2000	CORDEX (6 RCMs) CMIP5, bias corrected	RCP4.5	2091‒2100			Based on a min/max temp. increase of 1.35‒2°C, overall stream flow to increase by an average of 21% with pronounced seasonal variations, resulting in increases in power generation (72% winter, 15% autumn) and decreasing (-14%) in summer		(Chilkoti et al. 2017)
Energy (Hydropower)	Global	Gross hydropower potential; global mean cooling water discharge	1971–2000	5 bias-corrected GCMs	RCP2.6 RCP8.5	2080			Global gross hydropower potential expected to increase (+2.4% RCP2.6;	Socio-economic pathways	(van Vliet et al. 2016)

									+6.3% RCP8.5) Strongest increases in central Africa, Asia, India, and northern high latitudes. 4.5−15% decrease in global mean cooling water discharge with largest reductions in US and Europe		
Energy (Hydropower)	Brazil	Hydrological Model for natural water inflows (MGB)	1960−1990	HadCM3 Eta-CPTEC-40		2011−2100		A decrease in electricity generation of about 15% and 28% for existing and future generation systems starting in 2040		Other water use and economic development scenarios	(de Queiroz et al. 2016)

Energy (Hydropower)	Ecuador	CRU TS v.3.24 monthly mean temperature, precipitation and potential evapotranspiration (PET) conceptual hydrological model assessing runoff and hydropower electricity model	1971–2000	CMIP5 bias corrected using PET	RCP8.5 RCP4.5 RCP2.6	2071–2100			Annual hydroelectric power production to vary between −55 and +39% of the mean historical output. Inter-GCM range of projections is extremely large (−82%−+277%)	ENSO impacts	(Carvajal et al. 2017)

Energy (Wind)	Europe	Near surface wind data: Wind energy density means; Intra and inter annual variability	1986–2005	21 CMIP5 Euro-CORDEX	RCP8.5 RCP4.5	2016–2035 2046–2065 2081–2100		No major differences in large scale wind energetic resources, inter-annual or intra-annual variability in near term future (2016–2035)	Decreases in wind energy density in eastern Europe, Increases in Baltic regions (−30% vs. +30%). Increase of intra-annual variability in Northern Europe, decrease in Southern. Inter-annual variability not expected to change	Changes in wind turbine technology	(Carvalho et al. 2017)
Energy (Wind)	Europe	Near Surface Wind Speed Wind Power Simulated energy mix scenario		Euro-CORDEX	RCP4.5 RCP8.5	2050		Changes in the annual energy yield of the future European wind farms fleet as a whole will remain within ±5%			(Tobin et al. 2016)
Energy (Wind)	Europe	Potential wind power		ENSEMBLES 15 RCM	SRES A1B				In Europe, changes in		(Tobin et al. 2015)

		generation		6 GCM					wind power potential will remain within ±15% and ±20%		
Energy (Solar)	Europe	Mean PV power generation potential (PVPot); Surface wind velocity (SWV); radiation (RSDS); Surface air temp (TAS)	1970−1999	Euro-CORDEX	RCP4.5 RCP8.5	2070−2099			Solar PV supply by the end of 2100 should range from −14_+2% with largest decreases in Northern countries	Solar spectrum distribution and the air mass effect	(Jerez et al. 2015)
Energy (solar)	Global	Energy yields of photovoltaic (PV) systems		CMIP5	RCP8.5	2006−2049		Decreases in PV outputs in large parts of the world, but notable exceptions with positive trends in large parts of Europe, South-East of North America and the South-East of			(Wild et al. 2015)

								China.			
Energy (Electricity: wind, solar PV, hydro, thermal)	Europe	Wind power production; PV power generation potential; gross hydropower potential (VIC model); thermoelectric power generation (VIC-RBM models)	1971−2000	Euro-CORDEX (ensemble of 3 RCMs and 3 GCMs)	RCP4.5 RCP8.5	+1.5°C (2004-2043) +2.0°C (2016−2059) +3.0°C (2037−2084)		Impacts remain limited for most countries. PV and wind power potential may reduce 10%, hydro and thermal may reduce 20%	At 2.0°C impacts across sub-sectors remain limited, negative impacts double at 3°C. Impacts more severe in southern Europe	No spatial distribution accounted for in analysis	(Tobin et al. 2018)
Energy (hydropower)	Suriname	VHM hydrological model	1960−1990	CMIP5	RCP2.6 RCP4.5 RCP6.0 RCP8.5	1.5°C (2070−2100)		40% decrease in hydropower potential (RCP2.6)	50% decrease in hydropower potential (RCP4.5) 80% decrease in hydropower potential at 3°C GMST increases (RCP8.5)		Donk et al. 2018
Tourism	Europe	Climate Index for Tourism; Tourism Climatic Index (three variants)		Euro-CORDEX	RCP4.5 RCP8.5	+2°C			Varying magnitude of change across different indices; Improved		(Grillakis et al. 2016)

									climate comfort for majority of areas for May to October period; June to August period climate favorability projected to reduce in Iberian peninsula due to high temperatures		
Tourism	Southern Ontario (Canada)	Weather-visitation models (peak, shoulder, off-season)				1–5°C warming		Each additional degree of warming experienced annual park visitation could increase by 3.1%, annually.		Social variables e.g., weekends or holidays	(Hewer et al. 2016)
Tourism	Europe	Natural snow conditions (VIC); Monthly overnight stay;	1971−2000	Euro-CORDEX	RCP2.6 RCP4.5 RCP8.5	+2°C periods: 2071−2100 2036−2			Under a +2°C global warming up to 10 million overnight	Tourism trends based on economic conditions	(Damm et al. 2017)

		Weather Value at Risk				065 2026−2055			stays are at risk (+7.3 million nights) Austria and Italy are most affected.		
Tourism	Sardinia (Italy) and the Cap Bon peninsula (Tunisia)	Overnight stays; weather/climate data (E-OBS)	1971−2000	EU-FP6 ENSEMBLES (ECH-REM, ECH-RMO, HCH-RCA and ECH-RCA)		2041−2070			Climate-induced tourism revenue gains especially in the shoulder seasons during spring and autumn; threat of climate-induced revenue losses in the summer months due to increased heat stress.	GDP; Prices, Holidays; Events	(Köberl et al. 2016)
Tourism	Iran (Zayandehroud River route)	Physiologically equivalent temperature (PET)	1983−2013	HADCM3	B1 A1B	2014–2039		The PET index shows a positive trend with a reduction in number of			(Yazdanpanah et al. 2016)

								climate comfort days (18 < PET < 29), particularly in the western area			
Tourism	Portugal	Arrivals of inbound tourists; GDP						Increasing temperatures are projected to lead to a decrease of inbound tourism arrivals between 2.5% and 5.2%, which is expected to reduce Portuguese GDP between 0.19% and 0.40%.			(Pintassilgo et al. 2016)
Transportation (shipping)	Arctic Sea (North Sea route)	Climatic loses; Gross gains; Net gains		PAGE-ICE	RCP4.5 RCP8.5 SSP2	2013–2200		Large-scale commercial shipping is unlikely possible until 2030 (bulk) and 2050 (container) under	The total climate feedback of NSR could contribute 0.05% to global mean temperature rise by 2100	Business restrictions	(Yumashev et al. 2017)

								RCP8.5.	under RCP8.5 adding $2.15 Trillion to the Net Present Value of total impacts of climate change over the period until 2200. The climatic losses offset 33% of the total economic gains from NSR under RCP8.5 with the biggest losses set to occur in Africa and India.		
Transportation (shipping)	Arctic Sea	Sea-ice ship speed (in days) Sea Ice Thickness (SIT)	1995–2014	CMIP5	RCP2.6 RCP4.5 RCP8.5	2045–2059 2075–2089			Shipping season 4–8 under RCP8.5, double that of RCP2.6 Average transit times decline to 22		(Melia et al. 2016)

									days (RCP2.6) and 17 days (RCP8.5)		
Transportation (shipping)	Arctic Sea (Northern Sea Route)	Mean time of NSR transit window; Sea ice concentration	1980−2014	CMIP5	RCP4.5 RCP8.5	2020−2100			Increase in transit window by 4 (RCP4.5) and 6.5 (RCP8.5) months		(Khon et al. 2017)
Water	Europe	Runoff Discharge Snowpack based on hydrological models: E-HYPE Lisflood WBM LPJmL		CMIP5 CORDEX (11) Bias corrected to E-OBS	RCP2.6 RCP4.5 RCP8.5	1.5°C 2°C 3°C		Increases in runoff affect the Scandinavian mountains; Decreases in runoff in Portugal	Increases in runoff in Norway, Sweden, & N. Poland; Decreases in runoff around Iberian, Balkan, and parts of French coasts.		(Donnelly et al. 2017)
Water	Global (8 river regions)	River runoff Glob-HM Cat-HM		HadGEM2-ES IPSL-CM5A-LR; MIROCESM-CHEM; GFDL-ESM2; NorESM1-M;	RCP8.5	1°C 2°C 3°C 1971−2099		Projected runoff changes for the Rhine (decrease), Tagus (decrease) and Lena (increase) with global	Increased risk of decreases in low flows (Rhine) (−11% at 2°C to −23% at 3°C) Risk of increases in high		(Gosling et al. 2017)

								warming	flows increases for Lena +17% (2°C) to +26% (3°C)		

References

Arnell, N. W., J. A. Lowe, B. Lloyd-Hughes, and T. J. Osborn, 2018: The impacts avoided with a 1.5°C climate target: a global and regional assessment. Clim. Change, 147, 61–76, doi:10.1007/s10584-017-2115-9.

Byers, E., and Coauthors, 2018: Global exposure and vulnerability to multi-sector development and climate change hotspots. Environ. Res. Lett.,.

Carvajal, P. E., G. Anandarajah, Y. Mulugetta, and O. Dessens, 2017: Assessing uncertainty of climate change impacts on long-term hydropower generation using the CMIP5 ensemble---the case of Ecuador. Clim. Change, 144, 611–624, doi:10.1007/s10584-017-2055-4.

Carvalho, D., A. Rocha, M. Gómez-Gesteira, and C. Silva Santos, 2017: Potential impacts of climate change on European wind energy resource under the CMIP5 future climate projections. Renew. Energy, 101, 29–40, doi:10.1016/j.renene.2016.08.036.

Chilkoti, V., T. Bolisetti, and R. Balachandar, 2017: Climate change impact assessment on hydropower generation using multi-model climate ensemble. Renew. Energy, 109, 510–517, doi:10.1016/j.renene.2017.02.041.

Damm, A., J. Köberl, F. Prettenthaler, N. Rogler, and C. Töglhofer, 2017: Impacts of +2°C global warming on electricity demand in Europe. Clim. Serv., 7, 12–30, doi:10.1016/j.cliser.2016.07.001.

Donnelly, C., W. Greuell, J. Andersson, D. Gerten, G. Pisacane, P. Roudier, and F. Ludwig, 2017: Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level. Clim. Change, 143, 13–26, doi:10.1007/s10584-017-1971-7.

Gosling, S. N., and Coauthors, 2017: A comparison of changes in river runoff from multiple global and catchment-scale hydrological models under global warming scenarios of 1°C, 2°C and 3°C. Clim. Change, 141, 577–595, doi:10.1007/s10584-016-1773-3.

Grillakis, M. G., A. G. Koutroulis, K. D. Seiradakis, and I. K. Tsanis, 2016: Implications of 2°C global warming in European summer tourism. Clim. Serv., 1, 30–38, doi:10.1016/j.cliser.2016.01.002.

Hewer, M., D. Scott, and A. Fenech, 2016: Seasonal weather sensitivity, temperature thresholds, and climate change impacts for park visitation. Tour. Geogr., 18, 297–321, doi:10.1080/14616688.2016.1172662.

Hosking, J. S., D. MacLeod, T. Phillips, C. R. Holmes, P. Watson, E. Shuckburgh, and D. Mitchell, 2018: Changes in European wind energy generation potential within a 1.5°C warmer world. Environ. Res. Lett.,.

Jerez, S., and Coauthors, 2015: The impact of climate change on photovoltaic power generation in Europe. Nat. Commun., 6, 10014, doi:10.1038/ncomms10014.

Khon, V. C., I. I. Mokhov, and V. A. Semenov, 2017: Transit navigation through Northern Sea Route from satellite data and CMIP5 simulations. Environ. Res. Lett., 12, 24010.

Köberl, J., F. Prettenthaler, and D. N. Bird, 2016: Modelling climate change impacts on tourism demand: A comparative study from Sardinia (Italy) and Cap Bon (Tunisia). Sci. Total Environ., 543, 1039–1053, doi:10.1016/j.scitotenv.2015.03.099.

McFarland, J., and Coauthors, 2015: Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the United States: a multi-model comparison. Clim. Change, 131, 111–125, doi:10.1007/s10584-015-1380-8.

Melia, N., K. Haines, and E. Hawkins, 2016: Sea ice decline and 21st century trans-Arctic shipping routes. Geophys. Res. Lett., 43, 9720–9728, doi:10.1002/2016GL069315.

Park, C., S. Fujimori, T. Hasegawa, J. Takakura, K. Takahashi, and Y. Hijioka, 2018: Avoided economic impacts of energy demand changes by 1.5 and 2 °C climate stabilization. Environ. Res. Lett., 13, 45010.

Pintassilgo, P., J. Rosselló, M. Santana-Gallego, and E. Valle, 2016: The economic dimension of climate change impacts on tourism: The case of Portugal. Tour. Econ., 22, 685–698, doi:10.1177/1354816616654242.

de Queiroz, A. R., L. M. Marangon Lima, J. W. Marangon Lima, B. C. da Silva, and L. A. Scianni, 2016: Climate change impacts in the energy supply of the Brazilian hydro-dominant power system. Renew. Energy, 99, 379–389, doi:10.1016/j.renene.2016.07.022.

Tobin, I., and Coauthors, 2015: Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections. Clim. Change, 128, 99–112, doi:10.1007/s10584-014-1291-0.

——, and Coauthors, 2016: Climate change impacts on the power generation potential of a European mid-century wind farms scenario. Environ. Res. Lett., 11, 34013.

Tobin, I., W. Greuell, S. Jerez, F. Ludwig, R. Vautard, M. T. H. van Vliet, and F.-M. Bréon, 2018: Vulnerabilities and resilience of European power generation to 1.5 °C, 2 °C and 3 °C warming. Environ. Res. Lett., 13, 44024.

van Vliet, M. T. H., L. P. H. van Beek, S. Eisner, M. Fl??rke, Y. Wada, and M. F. P. Bierkens, 2016: Multi-model assessment of global hydropower and cooling water discharge potential under climate change. Glob. Environ. Chang., 40, 156–170, doi:10.1016/j.gloenvcha.2016.07.007.

Wild, M., D. Folini, F. Henschel, N. Fischer, and B. Müller, 2015: Projections of long-term changes in solar radiation based on CMIP5 climate models and their influence on energy yields of photovoltaic systems. Sol. Energy, 116, 12–24, doi:https://doi.org/10.1016/j.solener.2015.03.039.

Yazdanpanah, H., H. Barghi, and A. Esmaili, 2016: Effect of climate change impact on tourism: A study on climate comfort of Zayandehroud River route from 2014 to 2039. Tour. Manag. Perspect., 17, 82–89, doi:10.1016/j.tmp.2015.12.002.

Yumashev, D., K. van Hussen, J. Gille, and G. Whiteman, 2017: Towards a balanced view of Arctic shipping: estimating economic impacts of emissions from increased traffic on the Northern Sea Route. Clim. Change, 143, 143–155, doi:10.1007/s10584-017-1980-6.

SI_S3_Supplementary information to Cross-Chapter Box 6 Food Security

Table S11. Projected health risks of undernutrition and dietary change at 1.5°C and 2°C. *Abbreviations: DALY: Disability adjusted life year; RCP: Representative Concentration Pathway; SSP: Shared Socioeconomic Pathway*

Region	*Health outcome metric*	*Study baseline*	*Climate model(s)*	*Scenario*	*Time periods of interest*	*Impacts at study baseline*	*Projected impacts at 1.5°C*	*Projected impacts at 2°C*	*Other factors considered*	*Reference*
Global and 21 regions	Undernutrition	1961–1990	BCM2.0, EGMAM1, EGMAM2, EGMAM3, CM4vl	A1B	2030, 2050		In 2030, 95,175 additional undernutrition deaths without adaptation and (ensemble mean) 131,634 with adaptation under the low growth scenario and 77,205 under the high growth scenario; Asia, and sub-Saharan Africa, at highest risk	In 2050 risks are generally lower in most regions because of underlying trends, with 84,695 additional undernutrition deaths without adaptation, 101,484 with adaptation under the low growth scenario and 36,524 under the high growth scenario	Population growth; improved population health; crop models include adaptation measures	(Hales et al. 2014)

Global and 17 regions	Undernourished population; DALY (disability) caused by underweight of a child under 5 years of age	2005–2100	5 models from ISIMIP (GFDL-ESM2, NorESM1-M, IPSL-CM5A-LR, HadGEM2-ES, MIROC-ESM-CHEM)	RCP2.6 and 8.5 with SSP2 and SSP3	2005–2100	Baseline assumed no climate change (no temperature increase from present)	In 2025 under SSP3, global undernourished population is 530–550 million at 1.5°C. Global mean DALYs of 11.2 per 1,000 persons at 1.5°C.	In 2050 under SSP3, global undernourished population is 540–590 million at 2.0 °C. Global mean DALYs of 12.4 per 1,000 persons at 2°C.	Population growth and aging; equity of food distribution	(Hasegawa et al. 2016)
Global divided into 17 regions	DALYs from stunting associated with undernutrition	1990–2008	12 GCMs from CMIP5	Six scenarios: RCP2.6 + SSP1, RCP4.5 + SSPs 1–3, RCP8.5 + SSP2, SSP3	2005–2050	57.4 million DALYs in 2005	In 2030, DALYs decrease by 36.4 million (63%), for RCP4.5, SSP1, and by 30.4 million (53%) and 16.2 million (28%) for RCP8.5, SSP2 and SSP3, respectively	By 2050, DALYs decrease further to 17.0 million for RCP4.5, SSP1, and to 11.6 million for RCP8.5, SSP2. DALYs increase to 43.7 million under RCP8.5, SSP3	Future population and per capita GDP from the SSP database	(Ishida et al. 2014)

References

Hales, S., S. Kovats, S. Lloyd, and D. Campbell-Lendrum, 2014: Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. S. Hales, S. Kovats, S. Lloyd, and D. Campbell-Lendrum, Eds. Geneva, Switzerland, 115 pp.

Hasegawa, T., S. Fujimori, K. Takahashi, T. Yokohata, and T. Masui, 2016: Economic implications of climate change impacts on human health through undernourishment. Clim. Change, 136, 189–202, doi:10.1007/s10584-016-1606-4.

Ishida, H., and Coauthors, 2014: Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research. Environ. Res. Lett., 9, 064014, doi:10.1088/1748-9326/9/6/064014.

Chapter 4: Strengthening and implementing the global response

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Executive Summary

Limiting warming to 1.5°C would require transformative systemic change, integrated with sustainable development. Such change would require the upscaling and acceleration of the implementation of far-reaching, multi-level and cross-sectoral climate mitigation and addressing barriers. Such systemic change would need to be linked to complementary adaptation actions, including transformational adaptation, especially for pathways that temporarily overshoot 1.5°C {Chapter 2, Chapter 3, 4.2.1, 4.4.5, 4.5} (*medium evidence, high agreement*). Current national pledges on mitigation and adaptation are not enough to stay below the Paris Agreement temperature limits and achieve its adaptation goals. While transitions in energy efficiency, carbon intensity of fuels, electrification and land use change are underway in various countries, limiting warming to 1.5°C will require a greater scale and pace of change to transform energy, land, urban and industrial systems globally. {4.3, 4.4, Cross-Chapter Box CB9 in this Chapter}

Although multiple communities around the world are demonstrating the possibility of implementation consistent with 1.5°C pathways {Boxes 4.1-4.10}, very few countries, regions, cities, communities or businesses can currently make such a claim (*high confidence*). To strengthen the global response, almost all countries would need to significantly raise their level of ambition. Implementation of this raised ambition would require enhanced institutional capabilities in all countries, including building the capability to utilise Indigenous and local knowledge (*medium evidence, high agreement*)**.** In developing countries and for poor and vulnerable people, implementing the response would require financial, technological and other forms of support to build capacity, for which additional local, national and international resources would need to be mobilised (*high confidence*). However, public, financial, institutional and innovation capabilities currently fall short of implementing far-reaching measures at scale in all countries *(high confidence)*. Transnational networks that support multi-level climate action are growing, but challenges in their scale-up remain. {4.4.1, 4.4.2, 4.4.4, 4.4.5, Box 4.1, Box 4.2, Box 4.7}

Adaptation needs will be lower in a 1.5°C world compared to a 2°C world *(high confidence)* {Chapter 3; Cross-Chapter Box CB11 in this Chapter}. Learning from current adaptation practices and strengthening them through adaptive governance {4.4.1}, lifestyle and behavioural change {4.4.3} and innovative financing mechanisms {4.4.5} can help their mainstreaming within sustainable development practices. Preventing maladaptation, drawing on bottom-up approaches {Box 4.6} and using Indigenous knowledge {Box 4.3} would effectively engage and protect vulnerable people and communities. While adaptation finance has increased quantitatively, significant further expansion would be needed to adapt to 1.5°C. Qualitative gaps in the distribution of adaptation finance, readiness to absorb resources and monitoring mechanisms undermine the potential of adaptation finance to reduce impacts. {Chapter 3, 4.4.2, 4.4.5, 4.6}

System transitions

The energy system transition that would be required to limit global warming to 1.5°C is underway in many sectors and regions around the world (*medium evidence, high agreement*). The political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years, while that of nuclear energy and Carbon Dioxide Capture and Storage (CCS) in the electricity sector have not shown similar improvements. {4.3.1}

Electrification, hydrogen, bio-based feedstocks and substitution, and in several cases carbon dioxide capture, utilisation and storage (CCUS), would lead to the deep emissions reductions required in energy-intensive industry to limit warming to 1.5°C. However, those options are limited by institutional, economic and technical constraints, which increase financial risks to many incumbent firms (*medium evidence, high agreement*). Energy efficiency in industry is more economically feasible and an enabler of industrial system transitions but would have to be complemented with Greenhouse Gas (GHG)-neutral processes or Carbon Dioxide Removal (CDR) to make energy-intensive industry consistent with 1.5°C (*high confidence*). {4.3.1, 4.3.4}

Global and regional land-use and ecosystems transitions and associated changes in behaviour that would be required to limit warming to 1.5°C can enhance future adaptation and land-based agricultural and forestry mitigation potential. Such transitions could, however, carry consequences for livelihoods that depend on agriculture and natural resources {4.3.2, Cross-Chapter Box CB6 in chapter 3}. Alterations of agriculture and forest systems to achieve mitigation goals could affect current ecosystems and their services and potentially threaten food, water and livelihood security. While this could limit the social and environmental feasibility of land-based mitigation options, careful design and implementation could enhance their acceptability and support sustainable development objectives (*medium evidence, medium agreement*). {4.3.2, 4.5.3}

Changing agricultural practices can be an effective climate adaptation strategy. A diversity of adaptation options exists, including mixed crop-livestock production systems which can be a cost-effective adaptation strategy in many global agriculture systems (*robust evidence, medium agreement)*. Improving irrigation efficiency could effectively deal with changing global water endowments, especially if achieved via farmers adopting new behaviour and water-efficient practices rather than through large-scale infrastructure (*medium evidence, medium agreement*). Well-designed adaptation processes such as community-based adaptation can be effective depending upon context and levels of vulnerability. {4.3.2, 4.5.3}

Improving the efficiency of food production and closing yield gaps have the potential to reduce emissions from agriculture, reduce pressure on land and enhance food security and future mitigation potential (*high confidence*). Improving productivity of existing agricultural systems generally reduces the emissions intensity of food production and offers strong synergies with rural development, poverty reduction and food security objectives, but options to reduce absolute emissions are limited unless paired with demand-side measures. Technological innovation including biotechnology, with adequate safeguards, could contribute to resolving current feasibility constraints and expand the future mitigation potential of agriculture. {4.3.2, 4.4.4}

Dietary choices towards foods with lower emissions and requirements for land, along with reduced food loss and waste, could reduce emissions and increase adaptation options (*high confidence*). Decreasing food loss and waste and behavioural change around diets could lead to effective mitigation and adaptation options (*high confidence*) by reducing both emissions and pressure on land, with significant co-benefits for food security, human health and sustainable development {4.3.2, 4.4.5, 4.5.2, 4.5.3, 5.4.2}, but evidence of successful policies to modify dietary choices remains limited.

Mitigation and Adaptation Options and other Measures

A mix of mitigation and adaptation options implemented in a participatory and integrated manner can enable rapid, systemic transitions in urban and rural areas that are necessary elements of an accelerated transition to 1.5°C worlds. Such options and changes are most effective when aligned with economic and sustainable development, and when local and regional governments are supported by national governments {4.3.3, 4.4.1, 4.4.3}, Various mitigation options are expanding rapidly across many geographies. Although many have development synergies, not all income groups have so far benefited from them. Electrification, end-use energy efficiency and increased share of renewables, amongst other options, are lowering energy use and decarbonising energy supply in the built environment, especially in buildings. Other rapid changes needed in urban environments include demotorisation and decarbonisation of transport, including the expansion of electric vehicles, and greater use of energy-efficient appliances (*medium evidence, high agreement*). Technological and social innovations can contribute to limiting warming to 1.5ºC, e.g. by enabling the use of smart grids, energy storage technologies and general-purpose technologies, such as Information and Communication Technology (ICT) that can be deployed to help reduce emissions. Feasible adaptation options include green infrastructure, resilient water and urban ecosystem services, urban and peri-urban agriculture, and adapting buildings and land use through regulation and planning (*medium evidence, medium to high agreement*). {4.3.3}

Synergies can be achieved across systemic transitions through several overarching adaptation options in rural and urban areas. Investments in health, social security and risk sharing and spreading are cost-effective adaptation measures with high potential for scaling-up (*medium evidence, medium to high agreement*). Disaster risk management and education-based adaptation have lower prospects of scalability and cost-effectiveness (*medium evidence, high agreement*) but are critical for building adaptive capacity. {4.3.5, 4.5.3}

Converging adaptation and mitigation options can lead to synergies and potentially increase cost effectiveness, but multiple trade-offs can limit the speed of and potential for scaling up. Many examples of synergies and trade-offs exist in all sectors and system transitions. For instance, sustainable water management (*high evidence, medium agreement*) and investment in green infrastructure (*medium evidence, high agreement*) to deliver sustainable water and environmental services and to support urban agriculture are less cost-effective but can help build climate resilience. Achieving the governance, finance and social support required to enable these synergies and to avoid trade-offs is often challenging, especially when addressing multiple objectives, and appropriate sequencing and timing of interventions. {4.3.2, 4.3.4, 4.4.1, 4.5.2, 4.5.3, 4.5.4}

Though CO_2 dominates long-term warming, the reduction of warming Short-Lived Climate Forcers (SLCFs), such as methane and black carbon, can in the short term contribute significantly to limiting warming to 1.5°C. Reductions of black carbon and methane would have substantial co-benefits (*high confidence)*, including improved health due to reduced air pollution. This, in turn, enhances the institutional and socio-cultural feasibility of such actions. Reductions of several warming SLCFs are constrained by economic and social feasibility *(low evidence, high agreement)*. As they are often co-emitted with CO_2, achieving the energy, land and urban transitions necessary to limit warming to 1.5°C would see emissions of warming SLCFs greatly reduced. {2.3.3.2, 4.3.6}

Most CDR options face multiple feasibility constraints, that differ between options, limiting the potential for any single option to sustainably achieve the large-scale deployment in 1.5°C-consistent pathways in Chapter 2 (*high confidence*). Those 1.5°C pathways typically rely on Bioenergy with Carbon Capture and Storage (BECCS), Afforestation and Reforestation (AR), or both, to neutralise emissions that are expensive to avoid, or to draw down CO_2 emissions in excess of the carbon budget {Chapter 2}. Though BECCS and AR may be technically and geophysically feasible, they face partially overlapping yet different constraints related to land use. The land footprint per tonne CO_2 removed is higher for AR than for BECCS, but in the light of low current deployment, the speed and scales required for limiting warming to 1.5°C pose a considerable implementation challenge, even if the issues of public acceptance and missing economic incentives were to be resolved (*high agreement, medium evidence*). The large potentials of afforestation and their co-benefits if implemented appropriately (e.g. on biodiversity, soil quality) will diminish over time, as forests saturate (*high confidence*). The energy requirements and economic costs of Direct Air Carbon Capture and Storage (DACCS) and enhanced weathering remain high (*medium evidence, medium agreement*). At the local scale, soil carbon sequestration has co-benefits with agriculture and is cost-effective even without climate policy *(high confidence)*. Its potential global feasibility and cost effectiveness appears to be more limited. {4.3.7}

Uncertainties surrounding Solar Radiation Modification (SRM) measures constrain their potential deployment. These uncertainties include: technological immaturity; limited physical understanding about their effectiveness to limit global warming; and a weak capacity to govern, legitimise, and scale such measures. Some recent model-based analysis suggests SRM would be effective but that it is too early to evaluate its feasibility. Even in the uncertain case that the most adverse side-effects of SRM can be avoided, public resistance, ethical concerns and potential impacts on sustainable development could render SRM economically, socially and institutionally undesirable (*low agreement, medium evidence*). {4.3.8, Cross-Chapter Box CB10 in this Chapter}

Enabling Rapid and Far-reaching Change

The speed and scale of transitions and of technological change required to limit warming to 1.5°C has been observed in the past within specific sectors and technologies {4.2.2.1}. But the geographical and economic scales at which the required rates of change in the energy, land, urban, infrastructure and industrial systems would need to take place, are larger and have no documented historic precedent (*limited evidence, medium agreement*). To reduce inequality and alleviate poverty, such transformations would require more planning and stronger institutions (including inclusive markets) than observed in the past, as well as stronger coordination and disruptive innovation across actors and scales of governance. {4.3, 4.4}

Governance consistent with limiting warming to 1.5°C and the political economy of adaptation and mitigation can enable and accelerate systems transitions, behavioural change, innovation and technology deployment (*medium evidence, medium agreement*). For 1.5°C-consistent actions, an effective governance framework would include: accountable multi-level governance that includes non-state actors such as industry, civil society and scientific institutions; coordinated sectoral and cross-sectoral policies that enable collaborative multi-stakeholder partnerships; strengthened global-to-local financial architecture that enables greater access to finance and technology; and addresses climate-related trade barriers; improved climate education and greater public awareness; arrangements to enable accelerated behaviour change; strengthened climate monitoring and evaluation systems; and reciprocal international agreements that are sensitive to equity and the Sustainable Development Goals (SDGs). System transitions can be enabled by enhancing the capacities of public, private and financial institutions to accelerate climate change policy planning and implementation, along with accelerated technological innovation, deployment and upkeep. {4.4.1, 4.4.2, 4.4.3, 4.4.4}

Behaviour change and demand-side management can significantly reduce emissions, substantially limiting the reliance on CDR to limit warming to 1.5°C {Chapter 2, 4.4.3}. Political and financial stakeholders may find climate actions more cost-effective and socially acceptable, if multiple factors affecting behaviour are considered, including aligning them with people's core values (*medium evidence, high agreement*). Behaviour- and lifestyle-related measures and demand-side management have already led to emission reductions around the world and can enable significant future reductions *(high confidence)*. Social innovation through bottom-up initiatives can result in greater participation in the governance of systems transitions and increase support for technologies, practices and policies that are part of the global response to 1.5°C. {Chapter 2, 4.4.1, 4.4.3, Figure 4.3}

This rapid and far-reaching response required to keep warming below 1.5°C and enhance the adaptive capacity to climate risks needs large investments in low-emission infrastructure and buildings that are currently underinvested, along with a redirection of financial flows towards low-emission investments *(robust evidence, high agreement)*. An estimated annual incremental investment of 1% to 1.5% of global Gross Fixed Capital Formation (GFCF) for the energy sector is indicated; and 1.7% to 2.5% of global GFCF for other development infrastructure that could also address SDG implementation. Though quality policy design and effective implementation may enhance efficiency, they cannot substitute for these investments. {2.5.2, 4.2.1}

Enabling this investment requires the mobilisation and better integration of a range of policy instruments that include: the reduction of socially inefficient fossil fuel subsidy regimes and innovative price and non-price national and international policy instruments and would need to be complemented by de-risking financial instruments and the emergence of long-term low-emission assets. These instruments would aim to reduce the demand for carbon-intensive services and shift market preferences away from fossil fuel-based technology. Evidence and theory suggest that carbon pricing alone, in the absence of sufficient transfers to compensate their unintended distributional cross-sector, cross-nation effects, cannot reach the levels needed to trigger system transitions *(robust evidence, medium agreement)*. But, embedded in consistent policy-packages, they can help mobilise incremental resources and provide flexible mechanisms that help reduce the social and economic costs of the triggering phase of the transition *(robust evidence, medium agreement)*. {4.4.3, 4.4.4, 4.4.5}

Increasing evidence suggests that a climate-sensitive realignment of savings and expenditure towards low-emission, climate-resilient infrastructure and services requires an evolution of global and national financial systems. Estimates suggest that, in addition to climate-friendly allocation of public investments, a potential redirection of 5% to 10% of the annual capital revenues[1] is necessary {4.4.5, Table 1 in Box 4.8}. This could be facilitated by a change of incentives for private day-to-day expenditure and the redirection of savings from speculative and precautionary investments, towards long-term productive low-emission assets and services. This implies the mobilisation of institutional investors and mainstreaming of climate finance within financial and banking system regulation. Access by developing countries to low-risk and low-interest finance through multilateral and national development banks would have to be facilitated *(medium evidence, high agreement)*. New forms of public-private partnerships may be needed with multilateral, sovereign and sub-sovereign guarantees to de-risk climate-friendly investments, support new business models for small-scale enterprises and help households with limited access to capital. Ultimately, the aim is to promote a portfolio shift towards long-term low-emission assets, that would help redirect capital away from potential stranded assets *(medium evidence, medium agreement).*{4.4.5}

Knowledge Gaps

Knowledge gaps around implementing and strengthening the global response to climate change would need to be urgently resolved if the transition to 1.5°C worlds is to become reality. Remaining questions include: how much can be realistically expected from innovation, behaviour and systemic political and economic change in improving resilience, enhancing adaptation and reducing GHG emissions? How can rates of changes be accelerated and scaled up? What is the outcome of realistic assessments of mitigation and adaptation land transitions that are compliant with sustainable development, poverty eradication and addressing inequality? What are life-cycle emissions and prospects of early-stage CDR options? How can climate and sustainable development policies converge, and how can they be organised within a global governance framework and financial system, based on principles of justice and ethics (including Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC)), reciprocity and partnership? To what extent limit warming to 1.5°C needs a harmonisation of macro-financial and fiscal policies, that could include financial regulators such as central banks? How can different actors and processes in climate governance reinforce each other, and hedge against the fragmentation of initiatives? {4.1, 4.4.1, 4.3.7, 4.4.5, 4.6}

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[1] FOOTNOTE: Annual capital revenues are the paid interests plus the increase of the asset value.

4.1 Accelerating the Global Response to Climate Change

This chapter discusses how the global economy and socio-technical and socio-ecological systems can transition to 1.5°C-consistent pathways and adapt to warming of 1.5°C. In the context of systemic transitions, the chapter assesses adaptation and mitigation options, including Carbon Dioxide Removal (CDR), and potential Solar Radiation Modification (SRM) remediative measures (Section 4.3), as well as the enabling conditions that would facilitate implementing the rapid and far-reaching global response (Section 4.4), and render the options more or less feasible (Section 4.5).

The impacts of 1.5°C warmer worlds, while less than in a 2°C warmer world, would require complementary adaptation and development action, typically at local and national scale. From a mitigation perspective, 1.5°C-consistent pathways require immediate action on a greater and global scale so as to achieve net-zero emissions by mid-century, or earlier (Chapter 2). This chapter and Chapter 5 highlight the potential that combined mitigation, development and poverty reduction offer for accelerated decarbonisation.

The global context is an increasingly interconnected world, with the human population growing from the current 7.6 billion to over 9 billion by mid-century (UN, 2017). There has been a consistent growth of global economic output, wealth and trade with a significant reduction in extreme poverty. These trends could continue for the next few decades (Burt et al., 2014), potentially supported by new and disruptive information and communication, and nano- and bio-technologies. They however co-exist with rising inequality (Piketty, 2014), exclusion and social stratification, and regions locked in poverty traps (Deaton, 2013) that could fuel social and political tensions.

The aftermath of the 2008 financial crisis generated a challenging environment on which leading economists have issued repeated alerts about the ‘discontents of globalisation’ (Stiglitz, 2002), ‘depression economics’ (Krugman, 2009), an excessive reliance of export-led development strategies (Rajan, 2011), and risks of ‘secular stagnation’ due to the ‘saving glut’ that slows down the flow of global savings towards productive 1.5°C-consistent investments (Summers, 2016). Each of these impacts the implementation of both 1.5°C-consistent pathways and sustainable development (Chapter 5).

The range of mitigation and adaptation actions that can be deployed in the short run are well-known: for example, low-emission technologies, new infrastructure, energy efficiency measures in buildings, industry and transport; transformation of fiscal structures; reallocation of investments and human resources towards low-emission assets; sustainable land and water management, ecosystem restoration, enhancement of adaptive capacities to climate risks and impacts, disaster risk management; research and development; and mobilisation of new, traditional and Indigenous knowledge.

The convergence of short-term development co-benefits of mitigation and adaptation to address ‘everyday development failures’ (e.g., institutions, market structures and political processes) (Hallegatte et al., 2016; Pelling et al., 2018) could enhance the adaptive capacity of key systems at risk (e.g., water, energy, food, biodiversity, urban, regional and coastal systems) to 1.5°C climate impact (Chapter 3). The issue is whether aligning 1.5°C-consistent pathways with the Sustainable Development Goals (SDGs) will secure support for accelerated change and a new growth cycle (Stern, 2013, 2015). It is difficult to imagine how a 1.5°C world would be attained unless the SDG on cities and sustainable urbanisation is attained in developing countries (Revi, 2016), or without reforms in the global financial intermediation system.

Unless affordable and environmentally and socially acceptable CDR become feasible and available at scale well before 2050, 1.5°C-consistent pathways will be difficult to realise, especially in overshoot scenarios. The social costs and benefits of 1.5°C-consistent pathways depend on the depth and timing of policy responses and their alignment with short term and long-term development objectives, through policy packages that bring together a diversity of policy instruments, including public investment (Campiglio 2016; Winkler and Dubash 2015; Grubb et al. 2014).

Whatever its potential long-term benefits, a transition to a 1.5°C world may suffer from a lack of broad political and public support, if it exacerbates existing short-term economic and social tensions, including unemployment, poverty, inequality, financial tensions, competitiveness issues and the loss of economic value of carbon-intensive assets (Mercure et al., 2018). The challenge is therefore how to strengthen climate policies without inducing economic collapse or hardship, and to make them contribute to reducing some of the 'fault lines' of the world economy (Rajan, 2011).

This chapter reviews literature addressing the alignment of climate with other public policies (e.g., fiscal, trade, industrial, monetary, urban planning, infrastructure, innovation) and with a greater access to basic needs and services, defined by the SDGs. It also reviews how de-risking low-emission investments and the evolution of the financial intermediation system can help reduce the 'savings glut' (Arezki et al., 2016) and the gap between cash balances and long-term assets (Aglietta et al., 2015b) to support more sustainable and inclusive growth.

As the transitions associated with 1.5°C-consistent pathways require accelerated and coordinated action, in multiple systems across all world regions, they are inherently exposed to risks of freeriding and moral hazards. A key governance challenge is how the convergence of voluntary domestic policies can be organised via aligned global, national and sub-national governance, based on reciprocity (Ostrom and Walker, 2005) and partnership (UN, 2016), and how different actors and processes in climate governance can reinforce each other to enable this (Gupta, 2014; Andonova et al., 2017). The emergence of polycentric sources of climate action and transnational and subnational networks that link these efforts (Abbott et al., 2012) offer the opportunity to experiment and learn from different approaches, thereby accelerating approaches led by national governments (Cole, 2015; Jordan et al., 2015).

Section 4.2 of this chapter outlines existing rates of change and attributes of accelerated change. Section 4.3 identifies global systems, and their components, that offer options for this change. Section 4.4 documents the enabling conditions that influence the feasibility of those options, including economic, financial and policy instruments that could trigger the transition to 1.5°C-consistent pathways. Section 4.5 assesses mitigation and adaptation options for feasibility, strategies for implementation and synergies and trade-offs between mitigation and adaptation.

4.2 Pathways Compatible with 1.5°C: Starting Points for Strengthening Implementation

4.2.1 Implications for Implementation of 1.5°C-consistent Pathways

The 1.5°C-consistent pathways assessed in Chapter 2 form the basis for the feasibility assessment in section 4.3. A wide range of 1.5°C-consistent pathways from both Integrated Assessment Modelling (IAM), supplemented by other literature, are assessed by Chapter 2 (Sections 2.1, 2.3, 2.4, and 2.5). The most common feature shared by these pathways is their requirement for faster and more radical changes compared to 2°C and higher warming pathways.

A variety of 1.5°C-consistent technological options and policy targets is identified in the assessed modelling literature (Sections 2.3, 2.4, 2.5). These technology and policy options include energy demand reduction, greater penetration of low-emission and carbon-free technologies as well as electrification of transport and industry, and reduction of land-use change. Both the detailed integrated modelling pathway literature and a number of broader sectoral and bottom-up studies provide examples of how these sectoral technological and policy characteristics can be broken down sectorally for 1.5°C-consistent pathways (see Table 4.1).

Both the integrated pathway literature and the sectoral studies agree on the need for rapid transitions in the production and use of energy across various sectors, to be consistent with limiting global warming to 1.5°C. The pace of these transitions are particularly significant for the supply mix and electrification, with sectoral studies projecting a higher pace of change compared to IAMs (Table 4.1). These trends and transformation patterns create opportunities and challenges for both mitigation and adaptation (Sections 4.2.1.1 and 4.2.1.2), and have significant implications for the assessment of feasibility and enablers, including governance, institutions, and policy instruments addressed in Sections 4.3 and 4.4.

Table 4.1: Sectoral indicators of the pace of transformation in 1.5°C-consistent pathways, based on selected integrated pathways assessed in Chapter 2 (from the scenario database) and sectoral studies reviewed in Chapter 2 that assess mitigation transitions consistent with limiting warming to 1.5°C. Values for '1.5C low OS' and '1.5C high OS' indicate the median and the interquartile ranges for 1.5°C scenarios distinguishing high and low overshoot. S1, S2, S5 and LED represent the four illustrative pathway archetypes selected for this assessment (see Section 2.1 and Supplementary Material 4.A for detailed description).

		Energy		**Buildings**	**Transport**		**Industry**
		Share of renewable in primary energy [%]	Share of renewable in electricity [%]	Change in energy demand for buildings (2010 baseline) [%]	Share of low carbon fuels (electricity, hydrogen and biofuel) in transport [%]	Share of electricity in transport [%]	Industrial emissions reductions (based on current level) [%]
IAM Pathways 2030	1.5C low OS	29 (35; 25)	53 (59; 44)	-3 (5; -8)	10 (15; 8)	5 (7; 3)	40 (50; 30)
	1.5C high OS	24 (27; 20)	43 (54; 37)	-17 (-12; -20)	7 (8; 6)	3 (5; 3)	18 (28; -13)
	S1	29	58	-8	NA	4	49
	S2	29	48	-14	5	4	19
	S5	14	25	NA	3	1	NA
	LED	37	60	30	NA	21	42
Sectorial studies 2030	Löffler et al. (2017)	50	78				
	Rockström et al. (2017)	20					
	Kuramochi et al. (2017)						20
	IEA (2017)	20	47	7	16	6	14
	WBCSD (2017)			-11			
IAM Pathways 2050	1.5C low OS	58 (67; 50)	76 (85; 69)	-19 (2; -37)	53 (65; 34)	23 (30; 17)	79 (89; 71)
	1.5C high OS	62 (68; 47)	82 (88; 64)	-37 (-13; -51)	38 (44; 27)	18 (23; 14)	68 (81; 54)
	S1	58	81	-21	NA	34	74
	S2	53	63	-25	26	23	73
	S5	67	70	NA	53	10	NA
	LED	73	77	45	NA	59	91
Sectorial studies 2050	Löffler et al. (2017)	100	100		98		
	Rockström et al. (2017)		100				
	Figueres et al. (2017)						50
	Kuramochi et al. (2017)		100				
	IEA (2017)	29	74	11	59	31	20
	WBCSD (2017)						

4.2.1.1 *Challenges and Opportunities for Mitigation Along the Reviewed Pathways*

4.2.1.1.1 *Greater scale, speed and change in investment patterns*

There is agreement in the literature reviewed by Chapter 2 that staying below 1.5°C would entail significantly greater transformation in terms of energy systems, lifestyles and investments patterns compared to 2°C-consistent pathways. Yet there is *limited evidence* and *low agreement* regarding the magnitudes and costs of the investments (Sections 2.5.1, 2.5.2 and 4.4.5). Based on the IAM literature reviewed in Chapter 2, climate policies in line with limiting warming to 1.5°C would require a marked upscaling of supply-side energy system investments between now and mid-century, reaching levels of between 1.6–3.8 trillion USD

yr^{-1} globally with an average of about 3.5 trillion USD yr^{-1} over 2016-2050 (see Figure 2.27). This can be compared to an average of about 3.0 trillion USD yr^{-1} over the same period for 2°C-consistent pathways (also in Figure 2.27).

Not only the level of investment but also the type and speed of sectoral transformation would be impacted by the transitions associated with 1.5°C-consistent pathways. IAM literature projects that investments in low-emission energy overtake fossil-fuel investments globally by 2025 in 1.5ºC-consistent pathways (Section 2.5.2). The projected low-emission investments in electricity generation allocations over the period 2016–2050 are: solar (0.09–1.0 trillion USD yr^{-1}), wind (0.1–0.35 trillion USD yr^{-1}), nuclear (0.1–0.25 trillion USD yr^{-1}), and transmission, distribution, and storage (0.3–1.3 trillion USD yr^{-1}). In contrast, investments in fossil-fuel extraction and unabated fossil electricity generation along a 1.5°C-consistent pathway are projected to drop by 0.3-0.85 trillion USD yr^{-1} over the period 2016–2050, with investments in unabated coal generation projected to halt by 2030 in most 1.5°C-consistent pathways (Section 2.5.2). Estimates of investments in other infrastructure are currently unavailable, but they could be considerably larger in volume than solely those in the energy sector (Section 4.4.5).

4.2.1.1.2 Greater policy design and decision-making implications

1.5°C-consistent pathways raise multiple challenges for effective policy design and responses to address the scale, speed, and pace of mitigation technology, finance and capacity building needs. They also need to deal with their distributional implications, while addressing adaptation to residual climate impacts (see Chapter 5). The available literature indicates that 1.5°C-consistent pathways would require robust, stringent and urgent transformative policy interventions targeting the decarbonisation of energy supply, electrification, fuel switching, energy efficiency, land-use change, and lifestyles (Sections 2.5, 4.4.2, 4.4.3). Examples of effective approaches to integrate mitigation with adaptation in the context of sustainable development and to deal with distributional implications proposed in the literature include the utilisation of dynamic adaptive policy pathways (Haasnoot et al., 2013; Mathy et al., 2016) and transdisciplinary knowledge systems (Bendito and Barrios, 2016).

Yet, even with good policy design and effective implementation, 1.5°C-consistent pathways would incur higher costs. Projections of the magnitudes of global economic costs associated with 1.5°C-consistent pathways and their sectoral and regional distributions from the currently assessed literature are scant, yet suggestive. For example, IAM simulations assessed in Chapter 2 project (with a probability greater than 50%) that marginal abatement costs, typically represented in IAMs through a carbon price, would increase by about threefold by 2050 under a 1.5°C-consistent pathway compared to a 2°C-consistent pathway (Section 2.5.2, Figure 2.26). Managing these costs and distributional effects would require an approach that takes account of unintended cross-sector, cross-nation, and cross-policy trade-offs during the transition (Droste et al., 2016; Stiglitz et al., 2017; Pollitt, 2018; Sands, 2018; Siegmeier et al., 2018).

4.2.1.1.3 Greater sustainable development implications

Few studies address the relations between the Shared Socioeconomic Pathways (SSPs) and the Sustainable Developments Goals (SDGs) (O’Neill et al., 2015; Riahi et al., 2017). Nonetheless, literature on potential synergies and trade-offs between 1.5°C-consistent mitigation pathways and sustainable development dimensions is emerging (Sections 2.5.3, 5.4). Areas of potential trade-offs include reduction in final energy demand in relation to SDG 7 (the universal clean energy access goal) and increase of biomass production in relation to land use, water resources, food production, biodiversity and air quality (Sections 2.4.3, 2.5.3). Strengthening the institutional and policy responses to deal with these challenges are discussed in Section 4.4 together with the linkage between disruptive changes in the energy sector and structural changes in other infrastructure (transport, building, water and telecommunication) sectors. A more in-depth assessment of the complexity and interfaces between 1.5°C-consistent pathways and sustainable development is presented in Chapter 5.

4.2.1.2 Implications for Adaptation Along the Reviewed Pathways

Climate variability and uncertainties in the underlying assumptions in Chapter 2's IAMs as well as in model comparisons complicate discerning the implications for climate impacts, adaptation options and avoided adaptation investments at the global level of 2°C compared to 1.5°C warming (James et al., 2017; Mitchell et al., 2017).

Incremental warming from 1.5°C to 2°C would lead to significant increases in temperature and precipitation extremes in many regions (Section 3.3.2, 3.3.3). Those projected changes in climate extremes under both warming levels, however, depend on the emissions pathways, as they have different greenhouse gas (GHG)/aerosol forcing ratios. Impacts are sector-, system- and region-specific, as described in Chapter 3. For example, precipitation-related impacts reveal distinct regional differences (Sections 3.3.3, 3.3.4, 3.3.5, 3.4.2). Similarly, regional reduction in water availability and the lengthening of regional dry spells have negative implications for agricultural yields depending on crop types and world regions (see for example Sections 3.3.4, 3.4.2, 3.4.6).

Adaptation helps reduce impacts and risks. However, adaptation has limits. Not all systems can adapt, and not all impacts can be reversed (Cross-Chapter Box 12 in Chapter 5). For example, tropical coral reefs are projected to be at risk of severe degradation due to temperature-induced bleaching (Box 3.4).

4.2.2 System Transitions and Rates of Change

Society-wide transformation involves socio-technical transitions and social-ecological resilience (Gillard et al., 2016). Transitional adaptation pathways would need to respond to low-emission energy and economic systems, and the socio-technical transitions for mitigation involve removing barriers in social and institutional processes that could also benefit adaptation (Pant et al., 2015; Geels et al., 2017; Ickowitz et al., 2017). In this chapter, transformative change is framed in mitigation around socio-technical transitions, and in adaptation around socio-ecological transitions. In both instances, emphasis is placed on the enabling role of institutions (including markets, and formal and informal regulation). 1.5°C-consistent pathways and adaptation needs associated with warming of 1.5°C imply both incremental and rapid, disruptive and transformative changes.

4.2.2.1 Mitigation: Historical Rates of Change and State of Decoupling

Realising 1.5°C-consistent pathways would require rapid and systemic changes on unprecedented scales (see Chapter 2 and Section 4.2.1). This section examines whether the needed rates of change have historical precedents and are underway.

Some studies conduct a de-facto validation of IAM projections. For CO_2 emission intensity over 1990–2010, this resulted in the IAMs projecting declining emission intensities while actual observations showed an increase. For individual technologies (in particular solar energy), IAM projections have been conservative regarding deployment rates and cost reductions (Creutzig et al., 2017), suggesting that IAMs do not always impute actual rates of technological change resulting from influence of shocks, broader changes and mutually reinforcing factors in society and politics (Geels and Schot, 2007; Daron et al., 2015; Sovacool, 2016; Battiston et al., 2017).

Other studies extrapolate historical trends into the future (Höök et al., 2011; Fouquet, 2016), or contrast the rates of change associated with specific temperature limits in IAMs (such as those in Chapter 2) with historical trends to investigate plausibility of emission pathways and associated temperature limits (Wilson et al., 2013; Gambhir et al., 2017; Napp et al., 2017). When metrics are normalised to Gross Domestic Product (GDP; as opposed to other normalisation metrics such as primary energy), low-emission technology deployment rates used by IAMs over the course of the coming century are shown to be broadly consistent with past trends, but rates of change in emission intensity are typically overestimated (Wilson et al., 2013;

Loftus et al., 2014; van Sluisveld et al., 2015). This bias is consistent with the findings from the 'validation' studies cited above, suggesting that IAMs may under-report the potential for supply-side technological change assumed in 1.5°-consistent pathways, but may be more optimistic about the systemic ability to realise incremental changes in reduction of emission intensity as a consequence of favourable energy efficiency payback times (Wilson et al., 2013). This finding suggests that barriers and enablers other than costs and climate limits play a role in technological change, as also found in the innovation literature (Hekkert et al., 2007; Bergek et al., 2008; Geels et al., 2016b).

One barrier to a greater rate of change in energy systems is that economic growth in the past has been coupled to the use of fossil fuels. Disruptive innovation and socio-technical changes could enable the decoupling of economic growth from a range of environmental drivers, including the consumption of fossil fuels, as represented by 1.5°C-consistent pathways (UNEP, 2014; Newman, 2017). This may be relative decoupling due to rebound effects that see financial savings generated by renewable energy used in the consumption of new products and services (Jackson and Senker, 2011; Gillingham et al., 2013), but in 2015 and 2016 total global GHG emissions have decoupled absolutely from economic growth (IEA, 2017g; Peters et al., 2017). A longer data trend would be needed before stable decoupling can be established. The observed decoupling in 2015 and 2016 was driven by absolute declines in both coal and oil use since the early 2000s in Europe, in the past seven years in the United States and Australia, and more recently in China (Newman, 2017). In 2017, decoupling in China reversed by 2% due to a drought and subsequent replacement of hydropower with coal-fired power (Tollefson, 2017), but this reversal is expected to be temporary (IEA, 2017c). Oil consumption in China is still rising slowly, but absolute decoupling is ongoing in megacities like Beijing (Gao and Newman, 2018) (see Box 4.9).

4.2.2.2 Transformational Adaptation

In some regions and places, incremental adaptation would not be sufficient to mitigate the impacts of climate change on social-ecological systems (see Chapter 3). Transformational adaptation would then be required (Bahadur and Tanner, 2014; Pant et al., 2015; Gillard, 2016; Gillard et al., 2016; Colloff et al., 2017; Termeer et al., 2017). Transformational adaptation refers to actions aiming at adapting to climate change resulting in significant changes in structure or function that go beyond adjusting existing practices (Dowd et al., 2014; IPCC, 2014a; Few et al., 2017), including approaches that enable new ways of decision-making on adaptation (Colloff et al., 2017). Few studies have assessed the potentially transformative character of adaptation options (Pelling et al., 2015; Rippke et al., 2016; Solecki et al., 2017), especially in the context of warming of 1.5°C.

Transformational adaptation can be adopted at a large scale, can lead to new strategies in a region or resource system, transform places and potentially shifts locations (Kates et al., 2012). Some systems might require transformational adaptation at 1.5°C. Implementing adaptation policies in anticipation of 1.5°C would require transformation and flexible planning of adaptation (sometimes called adaptation pathways) (Rothman et al., 2014; Smucker et al., 2015; Holland, 2017; Gajjar et al., 2018), an understanding of the varied stakeholders involved and their motives, and knowledge of less visible aspects of vulnerability based on social, cultural, political, and economic factors (Holland, 2017). Transformational adaptation would seek deep and long-term societal changes that influence sustainable development (Chung Tiam Fook, 2017; Few et al., 2017).

Adaptation requires multidisciplinary approaches integrating scientific, technological and social dimensions. For example, a framework for transformational adaptation, and the integration of mitigation and adaptation pathways can transform rural indigenous communities to address risks of climate change and other stressors (Thornton and Comberti, 2017). In villages in rural Nepal, transformational adaptation has taken place with villagers changing their agricultural and pastoralist livelihood strategies after years of lost crops due to changing rain patterns and degradation of natural resources (Thornton and Comberti, 2017). Instead, they are now opening stores, hotels, and tea shops. In another case, the arrival of an oil pipeline altered traditional Alaskan communities' livelihoods. With growth of oil production, investments were made for rural development. A later drop in oil production decreased these investments. Alaskan Indigenous populations are also dealing with impacts of climate change, such as sea level rise, which is altering their livelihood sources. Transformational adaptation is taking place by changing the energy matrix to renewable energy, in which indigenous people apply their knowledge to achieve environmental, economic, and social benefits (Thornton and Comberti, 2017).

4.2.2.3 Disruptive Innovation

Demand-driven disruptive innovations that emerge as the product of political and social changes across multiple scales can be transformative (Seba, 2014; Christensen et al., 2015; Green and Newman, 2017a). Such innovations would lead to simultaneous, profound changes in behaviour, economies and societies (Seba, 2014; Christensen et al. 2015), but are difficult to predict in supply-focussed economic models (Geels et al., 2016a; Pindyck, 2017). Rapid socio-technical change has been observed in the solar industry (Creutzig et al. (2017). Similar changes to socio-ecological systems can stimulate adaptation and mitigation options that lead to more climate-resilient systems (Adger et al., 2005; Ostrom, 2009; Gillard et al., 2016) (see the Alaska and Nepal examples in Section 4.2.2.2). The increase in roof-top solar and energy storage technology as well as the increase in passive housing and net zero-emissions buildings are further examples of such disruptions (Green and Newman, 2017b). Both roof-top solar and energy storage have benefitted from countries' economic growth strategy and associated price declines in photovoltaic technologies, particularly in China (Hsu et al., 2017; Shrivastava and Persson, 2018), as well as from new information and communication technologies (Koomey et al., 2013), rising demand for electricity in urban areas, and global concern regarding greenhouse gas emissions (Azeiteiro et al., 2017; Lutz and Muttarak, 2017; Wamsler, 2017).

System co-benefits can create the potential for mutually enforcing and demand-driven climate responses (Jordan et al., 2015; Hallegatte and Mach, 2016; Pelling et al., 2018), and rapid and transformational change (Cole, 2015; Geels et al., 2016b; Hallegatte and Mach, 2016; Peters et al., 2017). Examples of co-benefits include gender equality, agricultural productivity (Nyantakyi-Frimpong and Bezner-Kerr, 2015), reduced indoor air pollution (Satterthwaite and Bartlett, 2017), flood buffering (Colenbrander et al., 2017), livelihood support (Shaw et al., 2014; Ürge-Vorsatz et al., 2014), economic growth (GCEC, 2014; Stiglitz et al., 2017), social progress (Steg et al., 2015; Hallegatte and Mach, 2016) and social justice (Ziervogel et al., 2017; Patterson et al., 2018).

Innovations that disrupt entire systems may leave firms and utilities with stranded assets as the transition can happen very quickly (IPCC, 2014b; Kossoy et al., 2015). This may have consequences for fossil fuels that are rendered 'unburnable' (McGlade and Ekins, 2015) and fossil fuel-fired power and industry assets that would become obsolete (Caldecott, 2017; Farfan and Breyer, 2017). The presence of multiple barriers and enablers operating in a system implies that rapid change, whether the product of many small changes (Sterling et al., 2017; Termeer et al., 2017) or large-scale disruptions, is seldom an insular or discrete process. This finding informs the multi-dimensional nature of feasibility in Cross-Chapter Box 3 in Chapter 1 which is applied in Section 4.5. Climate responses that are aligned with multiple feasibility dimensions and combine adaptation and mitigation interventions with non-climate benefits can accelerate change and reduce risks and costs (Fazey et al., 2018). Also political, social and technological influences on energy transitions, for example, can accelerate them faster than narrow techno-economic analysis suggests is possible (Kern and Rogge, 2016), but could also introduce new constraints and risks (Geels et al., 2016b; Sovacool, 2016; Eyre et al., 2018).

Disruptive innovation and technological change may play a role in mitigation and in adaptation. The next section assesses mitigation and adaption options in energy, land and ecosystem, urban and infrastructure and industrial systems.

4.3 Systemic Changes for 1.5°C-Consistent Pathways

Section 4.2 emphasises the importance of systemic change for 1.5°C-consistent pathways. This section translates this into four main system transitions: energy, land and ecosystem, urban and infrastructure, and industrial system transitions. This section assesses the mitigation, adaptation and carbon dioxide removal options that offer the potential for such change within those systems, based on options identified by Chapter 2 and risks and impacts in Chapter 3.

The section puts more emphasis on those adaptation options (Sections 4.3.1-4.3.5) and mitigation options (Sections 4.3.1-4.3.4, 4.3.6 and 4.3.7) that are 1.5°C-relevant and have developed considerably since AR5. They also form the basis for the mitigation and adaptation feasibility assessments in Section 4.5. Section 4.3.8 discusses solar radiation modification methods.

This section emphasises that no single solution or option can enable a global transition to 1.5°C-consistent pathways or adapting to projected impacts. Rather, accelerating change, much of which is already starting or underway, in multiple global systems, simultaneously and at different scales, could provide the impetus for these system transition. The feasibility of individual options as well as the potential for synergies and reduce trade-offs will vary according to context and the local enabling conditions. These are explored at a high level in Section 4.4. Policy packages that bring together multiple enabling conditions can provide building blocks for a strategy to scale-up implementation and intervention impacts.

4.3.1 Energy System Transitions

This section discusses the feasibility of mitigation and adaptation options related to the energy system transition. As only options relevant to 1.5°C and with significant changes since AR5 are discussed, which means that for options like hydropower and geothermal energy, the chapter refers to AR5 and does not provide a discussion. Socio-technical inertia of energy options for 1.5°C-consistent pathways are increasingly being surmounted as fossil fuels start to be phased out. Supply-side mitigation and adaptation options, energy demand-side options, including energy efficiency in buildings and transportation, are discussed in Section 4.3.3, options around energy use in industry are discussed in Section 4.3.4.

Section 4.5 assesses the feasibility in a systematic manner based on the approach outlined in Cross-Chapter Box 3 in Chapter 1.

4.3.1.1 Renewable Electricity: Solar and Wind

All renewable energy options have seen considerable advances over the years since AR5, but solar energy and both onshore and offshore wind energy have had dramatic growth trajectories. They appear well underway to contribute to 1.5°C-consistent pathways (REN21, 2012; IEA, 2017c; IRENA, 2017b).

The largest growth driver for renewable energy since AR5 has been the dramatic reduction in the cost of solar PV (REN21, 2012). This has made rooftop solar competitive in sunny areas between 45° north and south (Green and Newman, 2017b), though IRENA (2018) suggests it is cost effective in many other places too. Solar Photovoltaics (PV) with batteries have been cost effective in many rural and developing areas (Pueyo and Hanna, 2015; Szabó et al., 2016; Jimenez, 2017), for example 19 million people in Bangladesh now have solar-battery electricity in remote villages and are reporting positive experiences on safety and ease of use (Kabir et al., 2017). Small-scale distributed energy projects are being implemented in developed and developing cities where residential and commercial rooftops offer potential for consumers becoming producers (called prosumers) (ACOLA, 2017; Kotilainen and Saari, 2018). Such prosumers could contribute significantly to electricity generation in sun-rich areas likeCalifornia (Kurdgelashvili et al., 2016) or Sub-Saharan Africa in combination with micro-grids and mini-grids Bertheau et al. (2017). It could also contribute to universal energy access (SDG 7) as shown by (IEA, 2017c).

The feasibility of renewable energy options depends to a large extent on geophysical characteristics of the area where the option is implemented. However, technological advances and policy instruments make renewable energy options increasingly attractive in other areas. For example, solar PV is deployed commercially in areas with low solar insolation, like North-Western Europe (Nyholm et al., 2017). Feasibility also depends on grid adaptations (e.g., storage, see below) as renewables grow (IEA, 2017c). For regions with high energy needs, such as industrial areas (see section 4.3.4), high-voltage DC transmission across long distances would be needed (MacDonald et al., 2016).

Another important factor affecting feasibility is public acceptance, in particular for wind energy and other large-scale renewable facilities (Yenneti and Day, 2016; Rand and Hoen, 2017; Gorayeb et al., 2018) that raise landscape management (Nadaï and Labussière, 2017) and distributional justice (Yenneti and Day, 2016) challenges. Research indicates that financial participation and community engagement can be effective in mitigating resistance (Brunes and Ohlhorst, 2011; Rand and Hoen, 2017) (see Section 4.4.3).

Bottom-up studies estimating the use of renewable energy in the future, either at the global or at the national level, are plentiful, especially in the grey literature. It is hotly debated whether a fully renewable energy or electricity system, with or without biomass, is possible (Jacobson et al., 2015, 2017) or not (Clack et al., 2017; Heard et al., 2017), and by what year. Scale-up estimates vary with assumptions about costs and technological maturity, as well as local geographical circumstances and the extent of storage used (REN21, 2012; Ghorbani et al., 2017). Several countries have adopted targets of 100% renewable electricity (IEA, 2017c) as this meets multiple social, economic and environmental goals and contribute to mitigation of climate change (REN21, 2012).

4.3.1.2 Bioenergy and Biofuels

Bioenergy is renewable energy from biomass. Biofuel is biomass-based energy used in transport. Chapter 2 suggests that pathways limiting warming to 1.5°C would enable supply of 67–310 (median 150) EJ yr^{-1} (see Table 2.8) from biomass. Most scenarios find that Bioenergy is combined with Carbon Dioxide Capture and Storage (CCS, BECCS) if it is available but also find robust deployment of bioenergy independent of the availability of CCS (see Section 2.3.4.2 and 4.3.7 for a discussion of BECCS). Detailed assessments indicate that deployment is similar for 2°C-consistent pathways (Chum et al., 2011; P. Smith et al., 2014; Creutzig et al., 2015). There is however *high agreement* that the sustainable bioenergy potential in 2050 would be restricted to around 100 EJ yr^{-1} (Slade et al., 2014; Creutzig et al., 2015b). Sustainable deployment at this or higher levels envisioned by 1.5°C-consistent pathways may put significant pressure on available land, food production and prices (Popp et al., 2014b; Persson, 2015; Kline et al., 2017; Searchinger et al., 2017), preservation of ecosystems and biodiversity (Creutzig et al., 2015b; Holland et al., 2015; Santangeli et al., 2016) as well as potential water and nutrient constraints (Gerbens-Leenes et al., 2009; Gheewala et al., 2011; Bows and Smith, 2012; Smith and Torn, 2013; Bonsch et al., 2016; Lampert et al., 2016; Mouratiadou et al., 2016; Smith et al., 2016b; Wei et al., 2016; Mathioudakis et al., 2017); but there is still *low agreement* on these interactions (Robledo-Abad et al., 2017). Some of the disagreement on the sustainable capacity for bioenergy stems from global versus local assessments. Global assessments may mask local dynamics that exacerbate negative impacts and shortages while at the same time niche contexts for deployment may avoid trade-offs and exploit co-benefits more effectively. In some regions of the world (e.g., the case of Brazilian ethanol, see Box 4.7, where land may be less of a constraint, the use of bioenergy is mature and the industry is well developed), land transitions could be balanced with food production and biodiversity to enable a global impact on CO_2 emissions (Jaiswal et al., 2017).

The carbon intensity of bioenergy, key for both bioenergy as an emission-neutral energy system and BECCS as a Carbon Dioxide Removal (CDR) measure, is still a matter of debate (Buchholz et al., 2016; Liu et al., 2018) and depends on management (Pyörälä et al., 2014; Torssonen et al., 2016; Baul et al., 2017; Kilpeläinen et al., 2017); direct and indirect land use change emissions (Plevin et al., 2010; Schulze et al., 2012; Harris et al., 2015; Repo et al., 2015; DeCicco et al., 2016; Qin et al., 2016)[2]; considered feedstock and time frame (Zanchi et al., 2012; Daioglou et al., 2017; Booth, 2018; Sterman et al., 2018), as well as the availability of coordinated policies and management to minimise negative side effects and trade-offs, particularly those around food security (Stevanović et al., 2017) and livelihood and equity considerations (Creutzig et al., 2013; Calvin et al., 2014) .

Biofuels are a part of the transport sector in some cities and countries, and may be deployed as a mitigation option for aviation, shipping and freight transport (see Section 4.3.3.5) as well as industrial decarbonisation (IEA, 2017g) (Section 4.3.4) though only Brazil has mainstreamed ethanol as a substantial, commercial option. Lower emissions and reduced urban air pollution have been achieved there by use of ethanol and biodiesel as fuels (Hill et al., 2006; Salvo et al., 2017) (see Box 4.7).

4.3.1.3 Nuclear Energy

Many scenarios in Chapter 2 and in AR5 (Bruckner et al., 2014) project an increase in the use of nuclear power, while others project a decrease. The increase can be realised through existing mature nuclear technologies or new options (generation III/IV reactors, breeder reactors, new uranium and thorium fuel cycles, small reactors or nuclear cogeneration).

Even though historically scalability and speed of scaling of nuclear plants have been high in many nations, such rates are currently not achieved anymore. In the 1960s and 1970s, France implemented a programme to rapidly get 80% of its power from nuclear in about 25 years (IAEA, 2018), but the current time-lag between the decision date and the commissioning of plants is observed to be 10-19 years (Lovins et al., 2018). The current deployment pace of nuclear energy is constrained by social acceptability in many countries due to concerns over risks of accidents and radioactive waste management (Bruckner et al., 2014). Though comparative risk assessment shows health risks are low per unit of electricity production (Hirschberg et al., 2016), and land requirement is lower than that of other power sources (Cheng and Hammond, 2017), the political processes triggered by societal concerns depend on the country-specific means of managing the political debates around technological choices and their environmental impacts (Gregory et al., 1993). Such differences in perception (Kim and Chung, 2017) explain why the 2011 Fukushima incident resulted in a confirmation or acceleration of phasing out nuclear energy in five countries (Roh, 2017) while 30 other countries have continued using nuclear energy, amongst which 13 are building new nuclear capacity including China, India and the United Kingdom (IAEA, 2017; Yuan et al., 2017).

Costs of nuclear power have increased over time in some developed nations, principally due to market conditions where increased investment risks of high-capital expenditure technologies have become significant. 'Learning by doing' processes often failed to compensate for this trend because they were slowed down by the absence of standardisation and series effects (Grubler, 2010). What are and have been the costs of nuclear power is debated in the literature (Lovering et al., 2016; Koomey et al., 2017). Countries with liberalised markets that continue to develop nuclear employ de-risking instruments through long-term contracts with guaranteed sale prices (Finon and Roques, 2013). For instance, the United Kingdom works with public guarantees covering part of the upfront investment costs of newly planned nuclear capacity. This dynamic differs in countries such as China and South Korea, where monopolistic conditions in the electric system allow for reducing investment risks, deploying series effects and enhancing the engineering capacities of users due to stable relations between the security authorities and builders (Schneider et al., 2017).

The safety of nuclear plants depends upon the public authorities of each country. However, because accidents affect worldwide public acceptance of this industry, questions have been raised about the risk of economic and political pressures weakening the safety of the plants (Finon, 2013; Budnitz, 2016). This raises the issue of international governance of civil nuclear risks and reinforced international cooperation involving governments, companies and engineering (Walker and Lönnroth, 1983; Thomas, 1988; Finon, 2013), based

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[2] FOOTNOTE: While there is high agreement that indirect Land Use Change (iLUC) could occur, there is low agreement about the actual extent of Iluc (P. Smith et al., 2014; Verstegen et al., 2015; David, 2017)

on the experience of the International Atomic Energy Agency.

4.3.1.4 Energy Storage

The growth in electricity storage for renewables has been around Grid Flexibility Resources (GFR) that would enable several places to source more than half their power from non-hydro renewables (Komarnicki, 2016). Ten types of GFRs within smart grids have been developed largely since AR5 as renewables have tested grid stability (Blaabjerg et al., 2004; IRENA, 2013; IEA, 2017d; Majzoobi and Khodaei, 2017) though demonstrations of how to do this without hydro or natural gas-based power back-up are still needed. Pumped hydro comprised 150 GW of storage capacity in 2016, and grid-connected battery storage just 1.7 GW, but the latter grew between 2015 to 2016 by 50% (REN21, 2012). Battery storage has been the main growth feature in energy storage since AR5 (Breyer et al., 2017). This appears to the result of significant cost reductions due to mass production for Electric Vehicles (EVs) (Nykvist and Nilsson, 2015; Dhar et al., 2017). Although costs and technical maturity look increasingly positive, the feasibility of battery storage is challenged by concerns over the availability of resources and the environmental impacts of its production (Peters et al., 2017). Lithium, a common element in the earth's crust, does not appear to be restricted and large increases in production have happened in recent years with eight new mines in Western Australia where most lithium is produced (GWA, 2016). Emerging battery technologies may provide greater efficiency and recharge rates (Belmonte et al., 2016) but remain significantly more expensive due to speed and scale issues compared to lithium ion batteries (Dhar et al., 2017; IRENA, 2017a).

Research and demonstration of energy storage in the form of thermal and chemical systems continues, but large scale commercial systems are rare (Pardo et al., 2014). Renewably derived synthetic liquid (like methanol and ammonia) and gas (like methane and hydrogen) are increasingly being seen as a feasible storage options for renewable energy (producing fuel for use in industry during times when solar and wind are abundant) (Bruce et al., 2010; Jiang et al., 2010; Ezeji, 2017) but, in the case of carbonaceous storage media, would need a renewable source of carbon to make a positive contribution to GHG reduction (von der Assen et al., 2013; Abanades et al., 2017) (see also Section 4.3.4.5). The use of electric vehicles as a form of storage has been modelled and evaluated as an opportunity, and demonstrations are emerging (Dhar et al., 2017; Green and Newman, 2017a), but challenges to upscaling remain.

4.3.1.5 Options for Adapting Electricity Systems to 1.5°C

Climate change has started to disrupt electricity generation and, if climate change adaptation options are not considered, it is predicted that these disruptions will be lengthier and more frequent (Jahandideh-Tehrani et al., 2014; Bartos and Chester, 2015; Kraucunas et al., 2015; van Vliet et al., 2016). Adaptation would both secure vulnerable infrastructure and ensure the necessary generation capacity (Minville et al., 2009; Eisenack and Stecker, 2012; Schaeffer et al., 2012; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Goytia et al., 2016). The literature shows *high agreement* that climate change impacts need to be planned for in the design of any kind of infrastructure, especially in the energy sector (Nierop, 2014), including interdependencies with other sectors that require electricity to function, including water, data, telecommunications and transport (Fryer, 2017).

Recent research has developed new frameworks and models that aim to assess and identify vulnerabilities in energy infrastructure and create more proactive responses (Francis and Bekera, 2014; Ouyang and Dueñas-Osorio, 2014; Arab et al., 2015; Bekera and Francis, 2015; Knight et al., 2015; Jeong and An, 2016; Panteli et al., 2016; Perrier, 2016; Erker et al., 2017; Fu et al., 2017). Assessments of energy infrastructure adaptation, while limited, emphasise the need for redundancy (Liu et al. 2017). The implementation of controllable and islandable microgrids including the use of residential batteries, and can increase resiliency, especially after extreme weather events (Qazi and Young Jr., 2014; Liu et al., 2017). Hybrid renewables-based power systems with non-hydro capacity, such as with high-penetration wind generation, could provide the required system flexibility (Canales et al., 2015). Overall, there is *high agreement* that hybrid systems, taking advantage of an array of sources and time of use strategies, can help make electricity generation more resilient (Parkinson and Djilali, 2015), given that energy security standards are in place (Almeida Prado et al., 2016).

Interactions between water and energy are complex (IEA, 2017g). Water scarcity patterns and electricity disruptions will differ across regions. There is *high agreement* that mitigation and adaptation options for thermal electricity generation (if that remains fitted with CCS) need to consider increasing water shortages, taking into account other factors such as ambient water resources and demand changes in irrigation water (Hayashi et al., 2018). Increasing the efficiency of power plants can reduce emissions and water needs (Eisenack and Stecker, 2012; van Vliet et al., 2016), but applying CCS would increase water consumption (Koornneef et al 2012). The technological, economic, social and institutional feasibility of efficiency improvements is high, but insufficient to limit temperature rise to 1.5°C (van Vliet et al., 2016).

In addition, a number of options for water cooling management systems have been proposed, such as hydraulic measures (Eisenack and Stecker, 2012) and alternative cooling technologies (Chandel et al., 2011; Eisenack and Stecker, 2012; Bartos and Chester, 2015; Murrant et al., 2015; Bustamante et al., 2016; van Vliet et al., 2016; Huang et al., 2017b). There is *high agreement* on the technological and economic feasibility of these technologies as their absence can severely impact the functioning of the power plant as well as safety and security standards.

4.3.1.6 Carbon Dioxide Capture and Storage in the Power Sector

The AR5 (IPCC, 2014b) as well as Section 2.4.2 assign significant emission reductions over the course of this century to CO_2 capture and storage (CCS) in the power sector. This section focuses on CCS in the fossil-fuelled power sector; Section 4.3.4 discusses CCS in non-power industry, and Section 4.3.7 bioenergy with CCS (BECCS). Section 2.4.2 puts the cumulative CO_2 stored from fossil-fuelled power at 410 (199–470 interquartile range) $GtCO_2$ over this century. Such modelling suggests that CCS in the power sector can contribute to cost-effective achievement of emission reduction requirements for limiting warming to 1.5°C. CCS may also offer employment and political advantages for fossil fuel-dependent economies (Kern et al., 2016), but may entail more limited co-benefits than other mitigation options (that, e.g., generate power) and therefore for its business case and economic feasibility relies on climate policy incentives. Since 2017, two CCS projects in the power sector capture 2.4 $MtCO_2$ annually, while 30 $MtCO_2$ is captured annually in all CCS projects (Global CCS Institute, 2017).

The technological maturity of CO_2 capture options in the power sectors has improved considerably (Abanades et al., 2015; Bui et al., 2018), but costs have not come down between 2005 and 2015 due to limited learning in commercial settings and increased energy and resources costs (Rubin et al., 2015). Storage capacity estimates vary greatly, but Section 2.4.2 as well as literature (V. Scott et al., 2015) indicate that perhaps 10,000 $GtCO_2$ could be stored in underground reservoirs. Regional availability of this may not be sufficient, and it requires efforts to have this storage and the corresponding infrastructure available at the necessary rates and times (de Coninck and Benson, 2014). CO_2 retention in the storage reservoir was recently assessed as 98% over 10,000 years for well-managed reservoirs, and 78% for poorly regulated ones Alcade et al 2018. A paper reviewing 42 studies on public perception of CCS (Seigo et al., 2014) found that social acceptance of CCS is predicted by trust, perceived risks and benefits. The technology itself mattered less than the social context of the project. Though insights on communication of CCS projects to the general public and inhabitants of the area around the CO_2 storage sites have been documented over the years, project stakeholders are not consistently implementing these lessons, although some projects have observed good practices (Ashworth et al., 2015).

CCS in the power sector is hardly being realised at scale, mainly because the incremental costs of capture, and the development of transport and storage infrastructures are not sufficiently compensated by market or government incentives (IEA, 2017c). In both full-scale projects in the power sector, part of the capture costs are compensated for by revenues from Enhanced Oil Recovery (EOR) (Global CCS Institute, 2017), demonstrating that EOR helps developing CCS further. EOR is a technique that uses CO_2 to mobilise more oil out of depleting oil fields, leading to additional CO_2 emissions by combusting the additionally recovered oil (Cooney et al., 2015).

4.3.2 Land and Ecosystem Transitions

This section assesses the feasibility of mitigation and adaptation options related to land use and ecosystems. Land transitions are grouped around agriculture and food, ecosystems and forests, and coastal systems.

4.3.2.1 Agriculture and Food

In a 1.5°C world, local yields are projected to decrease in tropical regions that are major food producing areas of the world (West Africa, South-East Asia, South-Asia, and Central and northern South America) (Schleussner et al., 2016). Some high-latitude regions may benefit from the combined effects of elevated CO_2 and temperature because their average temperatures are below optimal temperature for crops. In both cases there are consequences for food production and quality (Cross-Chapter Box 6 in Chapter 3 on Food Security), conservation agriculture, irrigation, food wastage, bioenergy and the use of novel technologies.

Food production and quality. Increased temperatures, including 1.5°C warming, would affect the production of cereals such as wheat and rice, impacting food security (Schleussner et al., 2016). There is *medium agreement* that elevated CO_2 concentrations can change food composition, with implications for nutritional security (Taub et al., 2008; Högy et al., 2009; DaMatta et al., 2010; Loladze, 2014; De Souza et al., 2015), with the effects being different depending on the region (Medek et al., 2017).

Meta-analyses of the effects of drought, elevated CO_2, and temperature conclude that at 2°C local warming and above, aggregate production of wheat, maize, and rice are expected to decrease in both temperate and tropical areas (Challinor et al., 2014). These production losses could be lowered if adaptation measures are taken (Challinor et al., 2014), such as developing varieties better adapted to changing climate conditions.

Adaptation options can help ensure access to sufficient, quality food. These include conservation agriculture, improved livestock management, increasing irrigation efficiency, agroforestry and management of food loss and waste. Complementary adaptation and mitigation options, for example, the use of climate services (Section 4.3.5), bioenergy (Section 4.3.1) and biotechnology (Section 4.4.4) can also serve to reduce emissions intensity and the carbon footprint of food production.

Conservation Agriculture (CA). Soil management that reduces the disruption of soil structure and biotic processes by minimising tillage. A recent meta-analysis showed that no-till practices work well in water-limited agroecosystems when implemented jointly with residue retention and crop rotation but may by themselves decrease yields in other situations (Pittelkow et al., 2014). Additional climate adaptations include adjusting planting times and crop varietal selection and improving irrigation efficiency. Adaptations such as these may increase wheat and maize yields by 7–12% under climate change (Challinor et al., 2014). CA can also help build adaptive capacity (*medium evidence, medium agreement)* (H. Smith et al., 2017; Pradhan et al., 2018) and have mitigation co-benefits through improved fertiliser use or efficient use of machinery and fossil fuels (Harvey et al., 2014; Cui et al., 2018; Pradhan et al., 2018). CA practices can also raise soil carbon and therefore remove CO_2 from the atmosphere (Poeplau and Don 2015; Vicente-Vicente et al. 2016; Aguilera et al. 2013). However, CA adoption can be constrained by inadequate institutional arrangements and funding mechanisms (Harvey et al., 2014; Baudron et al., 2015; Li et al., 2016; Dougill et al., 2017; Smith et al., 2017b).

Sustainable intensification of agriculture consists of agricultural systems with increased production per unit area but with management of the range of potentially adverse impacts on the environment (Pretty and Bharucha, 2014). Sustainable intensification can increase the efficiency of inputs and enhance health and food security (Ramankutty et al., 2018).

Livestock management. Livestock are responsible for more GHG emissions than all other food sources.

Emissions are caused by feed production, enteric fermentation, animal waste, land-use change and livestock transport and processing. Some estimates indicate that livestock supply chains could account for 7.1 $GtCO_2$, equivalent to 14.5% of global anthropogenic greenhouse gas emissions (Gerber et al., 2013). Cattle (beef, milk) are responsible for about two-thirds of that total, largely due to methane emissions resulting from rumen fermentation (Gerber et al., 2013; Opio et al., 2013).

Despite ongoing gains in livestock productivity and volumes, the increase of animal products in global diets is restricting overall agricultural efficiency gains because of inefficiencies in the conversion of agricultural primary production (e.g., crops) in the feed-animal products pathway (Alexander et al., 2017), offsetting the benefits of improvements in livestock production systems (Clark and Tilman, 2017).

There is increasing agreement that overall emissions from food systems could be reduced by targeting the demand for meat and other livestock products, particularly where consumption is higher than suggested by human health guidelines. Adjusting diets to meet nutritional targets could bring large co-benefits, through GHG mitigation and improvements in the overall efficiency of food systems (Erb et al., 2009; Tukker et al., 2011; Tilman and Clark, 2014; van Dooren et al., 2014; Ranganathan et al., 2016). Dietary shifts could contribute one-fifth of the mitigation needed to hold warming below 2°C, with one-quarter of low-cost options (Griscom et al., 2017). There, however, remains limited evidence of effective policy interventions to achieve such large-scale shifts in dietary choices, and prevailing trends are for increasing rather than decreasing demand for livestock products at the global scale (Alexandratos and Bruinsma, 2012; OECD/FAO, 2017). How the role of dietary shift could change in 1.5°C-consistent pathways is also not clear (see Chapter 2).

Adaptation of livestock systems can include a suite of strategies such as using different breeds and their wild relatives to develop a genetic pool resilient to climatic shocks and longer-term temperature shifts (Thornton and Herrero, 2014), improving fodder and feed management (Bell et al., 2014; Havet et al., 2014) and disease prevention and control (Skuce et al., 2013; Nguyen et al., 2016). Most interventions that improve the productivity of livestock systems and enhance adaptation to climate changes would also reduce the emissions intensity of food production, with significant co-benefits for rural livelihoods and security of food supply (Gerber et al., 2013; FAO & NZAGRC, 2017a, 2017b, 2017c). Whether such reductions in emission intensity result in lower or higher absolute GHG emissions depends on overall demand for livestock products, indicating the relevance of integrating supply-side with demand-side measures within food security objectives (Gerber et al., 2013; Bajželj et al., 2014). Transitions in livestock production systems (e.g., from extensive to intensive) can also result in significant emission reductions as part of broader land-based mitigation strategies (Havlik et al., 2014).

Overall, there is *high agreement* that farm strategies that integrate mixed crop-livestock systems can improve farm productivity and have positive sustainability outcomes (Havet et al., 2014; Thornton and Herrero, 2014; Herrero et al., 2015; Weindl et al., 2015). Shifting towards mixed crop-livestock systems is estimated to reduce agricultural adaptation costs to 0.3% of total production costs while abating deforestation by 76 million ha globally, making it a highly cost-effective adaptation option with mitigation co-benefits (Weindl et al., 2015). Evidence from various regions supports this (Thornton and Herrero, 2015), although the feasible scale varies between regions and systems, as well as being moderated by overall demand in specific food products. In Australia, some farmers have successfully shifted to crop-livestock systems where, each year, they allocate land and forage resources in response to climate and price trends (Bell et al., 2014) . However, there can be some unintended negative impacts of such integration, including an increased burdens on women, higher requirements of capital, competing uses of crop residues (e.g., feed vs. mulching vs. carbon sequestration) and higher requirements of management skills, which can be a challenge across several low income countries (Thornton and Herrero, 2015; Thornton et al., 2018). Finally, the feasibility of improving livestock efficiency is dependent on socio-cultural context and acceptability: there remain significant issues around widespread adoption of crossbred animals, especially by smallholders (Thornton et al., 2018).

Irrigation efficiency. Irrigation efficiency is especially critical since water endowments are expected to change, with 20–60 Mha of global cropland being projected to revert from irrigated to rain fed land, while other areas will receive higher precipitation in shorter time spans thus affecting irrigation demand (Elliott et al., 2014). While increasing irrigation system efficiency is necessary, there is mixed evidence on how to enact efficiency improvements (Fader et al., 2016; Herwehe and Scott, 2017). Physical and technical strategies include building large-scale reservoirs or dams, renovating or deepening irrigation channels, building on-farm rainwater harvesting structures, lining ponds, channels and tanks to reduce losses through percolation and evaporation, and investing in small infrastructure such as sprinkler or drip irrigation sets (Varela-Ortega et al., 2016; Sikka et al., 2018). Each strategy has differing costs and benefits relating to unique biophysical, social, and economic contexts. Other concerns relating to the increase of irrigation efficiency discuss fostering irrigation dependency, hence increasing climate sensitivity, which may be maladaptive in the long-term (Lindoso et al., 2014).

Improvements in irrigation efficiency would need to be supplemented with ancillary activities, such as shifting to crops that require less water, and improving soil and moisture conservation (Fader et al., 2016; Hong and Yabe, 2017; Sikka et al., 2018). Currently, the feasibility of improving irrigation efficiency is constrained by issues of replicability across scale and sustainability over time (Burney and Naylor, 2012), institutional barriers and inadequate market linkages (Pittock et al., 2017).

Growing evidence suggests that investing in behavioural shifts towards using irrigation technology such as micro-sprinklers or drip irrigation, is an effective and quick adaptation strategy (Varela-Ortega et al., 2016; Herwehe and Scott, 2017; Sikka et al., 2018) as opposed to large dams which have high financial, ecological and social costs (Varela-Ortega et al., 2016). While improving irrigation efficiency is technically feasible (R. Fishman et al., 2015) and has clear benefits for environmental values (Pfeiffer and Lin, 2014; R. Fishman et al., 2015), feasibility is regionally differentiated as shown by examples as diverse as Kansas (Jägermeyr et al., 2015), India (R. Fishman et al., 2015) and Africa (Pittock et al., 2017).

Agroforestry. The integration of trees and shrubs into crop and livestock systems, when properly managed, can potentially restrict soil erosion, facilitate water infiltration, improve soil physical properties and buffer against extreme events (Lasco et al., 2014; Mbow et al., 2014; Quandt et al., 2017; Sida et al., 2018). There is *medium evidence* and *high agreement* on the feasibility of agroforestry practices that enhance productivity, livelihoods and carbon storage (Lusiana et al., 2012; K Murthy, 2013; Coulibaly et al., 2017; Sida et al., 2018), including from indigenous production systems (Coq-Huelva et al., 2017), with variation by region, agroforestry type, and climatic conditions (Place et al., 2012; Coe et al., 2014; Mbow et al., 2014; Iiyama et al., 2017; Abdulai et al., 2018). Long-term studies examining the success of agroforestry, however, are rare (Coe et al., 2014; Meijer et al., 2015; Brockington et al., 2016; Zomer et al., 2016).

The extent to which agroforestry practices at farm-level could be scaled up globally while satisfying growing food demand is relatively unknown. Agroforestry adoption has been relatively low and uneven (Jacobi et al., 2017; Hernández-Morcillo et al., 2018), with constraints including the expense of establishment and lack of reliable financial support, insecure land tenure, landowner's lack of experience with trees, complexity of management practices, fluctuating market demand and prices for different food and fibre products, the time and knowledge required for management, low intermediate benefits to offset revenue lags, and inadequate market access (Pattanayak et al., 2003; Mercer, 2004; Sendzimir et al., 2011; Valdivia et al., 2012; Coe et al., 2014; Meijer et al., 2015; Coulibaly et al., 2017; Jacobi et al., 2017).

Managing food loss and waste. The way food is produced, processed and transported strongly influences GHG emissions. Around one-third of the food produced on the planet is not consumed (FAO, 2013) affecting food security and livelihoods (See Cross-Chapter Box 6 on Food Security in Chapter 3). Food wastage is a combination of food loss–decrease in mass and nutritional value of food due to poor infrastructure, logistics, and lack of storage technologies and management – and food waste that derives from inappropriate human consumption that leads to food spoilage associated with inferior quality or overproduction. Food wastage could lead to an increase in emissions estimated to 1.9–2.5 $GtCO_2$-eq yr^{-1} (Hiç et al., 2016).

Decreasing food wastage has high mitigation and adaptation potential and could play an important role in land transitions towards 1.5°C, provided that reduced food waste results in lower production-side emissions rather than increased consumption (Foley et al., 2011). There is *medium agreement* that a combination of individual-institutional behaviour (Refsgaard and Magnussen, 2009; Thornton and Herrero, 2014), and improved technologies and management (Lin et al., 2013; Papargyropoulou et al., 2014) can transform food waste into products with marketable value. Institutional behaviour depends on investment and policies, which if adequately addressed could enable mitigation and adaptation co-benefits, in a relatively short time.

Novel technologies. New molecular biology tools have been developed that can lead to fast and precise genome modification (De Souza et al., 2016; Scheben et al., 2016) (e.g., CRISPR Cas 9 (Ran et al., 2013; Schaeffer and Nakata, 2015). Such genome editing tools may moderately assist in mitigation and adaptation of agriculture in relation to climate changes, CO_2 elevation, drought and flooding (DaMatta et al., 2010; De Souza et al., 2015, 2016). These tools could contribute to developing new plant varieties that can adapt to warming of 1.5°C and overshoot, potentially avoiding some of the costs of crop shifting (Schlenker and Roberts, 2009; De Souza et al., 2016). However, biosafety concerns and government regulatory systems can be a major barrier to the use of these tools as this increases the time and cost of turning scientific discoveries into ready applicable technologies (Andow and Zwahlen, 2006; Maghari and Ardekani, 2011).

The strategy of reducing enteric methane emissions by ruminants through the development of inhibitors or vaccines has already been attempted with some successes, although the potential for application at scale and in different situations remains uncertain. A methane inhibitor has been demonstrated to reduce methane from feedlot systems by 30% over a 12-week period (Hristov et al., 2015) with some productivity benefits but the ability to apply it in grazing systems will depend on further technological developments as well as costs and incentives. A vaccine could potentially modify the microbiota of the rumen and be applicable even in extensive grazing systems by reducing the presence of methanogenic micro-organisms (Wedlock et al., 2013) but has not yet been successfully demonstrated to reduce emissions in live animals. Selective breeding for lower-emitting ruminants is becoming rapidly feasible, offering small but cumulative emissions reductions without requiring substantial changes in farm systems (Pickering et al., 2015).

Technological innovation in culturing marine and freshwater micro and macro flora has significant potential to expand food, fuel and fibre resources, and could reduce impacts on land and conventional agriculture (Greene et al., 2017).

Technological innovation could assist in increased agricultural efficiency (e.g., via precision agriculture), decrease food wastage and genetics that enhance plant adaptation traits (Section 4.4.4). Technological and associated management improvements may be ways to increase the efficiency of contemporary agriculture to help produce enough food to cope with population increases in a 1.5°C warmer world, and help reduce the pressure on natural ecosystems and biodiversity.

4.3.2.2 Forests and Other Ecosystems

Ecosystem restoration. Biomass stocks in tropical, subtropical, temperate and boreal biomes currently hold 1085, 194, 176, 190 Gt CO_2, respectively. Conservation and restoration can enhance these natural carbon sinks (Erb et al., 2017).

Recent studies explore options for conservation, restoration and improved land management estimating up to 23 $GtCO_2$ (Griscom et al., 2017). Mitigation potentials are dominated by reduced rates of deforestation, reforestation and forest management, and concentrated in tropical regions (Houghton, 2013; Canadell and Schulze, 2014; Grace et al., 2014; Houghton et al., 2015; Griscom et al., 2017). Much of the literature focuses on REDD+ (Reducing Emissions from Deforestation and Degradation) as an institutional mechanism. However, restoration and management activities need not be limited to REDD+ and locally adapted implementation may keep costs low, capitalise on co-benefits and ensure consideration of competing for socio-economic goals (Jantke et al., 2016; Ellison et al., 2017; Perugini et al., 2017; Spencer et al., 2017).

Half of the estimated potential can be achieved at <100 USD/tCO_2; a third of the cost-effective potential <10 USD/tCO_2 (Griscom et al., 2017). Variation of costs in projects aiming to reduce emissions from deforestation is high when considering opportunity and transaction costs (Dang Phan et al., 2014; Overmars et al., 2014; Ickowitz et al., 2017; Rakatama et al., 2017).

However, the focus on forests raises concerns of cross-biome leakage *(medium evidence, low agreement)* (Popp et al., 2014a; Strassburg et al., 2014; Jayachandran et al., 2017) and encroachment on other ecosystems (Veldman et al., 2015). Reducing rates of deforestation limits the land available for agriculture and grazing with trade-offs between diets, higher yields and food prices (Erb et al., 2016a; Kreidenweis et al., 2016). Restoration and conservation are compatible with biodiversity (Rey Benayas et al., 2009; Jantke et al., 2016) and water resources; in the tropics, reducing rates of deforestation maintains cooler surface temperatures (Perugini et al., 2017) and rainfall (Ellison et al., 2017).

Its multiple potential co-benefits have made REDD+ important for local communities, biodiversity and sustainable landscapes (Ngendakumana et al., 2017; Turnhout et al., 2017). There is *low agreement* on whether climate impacts will reverse mitigation benefits of restoration (Le Page et al., 2013) by increasing the likelihood of disturbance (Anderegg 2015), or reinforce them through carbon fertilisation (P. Smith et al., 2014).

Emerging regional assessments offer new perspectives for upscaling. Strengthening coordination, additional funding sources, and access and disbursement points increase the potential of REDD+ in working towards 2°C and 1.5°C targets (Well and Carrapatoso, 2017). While there are indications that land tenure (Sunderlin et al., 2014) has a positive impact, a meta-analysis by (Wehkamp et al., 2018a) shows that there is *medium evidence* and *low agreement* on which aspects of governance improvements are supportive of conservation. Local benefits, especially for indigenous communities, will only be accrued if land tenure is respected and legally protected, which is not often the case (Sunderlin et al., 2014; Brugnach et al., 2017). Although payments for reduced rates of deforestation may benefit the poor, the most vulnerable populations could have limited, uneven access (Atela et al., 2014) and face lower opportunity costs from deforestation (Ickowitz et al., 2017).

Community-based Adaptation (CbA). There is *medium evidence* and *high agreement* for the use of CbA. The specific actions to take will depend upon the location, context, and vulnerability of the specific community. CbA is defined as ‘a community-led process, based on communities' priorities, needs, knowledge, and capacities, which aim to empower people to plan for and cope with the impacts of climate change’ (Reid et al., 2009). The integration of CbA with Ecosystems-based Adaptation (EbA) has been increasingly promoted, especially in efforts to alleviate poverty (Mannke, 2011; Reid, 2016).

Despite the potential and advantages of both CbA and EbA, including knowledge exchange, information access and increased social capital and equity; institutional and governance barriers still constitute a challenge for local adaptation efforts (Wright et al., 2014; Fernández-Giménez et al., 2015).

Wetland management. In wetland ecosystems, temperature rise has direct and irreversible impacts on species functioning and distribution, ecosystem equilibrium and services, and second order impacts on local livelihoods (see Section 3.4.3). The structure and function of wetland systems are changing due to climate change. Wetland management strategies, including adjustments in infrastructural, behavioural, and institutional practices have clear implications for adaptation (Colloff et al., 2016b; Finlayson et al., 2017; Wigand et al., 2017)

Despite international initiatives on wetland restoration and management through the Ramsar Convention on Wetlands, policies have not been effective (Finlayson, 2012; Finlayson et al., 2017). Institutional reform such as flexible, locally relevant governance, drawing on principles of adaptive co-management, and multi-stakeholder participation becomes increasingly necessary for effective wetland management (Capon et al., 2013; Finlayson et al., 2017).

4.3.2.3 Coastal Systems

Managing coastal stress. Particularly to allow for the landward relocation of coastal ecosystems under a transition to 1.5°C, planning for climate change would need to be integrated with the use of coastlines by humans (Saunders et al., 2014; Kelleway et al., 2017). Adaptation options for managing coastal stress include coastal hardening through the building of seawalls and the re-establishment of coastal ecosystems such as mangroves (André et al., 2016; Cooper et al., 2016). While the feasibility of the solutions is high, they are expensive to scale (*robust evidence, medium agreement*).

There is *low evidence* and *high agreement* that reducing the impact of local stresses (Halpern et al., 2015) will improve the resilience of marine ecosystems as they transition to a 1.5°C world (O'Leary et al., 2017). Approaches to reducing local stresses are considered feasible, cost-effective and highly scalable. Ecosystem resilience may be increased through alternative livelihoods (e.g., sustainable aquaculture), which are among a suite of options for building resilience in coastal ecosystems. These options enjoy high levels of feasibility yet are expensive, which stands in the way of scalability (*robust evidence, medium agreement*) (Hiwasaki et al., 2015; Brugnach et al., 2017).

Working with coastal communities has the potential for improving the resilience of coastal ecosystems. Combined with the advantages of using Indigenous knowledge to guide transitions, solutions can be more effective when undertaken in partnership local communities, cultures, and knowledge (See Box 4.3).

Restoration of coastal ecosystems and fisheries. Marine restoration is expensive compared to terrestrial restoration, and the survival of projects is currently low, with success depending on the ecosystem and site, rather than the size of the financial investment (Bayraktarov et al., 2016). Mangrove replanting shows evidence of success globally, with numerous examples of projects that have established forests (Kimball et al., 2015; Bayraktarov et al., 2016).

Efforts with reef-building corals have been attempted with a low level of success (Bayraktarov et al., 2016). Technologies to help re-establish coral communities are limited (Rinkevich, 2014), as are largely untested disruptive technologies (e.g., genetic manipulation, assisted evolution) (van Oppen et al., 2015). Current technologies also have trouble scaling given the substantial costs and investment required (Bayraktarov et al., 2016).

(Johannessen and Macdonald, 2016) report the 'blue carbon' sink to be 0.4–0.8% of global anthropogenic emissions. However, this does not adequately account for post-depositional processes and could overestimate removal potentials, subject to a risk of reversal. Seagrass beds will thus not contribute significantly to enabling 1.5°C-consistent pathways.

4.3.3 Urban and Infrastructure System Transitions

There will be approximately 70 million additional urban residents every year through to the mid part of this century (UN, 2014). The majority of these new urban citizens will reside in small and medium sized cities in low- and middle-income countries (Cross-Chapter Box13 in Chapter 5). The combination of urbanisation and economic and infrastructure development could account for an additional 226 $GtCO_2$ by 2050 (Bai et al. 2018). However, urban systems can harness the mega-trends of urbanisation, digitalisation, financialisation and growing sub-national commitment to smart cities, green cities, resilient cities, sustainable cities and adaptive cities, for the type of transformative change required by 1.5°C-consistent pathways (Revi and Rosenzweig, 2013; Parag and Sovacool, 2016; Roberts, 2016; Wachsmuth et al., 2016; Revi, 2017; Solecki et al., 2018). There is a growing number of urban climate responses driven by cost-effectiveness, development, work creation and inclusivity considerations (Floater et al., 2014; Revi et al., 2014a; Villarroel Walker et al., 2014; Kennedy et al., 2015; Rodríguez, 2015; Newman et al., 2017; UN-Habitat, 2017; Westphal et al., 2017) (Solecki et al. 2013; Ahern et al. 2014; McGranahan et al. 2016; Dodman et al. 2017a).

In addition, low-carbon cities could reduce the need to deploy Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM) (Fink, 2013; Thomson and Newman, 2016).

Cities are also places in which the risks associated with warming of 1.5°C, such as heat stress, terrestrial and coastal flooding, new disease vectors, air pollution and water scarcity, will coalesce (see Section 3.3) (Dodman et al., 2017a; Satterthwaite and Bartlett, 2017). Unless adaptation and mitigation efforts are designed around the need to decarbonise urban societies in the developed world and provide low-carbon solutions to the needs of growing urban populations in developing countries, they will struggle to deliver the pace or scale of change required by 1.5°C-consistent pathways (Hallegatte et al., 2013; Villarroel Walker et al., 2014; Roberts, 2016; Solecki et al., 2018). The pace and scale of urban climate responses can be enhanced by attention to social equity (including gender equity), urban ecology (Brown and McGranahan, 2016; Wachsmuth et al., 2016; Ziervogel et al., 2016a) and participation in sub-national networks for climate action (Cole, 2015; Jordan et al., 2015).

The long-lived urban transport, water and energy systems that will be constructed in the next three decades to support urban populations in developing countries and to retrofit cities in developed countries will have to be different to that built in Europe and North America in the 20th century, if they are to support the required transitions (Freire et al., 2014; Cartwright, 2015; McPhearson et al., 2016; Roberts, 2016; Lwasa, 2017). Recent literature identifies energy, infrastructure, appliances, urban planning, transport and adaptation options as capable of facilitating systemic change. It is these aspects of the urban system that are discussed below and from which options in Section 4.5 are selected.

4.3.3.1 Urban Energy Systems

Urban economies tend to be more energy intensive than national economies due to higher levels of *per capita* income, mobility and consumption (Kennedy et al., 2015; Broto, 2017; Gota et al., 2018). However, some urban systems have begun decoupling development from the consumption of fossil fuel powered energy through energy efficiency, renewable energy and locally managed smart-grids (Dodman, 2009; Freire et al., 2014; Eyre et al., 2018; Glazebrook and Newman, 2018a).

The rapidly expanding cities of Africa and Asia, where energy poverty currently undermines adaptive capacity (Westphal et al., 2017; Satterthwaite et al., 2018), have the opportunity to benefit from recent price changes in renewable energy technologies to enable clean energy access to citizens (SDG 7) (Cartwright, 2015; Watkins, 2015; Lwasa, 2017; Kennedy et al., 2018; Teferi and Newman, 2018). This will require strengthened energy governance in these countries (Eberhard et al., 2017). Where renewable energy displaces paraffin, wood fuel or charcoal feedstocks in informal urban settlements, it provides the co-benefits of improved indoor air quality, reduced fire-risk and reduced deforestation, all of which can enhance adaptive capacity and strengthen demand for this energy (Newham and Conradie, 2013; Winkler, 2017; Kennedy et al., 2018; Teferi and Newman, 2018).

4.3.3.2 Urban Infrastructure, Buildings and Appliances

Buildings are responsible for 32% of global energy consumption (IEA, 2016c) and have a large energy saving potential with available and demonstrated technologies such as energy efficiency improvements in technical installations and in thermal insulation (Toleikyte et al., 2018) and energy sufficiency (Thomas et al., 2017). (Kuramochi et al., 2017) show that 1.5°C-consistent pathways require building emissions to be reduced by 80–90% by 2050, new construction to be fossil-free and near-zero energy by 2020, and an increased rate of energy refurbishment of existing buildings to 5% per annum in OECD (Organisation for Economic Co-operation and Development) countries (see also Section 4.2.1).

Chapter 2 based on the IEA-ETP (IEA, 2017g) identifies large saving potential in heating and cooling through improved building design, efficient equipment, lighting and appliances. Several examples of net zero energy in buildings are now available (Wells et al., 2018). In existing buildings, refurbishment enables energy saving (Semprini et al., 2017; Brambilla et al., 2018; D'Agostino and Parker, 2018; Sun et al., 2018) and cost savings (Toleikyte et al., 2018; Zangheri et al., 2018).

Reducing the embodied energy in buildings material provides further energy and GHG savings (Cabeza et al., 2013; Oliver and Morecroft, 2014; Koezjakov et al., 2018), in particular through bio-based materials (Lupíšek et al., 2015) and wood construction (Ramage et al., 2017). The United Nations Environment Programme (UNEP[3]) estimates that improving embodied energy, thermal performance, and direct energy use of buildings can reduce emissions by 1.9 $GtCO_2e\ yr^{-1}$(UNEP, 2017b), with an additional reduction of 3 $GtCO_2e\ yr^{-1}$ through energy efficient appliances and lighting (UNEP, 2017b). Further increasing the energy efficiency of appliances and lighting, heating and cooling offers the potential for further savings (Parikh and Parikh, 2016; Garg et al., 2017).

Smart technology, drawing on the Internet of Things (IoT) and building information modelling, offer opportunities to accelerate energy efficiency in buildings and cities (Moreno-Cruz and Keith, 2013; Hoy, 2016) (see also Section 4.4.4). Some developing country cities are drawing on these technologies to adopt 'leapfrog' infrastructure, buildings and appliances to pursue low-carbon development (Newman et al., 2017; Teferi and Newman, 2017) (Cross-Chapter Box 13 in Chapter 5).

4.3.3.3 Urban Transport and Urban Planning

Urban form impacts demand for energy (Sims et al., 2014) and other welfare related factors: a meta-analysis of 300 papers reported energy savings of 26 USD per person per year attributable to a 10% increase in urban population density (Ahlfeldt and Pietrostefani, 2017). Significant reductions in car use are associated with dense, pedestrianised cities and towns and medium-density transit corridors (Newman and Kenworthy, 2015; Newman et al., 2017) relative to low-density cities in which car dependency is high (Kenworthy and Schiller, 2018). Combined dense urban forms and new mass transit systems in Shanghai and Beijing have yielded less car use (Gao and Newman, 2018) (see Box 4.9). Compact cities also create the passenger density required to make public transport more financially viable (Ahlfeldt and Pietrostefani, 2017; Rode et al., 2017) and enable combinations of cleaner fuel feed stocks and urban smart-grids, in which vehicles form part of the storage capacity (Oldenbroek et al., 2017). Similarly, the spatial organisation of urban energy influenced the trajectories of urban development in cities as diverse as Hong Kong, Bengaluru and Maputo (Broto, 2017).

The informal settlements of middle- and low-income cities where urban density is more typically associated with a range of water- and vector-borne health risks, may provide a notable exception to the adaptive advantages of urban density (Mitlin and Satterthwaite, 2013; Lilford et al., 2017) unless new approaches and technologies are harnessed to accelerate slum upgrading (Teferi and Newman, 2017)

Scenarios consistent with 1.5°C pathways, depend on an almost 40% reduction in final energy use by the transport sector by 2050 (Chapter 2, Figure 2.12). In one analysis the phasing out of fossil fuel passenger vehicle sales by 2035-2050 was identified as a benchmark for aligning with 1.5°C-consistent pathways (Kuramochi et al., 2017). Reducing emissions from transport has lagged the power sector (Sims et al., 2014; Creutzig et al., 2015a) but evidence since AR5 suggests that cities are urbanising and re-urbanising in ways that co-ordinate transport sector adaptation and mitigation (Colenbrander et al., 2017; Newman et al., 2017; Salvo et al., 2017; Gota et al., 2018). The global transport sector could reduce 4.7$GtCO2e\ yr^{-1}$ (4.1–5.3) by 2030. This is significantly more than is predicted by Integrated Assessment Models (IAMs; UNEP, 2017b). Such a transition depends on cities that enable modal shifts, avoided journeys, provide incentives for uptake of improved fuel efficiency and changes in urban design that encourage walkable cities, non-motorised transport and shorter commuter distances (IEA, 2016a; Mittal et al., 2016; Zhang et al., 2016; Li and Loo, 2017). In at least four African cities, 43 Asian cities and 54 Latin American cities, Transit Oriented Development (TOD), has emerged as an organising principle for urban growth and spatial planning (Colenbrander et al., 2017; Lwasa, 2017; BRT Data, 2018). This trend is important to counter the rising

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[3] FOOTNOTE: Currently called UN Environment.

demand for private cars in developing country cities (OECD, 2016b). In India TOD has been combined with localized solar PV installations and new ways of financing rail expansion (Sharma, 2018).

Cities pursuing sustainable transport benefit from reduced air pollution, congestion and road fatalities and are able to harness the relationship between transport systems, urban form, urban energy intensity and social cohesion (Goodwin and Van Dender, 2013; Newman and Kenworthy, 2015; Wee, 2015)

Technology and electrification trends since AR5 make carbon efficient urban transport easier (Newman et al., 2016), but realising urban transport's contribution to a 1.5°C-consistent pathways will require the type of governance that can overcome the financial, institutional, behavioural and legal barriers to change (Geels, 2014; Bakker et al., 2017).

Adaptation to a 1.5°C world is enabled by urban design and spatial planning policies that consider extreme weather conditions and reduce displacement by climate related disasters (UNISDR, 2009; UN-Habitat, 2011; Mitlin and Satterthwaite, 2013).

Building codes and technology standards for public lighting, including traffic lights (Beccali et al., 2015), play a critical role in reducing carbon emissions, enhancing urban climate resilience and managing climate risk (Steenhof and Sparling, 2011; Parnell, 2015; Shapiro, 2016; Evans et al., 2017). Building codes can support the convergence to zero emissions from buildings (Wells et al., 2018), and can be used retrofit the existing building stock for energy efficiency (Ruparathna et al., 2016).

The application of building codes and standards for 1.5°C-consistent pathways will require improved enforcement, which can be a challenge in developing countries where inspection resources are often limited and codes are poorly tailored to local conditions (Ford et al., 2015c; Chandel et al., 2016; Eisenberg, 2016; Shapiro, 2016; Hess and Kelman, 2017; Mavhura et al., 2017). In all countries, building codes can be undermined by industry interests, and can be maladaptive if they prevent buildings or land use from evolving to reduce climate impacts (Eisenberg, 2016; Shapiro, 2016).

The deficit in building codes and standards in middle-income and developing country cities need not be a constraint to more energy-efficient and resilient buildings (Tait and Euston-Brown, 2017). For example, the relatively high price that poor households pay for unreliable and at times dangerous household energy in African cities has driven the uptake of renewable energy and energy efficiency technologies in the absence of regulations or fiscal incentives (Eberhard et al., 2011, 2016; Cartwright, 2015; Watkins, 2015). The Kuyasa Housing Project in Khayelitsha, one of Cape Town's poorest suburbs, created significant mitigation and adaptation benefits by installing ceilings, solar water heaters and energy efficient lightbulbs in houses independent of the formal housing or electrification programme (Winkler, 2017).

4.3.3.4 Electrification of Cities and Transport

The electrification of urban systems, including transport, has shown global progress since AR5 (IEA, 2016a; Kennedy et al., 2018; Kenworthy and Schiller, 2018). High growth rates are now appearing in electric vehicles (Figure 4.1), electric bikes and electric transit (IEA, 2018), which would need to displace fossil-fuel powered passenger vehicles by 2035–2050 to remain in line with 1.5°C-consistent pathways. China's 2017 Road Map calls for 20% of new vehicle sales to be electric. India is aiming for exclusively electric vehicles (EVs) by 2032 (NITI Aayog and RMI, 2017). Globally, EV sales were up 42% in 2016 relative to 2015, and in the United States EV sales were up 36% over the same period (Johnson and Walker, 2016).

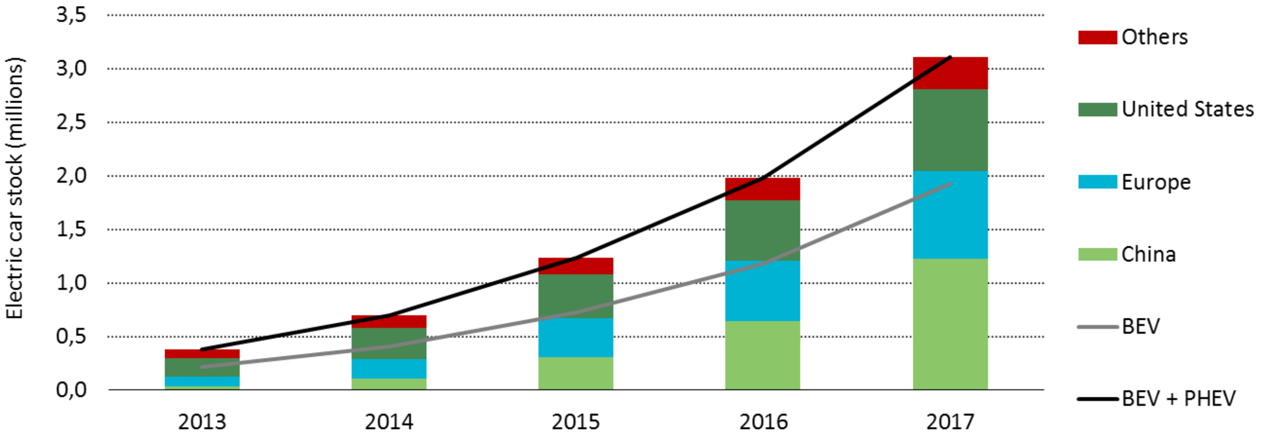

Figure 4.1: **Increase of the global electric car stock by country (2013–2017).** Source: (IEA, 2018). Based on IEA data from Global EV Outlook 2018 © OECD/IEA 2018, IEA Publishing.

The extent of electric railways in and between cities has expanded since AR5 (IEA, 2016a; Mittal et al., 2016; Zhang et al., 2016; Li and Loo, 2017). In high income cities there is *medium evidence* for the decoupling of car use and wealth since AR5 (Newman, 2017). In cities where private vehicle ownership is expected to increase, less carbon-intensive fuel sources and reduced car journeys will be necessary as well as electrification of all modes of transport (Mittal et al., 2016; van Vuuren et al., 2017). Some recent urban data show a decoupling of urban growth and GHG emissions (Newman and Kenworthy, 2015) and that 'peak car' has been reached in Shanghai and Beijing (Gao and Kenworthy, 2017) and beyond (Manville et al., 2017) (also see Box 4.9).

An estimated 800 cities globally have operational bike-share schemes (E. Fishman et al., 2015) and China had 250 million e-bikes in 2017 (Newman et al., 2017). Advances in Information and Communication Technologies (ICT) offer cities the chance to reduce urban transport congestion and fuel consumption by making better use of the urban vehicle fleet through car sharing, driverless cars and coordinated public transport, especially when electrified (Wee, 2015; Glazebrook and Newman, 2018b). Advances in 'big-data' can assist in creating a better understanding of the connections between cities, green infrastructure, environmental services and health (Jennings et al., 2016) and improve decision-making in urban development (Lin et al., 2017).

4.3.3.5 Shipping, Freight and Aviation

International transport hubs, including airports and ports and the associated mobility of people, are major economic contributors to most large cities even while under the governance of national authorities and international legislation. Shipping, freight and aviation systems have grown rapidly and little progress has been made since AR5 on replacing fossil fuels, though some trials are continuing (Zhang, 2016; Bouman et al., 2017; EEA, 2017). Aviation emissions do not yet feature in IAMs (Bows-Larkin, 2015), but could be reduced by between a third and two-thirds through energy efficiency measures and operational changes (Dahlmann et al., 2016). On shorter inter-city trips, aviation could be replaced by high-speed electric trains drawing on renewable energy (Åkerman, 2011). Some progress has been made on the use of electricity in planes and shipping (Grewe et al., 2017) though no commercial applications have arisen. Studies indicate that biofuels are the most viable means of decarbonising intercontinental travel, given their technical characteristics, energy content and affordability (Wise et al., 2017). The lifecycle emissions of bio-based jet fuels and marine fuels can be considerable (Cox et al., 2014; IEA, 2017g) depending on their location (Elshout et al., 2014), but can be reduced by feedstock and conversion technology choices (de Jong et al., 2017).

In recent years the potential for transport to use synfuels, such as ethanol, methanol, methane, ammonia and hydrogen, created from renewable electricity and CO_2, has gained momentum but has not yet demonstrated benefits on a scale consistent with 1.5ºC pathways (Ezeji, 2017; Fasihi et al., 2017). Decarbonising the fuel used by the world's 60,000 large vessels faces governance barriers and the need for a global policy (Bows and Smith, 2012; IRENA, 2015; Rehmatulla and Smith, 2015). Low-emission marine fuels could simultaneously address sulphur and black carbon issues in ports and around waterways and accelerate the electrification of all large ports (Bouman et al., 2017; IEA, 2017g).

4.3.3.6 Climate-Resilient Land Use

Urban land use influences energy intensity, risk exposure and adaptive capacity (Carter et al., 2015; Araos et al., 2016a; Ewing et al., 2016; Newman et al., 2016; Broto, 2017). Accordingly, urban land-use planning can contribute to climate mitigation and adaptation (Parnell, 2015; Francesch-Huidobro et al., 2017) and the growing number of urban climate adaptation plans provide instruments for planning (Carter et al., 2015; Dhar and Khirfan, 2017; Siders, 2017; Stults and Woodruff, 2017). Adaptation plans can reduce exposure to urban flood risk that, in a 1.5°C world, could double relative to 1976–2005 (Alfieri et al., 2017), reduce heat stress (Section 3.5.5.8), fire risk (Section 3.4.3.4) and sea-level rise (Section 3.4.5.1) (Schleussner et al., 2016).

Cities can reduce their risk exposure by considering investment in infrastructure and buildings that are more resilient to warming of 1.5°C or beyond. Where adaptation planning and urban planning generate the type of local participation that enhances capacity to cope with risks, they can be mutually supportive processes (Archer et al., 2014; Kettle et al., 2014; Campos et al., 2016; Chu et al., 2017; Siders, 2017; Underwood et al., 2017). Not all adaptation plans are reported as effective (Measham et al., 2011; Hetz, 2016; Woodruff and Stults, 2016; Mahlkow and Donner, 2017), especially in developing country cities (Kiunsi, 2013). Where adaptation planning further marginalises poor citizens through limited local control over establishing adaptation priorities, or the displacement of impacts onto poorer communities, justice, equity, and broad participation would need to be considered in the dimensions of successful urban risk reduction, and recognition of the political economy of adaptation (Archer, 2016; Shi et al., 2016; Ziervogel et al., 2016a, 2017; Chu et al., 2017).

4.3.3.7 Green Urban Infrastructure and Ecosystem Services

Integrating and promoting green urban infrastructure (including street trees, parks, green roofs and facades, water features) into city planning can be difficult (Leck et al., 2015) and increases urban resilience to impacts of 1.5°C warming (Table 4.2) in ways that can be more cost effective than conventional infrastructure (Culwick and Bobbins (2016) (Cartwright et al., 2013).

Table 4.2: Green urban infrastructure and benefits.

Green infrastructure	**Adaptation benefits**	**Mitigation benefits**	**References**
Urban trees planting, urban parks	Reduced heat island effect, psychological benefits	Less cement, reduced air-conditioning	(Demuzere et al., 2014; Mullaney et al., 2015; Soderlund and Newman, 2015; Beaudoin and Gosselin, 2016; Green et al., 2016; Lin et al., 2017)
Permeable surfaces	Water recharge	Less cement in city, some bio-sequestration, less water pumping	(Liu et al., 2014; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017)
Forest retention, and urban agricultural land	Flood mediation, healthy lifestyles	Air pollution reduction	(Nowak et al., 2006; Tallis et al., 2011; Elmqvist et al., 2013; Buckeridge, 2015; Culwick and Bobbins, 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; White et al., 2017)
Wetland restoration,	Reduced urban flooding, Low	Some bio-sequestration, Less	(Cartwright et al., 2013; Elmqvist et al., 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016;

riparian buffer zones	skilled local work, Sense of place	energy spent on water treatment	Culwick and Bobbins, 2016; McPhearson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; F. Li et al., 2017)
Biodiverse urban habitat	Psychological benefits, inner-city recreation	Carbon sequestration	(Beatley, 2011; Elmqvist et al., 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; McPhearson et al., 2016; Collas et al., 2017; F. Li et al., 2017)

Realising climate benefits from urban green infrastructure sometimes requires a city-region perspective (Wachsmuth et al., 2016). Where the urban impact on ecological systems in and beyond the city is appreciated, the potential for transformative change exists (Soderlund and Newman, 2015; Ziervogel et al., 2016a), and a locally appropriate combination of green space, ecosystem goods and services and the built environment can increase the set of urban adaptation options (Puppim de Oliveira et al., 2013).

Milan, Italy, a city with deliberate urban greening policies, planted 10,000 hectares of new forest and green areas over the last two decades (Sanesi et al., 2017). The accelerated growth of urban trees, relative to rural trees, in several regions of the world is expected to decrease tree longevity (Pretzsch et al., 2017), requiring monitoring and additional management of urban trees if their contribution to urban ecosystem based adaptation and mitigation is to be maintained in a 1.5°C world (Buckeridge, 2015; Pretzsch et al., 2017).

4.3.3.8 Sustainable Urban Water and Environmental Services

Urban water supply and wastewater treatment is energy intensive, and currently accounts for significant GHG emissions (Nair et al., 2014). Cities can integrate sustainable water resource management and the supply of water services in ways that support mitigation, adaptation and development through waste-water recycling and storm water diversion (Xue et al., 2015; Poff et al., 2016). Governance and finance challenges complicate balancing sustainable water supply and rising urban demand, particularly in low-income cities (Bettini et al., 2015; Deng and Zhao, 2015; Hill Clarvis and Engle, 2015; Lemos, 2015; Margerum and Robinson, 2015).

Urban surface sealing with impervious materials affects the volume and velocity of run-off and flooding during intense rainfall (Skougaard Kaspersen et al., 2015), but urban design in many cities now seeks to mediate run-off, encourage groundwater recharge and enhance water quality (Liu et al., 2014; Lamond et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017). Challenges remain for managing intense rainfall events that are reported to be increasing in frequency and intensity in some locations (Ziervogel et al., 2016b) and urban flooding is expected to increase at 1.5°C warming (Alfieri et al., 2017). This risk falls disproportionately on women and poor people in cities (Mitlin, 2005; Chu et al., 2016; Ziervogel et al., 2016b; Chant et al., 2017; Dodman et al., 2017a, b).

Nexus approaches that highlight urban areas as socio-ecological systems, can support policy coherence (Rasul and Sharma, 2016) and sustainable urban livelihoods (Biggs et al., 2015). The Water-Energy-Food (WEF) nexus is especially important to growing urban populations (Tacoli et al., 2013; Lwasa et al., 2014; Villarroel Walker et al., 2014).

4.3.4 Industrial Systems Transitions

Industry consumes about one third of global final energy and contributes, directly and indirectly, about one third of global GHG emissions (IPCC, 2014b). If global temperatures are to remain under 1.5°C, modelling indicates that industry cannot emit more than 2 $GtCO_2$ in 2050, corresponding > 70% GHG emission reduction compared to 2010 (see Figures 2.20 and 2.21). Moreover, the consequences of climate change of 1.5°C or more pose substantial challenges for industrial diversity. This section will first briefly discuss the limited literature on adaptation options for industry. Subsequently, new literature since AR5 on the feasibility of industrial mitigation options will be discussed.

Research assessing adaptation actions by industry indicates that only a small fraction of corporations have developed adaptation measures. Studies of adaptation in the private sector remain limited (Agrawala et al., 2011; Linnenluecke et al., 2015; Averchenkova et al., 2016; Bremer and Linnenluecke, 2016; Pauw et al., 2016a) and for 1.5ºC are largely absent. This knowledge gap is particularly evident for medium-sized enterprises and in low- and middle-income nations (Surminski, 2013).

Depending on the industrial sector, mitigation consistent with 1.5ºC would mean, across industries, a reduction of final energy demand by one-third, an increase of the rate of recycling of materials and the development of a circular economy in industry (Lewandowski, 2016; Linder and Williander, 2017), the substitution of materials in high-carbon products with those made up of renewable materials (e.g., wood instead of steel or cement in the construction sector, natural textile fibres instead of plastics), and a range of deep emission reduction options, including use of bio-based feedstocks, low-emission heat sources, electrification of production processes, and/or capture and storage of all CO_2 emissions by 2050 (Åhman et al., 2016). Some of the choices for mitigation options and routes for GHG-intensive industry are discrete and potentially subject to path dependency: if an industry goes one way (e.g., in keeping existing processes), it will be harder to transition to process change (e.g., electrification) (Bataille et al., 2018). In the context of rising demand for construction, an increasing share of industrial production may be based in developing countries (N. Li et al., 2017), where current efficiencies may be lower than in developed countries, and technical and institutional feasibility may differ (Ma et al., 2015).

Except for energy efficiency, costs of disruptive change associated with hydrogen- or electricity-based production, bio-based feedstocks and Carbon Dioxide Capture, (Utilisation) and Storage (CC(U)S) for trade-sensitive industrial sectors (in particular the iron and steel, petrochemical and refining industries) make policy action by individual countries challenging because of competitiveness concerns (Åhman et al., 2016; Nabernegg et al., 2017).

Table 4.3 provides an overview of applicable mitigation options for key industrial sectors.

Table 4.3: Overview of different mitigation options potentially consistent with 1.5ºC and applicable to main industrial sectors, including examples of application (Napp et al., 2014; Boulamanti and Moya, 2017; Wesseling et al., 2017).

	Iron/steel	Cement	Refineries and petrochemicals	Chemicals
Process and energy efficiency	Can make a difference on of between 10% and 50%, depending on the plant. Relevant but not enough for 1.5ºC			
Bio-based	Coke can be made from biomass instead of coal	Partial (only energy-related emissions)	Biomass can replace fossil feedstocks	
Circularity & substitution	More recycling and replacement by low-emission materials, including alternative chemistries for cement		Limited potential	
Electrification & hydrogen	Direct reduction with hydrogen. Heat generation through electricity	Partial (only electrified heat generation)	Electrified heat and hydrogen generation	
CCS	Possible for process emissions and energy. Reduces emissions by 80-95%, and become negative when combined with biofuel		Can be applied to energy emissions and different stacks but not on emissions of products in the use phase (e.g., gasoline)	

4.3.4.1 Energy Efficiency

Isolated efficiency implementation in energy-intensive industries is a necessary but insufficient condition for deep emission reductions (Napp et al., 2014; Aden, 2017). Various options specific to different industries are available. In general, their feasibility depends on lowering capital costs and raising awareness and expertise (Wesseling et al., 2017). General purpose technologies, such as ICT, and energy management tools can improve the prospects of energy efficiency in industry (see Section 4.4.4).

Cross-sector technologies and practices, which play a role in all industrial sectors including Small- and Medium-sized Enterprises (SMEs) and non-energy intensive industry, also offer potential for considerable energy efficiency improvements. They include motor systems (for example electric motors, variable speed drives, pumps, compressors and fans), responsible for about 10% of industrial energy consumption with an energy efficiency improvement potential of around 20–25%, worldwide (Napp et al., 2014); steam systems, responsible for about 30% of industrial energy consumption and energy saving potentials of about 10% (Hasanbeigi et al., 2014; Napp et al., 2014). Waste heat recovery from industry has substantial potential for energy efficiency and emission reduction (Forman et al., 2016). Low awareness and competition from other investments limit the feasibility of such options (Napp et al., 2014).

4.3.4.2 Substitution and Circularity

Recycling materials and developing a circular economy can be institutionally challenging as it requires advanced capabilities (Henry et al., 2006) and organisational changes (Cooper- Searle et al., 2018), but has advantages in terms of cost, health, governance and environment (Ali et al., 2017). An assessment of the impacts on energy use and environmental issues is not available, but substitution could play a large role in reducing emissions (Åhman et al., 2016) although its potential depends on the demand for material, and the turnover of for example in buildings (Haas et al., 2015). Material substitution and CO_2 storage options are under development, for example, the use of algae and renewable energy for carbon fibre production, which could become a net sink of CO_2 (Arnold et al., 2018).

4.3.4.3 Bio-Based Feedstocks

Bio-based feedstock processes could be partly seen as part of the circular materials economy (see Section above). In several sectors, bio-based feedstocks would leave the production process of materials relatively untouched, and a switch would not affect the product quality, making the option more attractive. However, energy requirements for processing bio-based feedstocks are often high, costs are also still higher, and the emissions over the full lifecycle, both upstream and downstream, could be significant (Wesseling et al., 2017). Bio-based feedstocks may put pressure on natural resources by increasing land demand, biodiversity impacts beyond bioenergy demand for electricity, transport and buildings (Slade et al., 2014), and, partly as a result, face barriers in public acceptance (Sleenhoff et al., 2015).

4.3.4.4 Electrification and Hydrogen

Electrification of manufacturing processes would constitute a significant technological challenge and a more disruptive innovation in industry than bio-based or CCS options, to get to very low or zero emissions, except potentially in steel-making (Philibert, 2017). The disruptive characteristics could potentially lead to stranded assets, and could reduce political feasibility and industry support (Åhman et al., 2016). Electrification of manufacturing would require further technological development in industry, as well as an ample supply of cost-effective low-emission electricity (Philibert, 2017).

Low-emission hydrogen can be produced either by natural gas with CCS, by electrolysis of water powered by zero-emission electricity, or potentially in the future by generation IV nuclear reactors. Feasibility of electrification and use of hydrogen in production processes or fuel cells is affected by technical development in terms of efficient hydrogen production and electrification of processes, by geophysical factors related to the availability of low-emission electricity (MacKay, 2013), by associated public perception and by economic feasibility, except in areas with ample solar and/or wind resources (Philibert, 2017; Wesseling et al., 2017).

4.3.4.5 CO_2 Capture, Utilisation and Storage in Industry

CO_2 capture in industry is generally considered more feasible than CCS in the power sector (Section 4.3.1) or from bioenergy sources (Section 4.3.7), although CCS in industry faces similar barriers. Almost all of the current full-scale (>1MtCO_2 yr^{-1}) CCS projects capture CO_2 from industrial sources, including the Sleipner project in Norway, which has been injecting CO_2 from a gas facility in an offshore saline formation since 1996 (Global CCS Institute, 2017). Compared to the power sector, retrofitting CCS on existing industrial plants would leave the production process of materials relatively untouched (Åhman et al., 2016), though significant investments and modifications still have to be made. Some industries, in particular cement, emit CO_2 as inherent process emissions and can therefore not reduce emissions to zero without CC(U)S. CO_2 stacks in some industries have a high economic and technical feasibility for CO_2 capture as the CO_2 concentration in the exhaust gases is relatively high (IPCC, 2005; Leeson et al., 2017), but others require strong modifications in the production process, limiting technical and economic feasibility, though costs remain lower than other deep GHG reduction options (Rubin et al., 2015). There are indications that the energy use in CO_2 capture through amine solvents (for solvent regeneration) can decrease by around 60%, from 5 GJ tCO_2^{-1} in 2005 to 2 GJ tCO_2^{-1} in the best-performing pilot plants (Idem et al., 2015), increasing both technical and economic potential for this option. The heterogeneity of industrial production processes might point to the need for specific institutional arrangements to incentivise industrial CCS (Mikunda et al., 2014), and may decrease institutional feasibility.

The contribution of Carbon Dioxide Utilisation (CCU) to limiting warming to 1.5°C depends on the origin of CO_2 (fossil, biogenic or atmospheric), the source of electricity for converting the CO_2 or regenerating catalysts, and the lifetime of the product. Review studies indicate that carbon dioxide utilisation in industry has a small role to play in limiting warming to 1.5°C because of the limited potential of re-using CO_2 with currently available technologies and the re-emission of CO_2 when used as a fuel (IPCC, 2005; Mac Dowell et al., 2017). However, there are new developments, in particular in CO_2 use as a feedstock for carbon-based materials that would isolate CO_2 from the atmosphere for a long time and greater availability of low-cost, low-emission electricity. The conversion of CO_2 to fuels using zero-emission electricity has a lower technical, economic and environmental feasibility than direct CO_2 capture and storage from industry (Abanades et al., 2017), although the economic prospects have improved recently (Philibert, 2017).

4.3.5 Overarching Adaptation Options Supporting Adaptation Transitions

This section assesses overarching adaptation options, which are specific solutions from which actors can choose and make decisions to reduce climate vulnerability and build resilience. We examine their feasibility in the context of transitions of energy, land and ecosystem, urban and infrastructure, and industrial systems here, and further in Section 4.5. These options can contribute to creating an enabling environment for adaptation (see Table 4.4 and Section 4.4).

4.3.5.1 Disaster Risk Management (DRM)

DRM is a process for designing, implementing and evaluating strategies, policies and measures to improve the understanding of disaster risk, and promoting improvement in disaster preparedness, response and recovery (IPCC, 2012). There is increased demand to integrate DRM and adaptation (Howes et al., 2015; Kelman et al., 2015; Serrao-Neumann et al., 2015; Archer, 2016; Rose, 2016; van der Keur et al., 2016; Kelman, 2017; Wallace, 2017) to reduce vulnerability, but institutional, technical and financial capacity challenges in frontline agencies constitute constraints (*medium evidence, high agreement)* (Eakin et al., 2015; Kita, 2017; Wallace, 2017).

4.3.5.2 Risk Sharing and Spreading

Risks associated with 1.5ºC warming (Section 3.4) have the potential to increase the demand for options that share and spread financial burdens. Formal, market-based (re)insurance spreads risk and provides a financial buffer against the impact of climate hazards (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; O'Hare et al., 2016; Glaas et al., 2017; Patel et al., 2017). As an alternative to traditional indemnity-based insurance, index-based micro-crop and livestock insurance programmes have been rolled out in regions with less developed insurance markets (Akter et al., 2016, 2017; Jensen and Barrett, 2017). There is *medium evidence* and *medium agreement* on the feasibility of insurance for adaptation, with financial, social, and institutional barriers to implementation and uptake, especially in low-income nations (García Romero and Molina, 2015; Joyette et al., 2015; Lashley and Warner, 2015; Jin et al., 2016). Social protection programmes include cash and in-kind transfers to protect poor and vulnerable households from the impact of economic shocks, natural disasters and other crises (World Bank, 2017b), and can build generic adaptive capacity and reduce vulnerability when combined with a comprehensive climate risk management approach (*medium evidence, medium agreement*) (Devereux, 2016; Lemos et al., 2016).

4.3.5.3 Education and Learning

Educational adaptation options motivate adaptation through building awareness (Butler et al., 2016; Myers et al., 2017), leveraging multiple knowledge systems (Pearce et al., 2015; Janif et al., 2016), developing participatory action research and social learning processes (Butler and Adamowski, 2015; Ensor and Harvey, 2015; Butler et al., 2016; Thi Hong Phuong et al., 2017; Ford et al., 2018), strengthening extension services, and building learning and knowledge sharing mechanisms through community-based platforms, international conferences and knowledge networks (Vinke-de Kruijf and Pahl-Wostl, 2016) (*medium evidence, high agreement*).

4.3.5.4 Population Health and Health System Adaptation Options

Until mid-century, climate change will exacerbate existing health challenges (Section 3.4.7). Enhancing current health services includes providing access to safe water and improved sanitation, enhancing access to essential services such as vaccination, and developing or strengthening integrated surveillance systems (WHO, 2015). Combining these with iterative management can facilitate effective adaptation (*medium evidence, high agreement).*

4.3.5.5 Indigenous Knowledge

There is *medium evidence* and *high agreement* that Indigenous knowledge is critical for adaptation, underpinning adaptive capacity through the diversity of Indigenous agro-ecological and forest management systems, collective social memory, repository of accumulated experience, and social networks (Hiwasaki et al., 2015; Pearce et al., 2015; Mapfumo et al., 2016; Sherman et al., 2016; Ingty, 2017) (Box 4.3). It is threatened by acculturation, dispossession of land rights and land grabbing, rapid environmental changes, colonisation, and social change, increasing vulnerability to climate change, which climate policy can exacerbate if based on limited understanding of Indigenous worldviews (Thornton and Manasfi, 2010; Ford, 2012; Nakashima et al., 2012; McNamara and Prasad, 2014). Many scholars argue that recognition of Indigenous rights, governance systems and laws is central to adaptation, mitigation and sustainable development (Magni, 2017; Thornton and Comberti, 2017; Pearce, 2018).

4.3.5.6 Human Migration

Human migration, whether planned, forced or voluntary, is increasingly gaining attention as a response, particularly where climatic risks are becoming severe (Section 3.4.10.2). There is *medium evidence* and *low agreement* as to whether migration is adaptive, in relation to cost effectiveness (Grecequet et al., 2017) and scalability (Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017) concerns. Migrating can have mixed outcomes on reducing socio-economic vulnerability (Birk and Rasmussen, 2014;

Kothari, 2014; Adger et al., 2015; Betzold, 2015; Kelman, 2015; Grecequet et al., 2017; Melde et al., 2017; World Bank, 2017a, 2018b) and its feasibility is constrained by low political and legal acceptability, and inadequate institutional capacity (Betzold, 2015; Methmann and Oels, 2015; Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017; Yamamoto et al., 2017).

4.3.5.7 Climate Services

There is *medium evidence* and *high agreement* that climate services can play a critical role in aiding adaptation decision making (Vaughan and Dessai, 2014; Wood et al., 2014; Lourenço et al., 2016; Trenberth et al., 2016; Singh et al., 2017; Vaughan et al., 2018). The higher uptake of short-term climate information such as weather advisories and daily forecasts contrast with lesser use of longer-term information such as seasonal forecasts and multi-decadal projections (Singh et al., 2017; Vaughan et al., 2018). Climate service interventions have met challenges with scaling-up due to low capacity, inadequate institutions, and difficulties in maintaining systems beyond pilot project stage (Sivakumar et al., 2014; Tall et al., 2014; Gebru et al., 2015; Singh et al., 2016b), and technical, institutional, design, financial and capacity barriers to the application of climate information for better decision-making remain (WMO, 2015; Briley et al., 2015; L. Jones et al., 2016; Lourenço et al., 2016; Snow et al., 2016; Harjanne, 2017; Singh et al., 2017; C.J. White et al., 2017).

Table 4.4: Assessment of overarching adaptation options in relation to enabling conditions. For more details, see Supplementary Material 4.B.

Option	Enabling Conditions	Examples
Disaster risk management (DRM)	Governance and institutional capacity: supports post-disaster recovery and reconstruction (Kelman et al., 2015; Kull et al., 2016).	Early warning systems (Anacona et al., 2015), and monitoring of dangerous lakes and surrounding slopes (including using remote sensing) offer DRM opportunities (Emmer et al., 2016; Milner et al., 2017).
Risk sharing and spreading: insurance	Institutional capacity and finance: buffers climate risk (Wolfrom and Yokoi-Arai, 2015; O'Hare et al., 2016; Glaas et al., 2017; Jenkins et al., 2017; Patel et al., 2017).	In 2007, the Caribbean Catastrophe Risk Insurance Facility was formed to pool risk from tropical cyclones, earthquakes, and excess rainfalls (Murphy et al., 2012; CCRIF, 2017).
Risk sharing and spreading: social protection programmes	Institutional capacity and finance: builds generic adaptive capacity and reduces social vulnerability (Weldegebriel and Prowse, 2013; Eakin et al., 2014; Lemos et al., 2016; Schwan and Yu, 2017).	In sub-Saharan Africa, cash transfer programmes targeting poor communities have proven successful in smoothing household welfare and food security during droughts, strengthening community ties, and reducing debt levels (del Ninno et al., 2016; Asfaw et al., 2017; Asfaw and Davis, 2018).
Education and learning	Behavioural change and institutional capacity: social learning strengthens adaptation and affects longer-term change (Clemens et al., 2015; Ensor and Harvey, 2015; Henly-Shepard et al., 2015).	Participatory scenario planning is a process by which multiple stakeholders work together to envision future scenarios under a range of climatic conditions (Oteros-Rozas et al., 2015; Butler et al., 2016; Flynn et al., 2018).
Population health and health system	Institutional capacity: 1.5°C warming will primarily exacerbate existing health challenges (K.R. Smith et al., 2014), which can be targeted by enhancing health services.	Heat wave early warning and response systems coordinate the implementation of multiple measures in response to predicted extreme temperatures (e.g. public announcements, opening public cooling shelters, distributing information on heat stress symptoms) (Knowlton et al., 2014; Takahashi et al., 2015; Nitschke et al., 2016, 2017).
Indigenous knowledge	Institutional capacity and behavioural change: knowledge of environmental conditions helps communities detect and monitor change (Johnson et al., 2015; Mistry and Berardi, 2016; Williams et al., 2017).	Options such as integration of Indigenous knowledge into resource management systems and school curricula, are identified as potential adaptations (Cunsolo Willox et al., 2013; McNamara and Prasad, 2014; MacDonald et al., 2015; Pearce et al., 2015; Chambers et al., 2017; Inamara and Thomas, 2017).

Human migration	Governance: revising and adopting migration issues in national disaster risk management policies, National Adaptation Plans and NDCs (Kuruppu and Willie, 2015; Yamamoto et al., 2017).	In dryland India, populations in rural regions already experiencing 1.5°C warming are migrating to cities (Gajjar et al., 2018) but are inadequately covered by existing policies (Bhagat, 2017).
Climate services	Technological innovation: rapid technical development (due to increased financial inputs and growing demand) is enabling quality of climate information provided (WMO, 2015; Rogers and Tsirkunov, 2010; Clements et al., 2013; Perrels et al., 2013; Gasc et al., 2014; Roudier et al., 2016).	Climate services are seeing wide application in sectors such as agriculture, health, disaster management, insurance (Lourenço et al., 2016; Vaughan et al., 2018) with implications for adaptation decision-making (Singh et al., 2017).

[START CROSS-CHAPTER BOX 9 HERE]

Cross-Chapter Box 9: Risks, Adaptation Interventions, and Implications for Sustainable Development and Equity Across Four Social-Ecological Systems: Arctic, Caribbean, Amazon, and Urban

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This box presents four case studies from different social-ecological systems as examples of risks of 1.5ºC warming and higher (Chapter 3); adaptation options that respond to these risks (Chapter 4); and their implications for poverty, livelihoods and sustainability (Chapter 5). It is not yet possible to generalise adaptation effectiveness across regions due to a lack of empirical studies and monitoring and evaluation of current efforts.

Arctic

The Arctic is undergoing the most rapid climate change globally (Larsen et al., 2014), warming by 1.9°C over the last 30 years (Walsh, 2014; Grosse et al., 2016). For 2°C warming relative to pre-industrial levels, chances of an ice-free Arctic during summer are substantially higher than at 1.5°C (see Sections 3.3.5 and 3.3.8), with permafrost melt, increased instances of storm surge, and extreme weather events anticipated along with later ice freeze up, earlier break up, and a longer ice free open water season (Bring et al., 2016; DeBeer et al., 2016; Jiang et al., 2016; Chadburn et al., 2017; Melvin et al., 2017). Negative impacts on health, infrastructure, and economic sectors (AMAP, 2017a, b, 2018) are projected, although the extension of the summer ocean shipping season has potential economic opportunities (Ford et al., 2015b; Dawson et al., 2016; K.Y. et al., 2018).

Communities, many with Indigenous roots, have adapted to environmental change, developing or shifting harvesting activities and patterns of travel and transitioning economic systems (Forbes et al., 2009; Wenzel, 2009; Ford et al., 2015a; Pearce et al., 2015), although emotional and psychological effects have been documented (Cunsolo Willox et al., 2012; Cunsolo and Ellis, 2018). Besides climate change (Keskitalo et al., 2011; Loring et al., 2016), economic and social conditions can constrain the capacity to adapt unless resources and cooperation are available from public and private sector actors (AMAP, 2017a, 2018)(see Box 5.3Section). In Alaska, the economic impacts of climate change on public infrastructure are significant, estimated at 5.5 billion USD to 4.2 billion USD from 2015 to 2099, with adaptation efforts halving these estimates (Melvin et al., 2017). Marginalisation, colonisation, and land dispossession provide broader underlying challenges facing many communities across the circumpolar north in adapting to change (Ford et al., 2015a; Sejersen, 2015) (see Section 4.3.5).

Adaptation opportunities include alterations to building codes and infrastructure design, disaster risk management, and surveillance (Ford et al., 2014a; AMAP, 2017a, b; Labbé et al., 2017). Most adaptation initiatives are currently occurring at local levels in response to both observed and projected environmental changes as well as social and economic stresses (Ford et al., 2015a). In a recent study of Canada, most adaptations were found to be in the planning stages (Labbé et al., 2017). Studies have suggested that a number of the adaptation actions are not sustainable, lack evaluation frameworks, and hold potential for maladaptation (Loboda, 2014; Ford et al., 2015a; Larsson et al., 2016). Utilising Indigenous and local knowledge and stakeholder engagement can aid the development of adaptation policies and broader sustainable development, along with more proactive and regionally coherent adaptation plans and actions, and regional cooperation (e.g. through the Arctic Council) (Larsson et al., 2016; AMAP, 2017a; Melvin et al., 2017; Forbis Jr and Hayhoe, 2018) (see Section 4.3.5).

Caribbean SIDS and Territories
Extreme weather, linked to tropical storms and hurricanes, represent one of the largest risks facing Caribbean island nations (Section 3.4.5.3). Non-economic damages include detrimental health impacts, forced displacement and destruction of cultural heritages. Projections of increased frequency of the most intense storms at 1.5ºC and higher warming levels (Wehner et al., 2018; Section 3.3.6; Box 3.5) are a significant cause for concern, making adaptation a matter of survival (Mycoo, 2017).

Despite a shared vulnerability arising from commonalities in location, circumstance and size (Bishop and Payne, 2012; Nurse et al., 2014), adaptation approaches are nuanced by differences in climate governance, affecting vulnerability and adaptive capacity (see Section 4.4.1). Three cases exemplify differences in disaster risk management.

Cuba: Together with a robust physical infrastructure and human resource base (Kirk, 2017), Cuba has implemented an effective civil defence system for emergency preparedness and disaster response, centred around community mobilisation and preparedness (Kirk, 2017). Legislation to manage disasters, an efficient and robust early warning system, emergency stockpiles, adequate shelter system and continuous training and education of the population help create a 'culture of risk' (Isayama and Ono, 2015; Lizarralde et al., 2015) which reduces vulnerability to extreme events (Pichler and Striessnig, 2013). Cuba's infrastructure is still susceptible to devastation, as seen in the aftermath of the 2017 hurricane season.

United Kingdom Outer Territories (UKOT): All UKOT have developed National Disaster Preparedness Plans (PAHO/WHO, 2016) and are part of the Caribbean Disaster Risk Management Program which aims to improve disaster risk management within the health sector. Different vulnerability levels across the UKOT (Lam et al., 2015) indicate the benefits of greater regional cooperation and capacity-building, not only within UKOT, but throughout the Caribbean (Forster et al., 2011). While sovereign states in the region can directly access climate funds and international support, Dependent Territories are reliant on their controlling states (Bishop and Payne, 2012). There tends to be low-scale management for environmental issues in UKOT, which increases UKOT's vulnerability. Institutional limitations, lack of human and financial resources, and limited long-term planning are identified as barriers to adaptation (Forster et al., 2011).

Jamaica: Disaster management is coordinated through a hierarchy of national, parish and community disaster committees under the leadership of the Office of Disaster Preparedness and Emergency Management (ODPEM). ODPEM coordinates disaster preparedness and risk reduction efforts among key state and non-state agencies (Grove, 2013). A National Disaster Committee provides technical and policy oversight to the ODPEM and is comprised of representatives from multiple stakeholders (Osei, 2007). Most initiatives are primarily funded through a mix of multi-lateral and bi-lateral loan and grant funding focusing on strengthening technical and institutional capacities of state and research-based institutions and supporting integration of climate change considerations into national and sectoral development plans (Robinson, 2017).

To improve climate change governance in the region, Pittman et al 2015 suggest incorporating holistic and integrated management systems, improving flexibility in collaborative processes, implementing monitoring programs, and increasing the capacity of local authorities. Implementation of the 2030 Sustainable Development Agenda and the Sustainable Development Goals (SDGs) can contribute to addressing the risks related with extreme events (Box 5.3).

The Amazon

Terrestrial forests, such as the Amazon, are sensitive to changes in the climate, particularly drought (Laurance and Williamson, 2001) which might intensify through the 21st century (Marengo and Espinoza, 2016) (Section 3.5.5.6).

The poorest communities in the region face substantial risks with climate change, and barriers and limits to adaptive capacity (Maru et al., 2014; Pinho et al., 2014, 2015; Brondízio et al., 2016). The Amazon is considered a hotspot with interconnections between increasing temperature, decreased precipitation and hydrological flow (Betts et al., 2018) (Sections 3.3.2.2, 3.3.3.2 and 3.3.5), low levels of socioeconomic development (Pinho et al., 2014), and high levels of climate vulnerability (Darela et al., 2016). Limiting temperature warming to 1.5°C could increase food and water security in the region compared to 2°C (Betts et al., 2018), reduce the impact on poor people and sustainable development, and make adaptation easier (O'Neill et al., 2017) particularly in the Amazon (Bathiany et al., 2018) (Section 5.2.2).

Climate policy in many Amazonian nations has focused on forests as carbon sinks (Soares-Filho et al., 2010). In 2009, the Brazilian National Policy on Climate Change acknowledged adaptation as a concern and the government sought to mainstream adaptation into public administration. Brazil's National Adaptation Plan sets guidelines for sectoral adaptation measures, primarily by developing capacity building, plans, assessments and tools to support adaptive decision making. Adaptation is increasingly being presented as having mitigation co-benefits in the Brazilian Amazon (Gregorio et al., 2016), especially within ecosystem-based adaptation (Locatelli et al., 2011). In Peru's Framework Law for Climate Change, every governmental sector will consider climatic conditions as potential risks and/or opportunities to promote economic development and to plan adaptation.

Drought and flood policies have had limited effectiveness in reducing vulnerability (Marengo et al., 2013). In the absence of effective adaptation, achieving the SDGs will be challenging, mainly in poverty, health, water and sanitation, inequality and gender equality (Section 5.2.3).

Urban systems

Around 360 million people reside in urban coastal areas where precipitation variability is exposing inadequacies of urban infrastructure and governance, with the poor especially vulnerable (Reckien et al., 2017)(Cross-Chapter Box 13 in Chapter 5). Urban systems have seen growing adaptation action (Revi et al., 2014b; Araos et al., 2016b; Amundsen et al., 2018). Developing cities spend more on health and agriculture-related adaptation options while developed cities spend more on energy and water (Georgeson et al., 2016). Current adaptation activities are lagging in emerging economies which are major centres of population growth facing complex interrelated pressures on investment in health, housing and education (Georgeson et al., 2016; Reckien et al., 2017).

New York: Adaptation plans are undertaken across government levels, sectors and departments (NYC Parks, 2010; Vision 2020 Project Team, 2011; The City of New York, 2013), and have been advanced by an expert science panel that is obligated by local city law to provide regular updates on policy relevant climate science (NPCC, 2015). Federal initiatives include 2013's Rebuild By Design competition to promote resilience through infrastructural projects (HUD, 2013). In 2013 the Mayor's office, in response to Hurricane Sandy, published the city's adaptation strategy (The City of New York, 2013). In 2015, the OneNYC Plan for a Strong and Just City (OneNYC Team, 2015) laid out a strategy for urban planning through a justice and equity lens. In 2017, new climate resiliency guidelines proposed that new construction must include sea level rise projections into planning and development (The City of New York, 2017). Although this attention to climate-resilient development may help reduce income inequality, its full effect could be constrained, if a policy focus on resilience obscures analysis of income redistribution for the poor (Fainstein, 2018).

Kampala: Kampala Capital City Authority (KCCA) has the statutory responsibility for managing the city. The Kampala Climate Change Action Strategy (KCCAS) is responding to climatic impacts of elevated temperature and more intense, erratic rain. KCCAS has considered multi-scale and temporal aspects of response (Chelleri et al., 2015; Douglas, 2017; Fraser et al., 2017), strengthened community adaptation (Lwasa, 2010; Dobson, 2017), responded to differential adaptive capacities (Waters and Adger, 2017) and believes in participatory processes and bridging of citywide linkages (KCCA, 2016). Analysis of the implications of uniquely adapted local solutions (e.g., motorcycle taxis) suggests sustainability can be enhanced when planning recognises the need to adapt to uniquely local solutions (Evans et al., 2018).

Rotterdam: The Rotterdam Climate Initiative (RCI) was launched to reduce Greenhouse Gas (GHG) emissions and climate-proof Rotterdam (RCI, 2017). Rotterdam has an integrated adaptation strategy, built on flood management, accessibility, adaptive building, urban water systems and urban climate, defined through Rotterdam Climate Proof and Rotterdam Climate Change Adaptation Strategy (RCI, 2008, 2013). Governance mechanisms that enabled integration of flood risk management plans with other policies, citizen participation, institutional eco-innovation, and focussing on green infrastructure (Albers et al., 2015; Dircke and Molenaar, 2015; de Boer et al., 2016a; Huang-Lachmann and Lovett, 2016) have contributed to effective adaptation (Ward et al., 2013). Entrenched institutional characteristics constrain the response framework (Francesch-Huidobro et al., 2017) but emerging evidence suggests that new governance arrangements and structures can potentially overcome these barriers in Rotterdam (Hölscher et al., 2018).

[END CROSS-CHAPTER BOX 9 HERE]

4.3.6 Short Lived Climate Forcers

The main Short-Lived Climate Forcer (SLCF) emissions that cause warming are methane (CH_4), other precursors of tropospheric ozone (i.e., carbon monoxide (CO), Non-Methane Volatile Organic Compounds (NMVOC)), black carbon (BC) and hydrofluorocarbons (HFCs) (Myhre et al., 2013). SLCFs also include emissions that lead to cooling, such as sulphur dioxide (SO_2) and organic carbon (OC). Nitrogen oxides (NOx) can have both warming and cooling effects, by affecting ozone (O_3) and CH_4, depending on timescale and location (Myhre et al., 2013).

Cross-Chapter Box 2 in Chapter 1 provides a discussion of role of SLCFs in comparison to long-lived GHGs. Chapter 2 shows that 1.5°C-consistent pathways require stringent reductions in CO_2 and CH_4, and that non-CO_2 climate forcers reduce carbon budgets by ~2200 $GtCO_2$ per degree of warming attributed to them (see Chapter 2 Annex).

Reducing non-CO_2 emissions is part of most mitigation pathways (IPCC, 2014c). All current GHG emissions and other forcing agents affect the rate and magnitude of climate change over the next few decades, while long-term warming is mainly driven by CO_2 emissions. CO_2 emissions result in a virtually permanent warming, while temperature change from SLCFs disappears within decades after emissions of SLCFs are ceased. Any scenario that fails to reduce CO_2 emissions to net zero would not limit global warming, even if SLCFs are reduced, due to accumulating CO_2-induced warming that overwhelms SLCFs' mitigation benefits in a couple of decades (Shindell et al., 2012; Schmale et al., 2014) and see Section 2.3.3.1).

Mitigation options for warming SLCFs often overlap with other mitigation options, especially since many warming SLCFs are co-emitted with CO_2. SLCFs are generally mitigated in 1.5°C- or 2°C-consistent pathways as an integral part of an overall mitigation strategy (Chapter 2). For example, section 2.3 indicates that most very low-emissions pathways include a transition away from the use of coal and natural gas in the energy sector and oil in transportation, which coincides with emission reduction strategies related to methane from the fossil fuel sector and BC from the transportation sector. Much SLCF emission reduction aims at BC-rich sectors and considers the impacts of several co-emitted SLCFs (Bond et al., 2013; Sand et al., 2015; Stohl et al., 2015). However, it is uncertain whether such strategies would lead to additional long-term climate benefits compared to BC emissions reductions achieved through CO_2 mitigation and associated co-control on BC-rich sectors in 1.5°C and 2°C pathways (Rogelj et al., 2014).

Some studies have evaluated the focus on SLCFs in mitigation strategies and point towards trade-offs between short-term SLCF benefits and lock in of long-term CO_2 warming (Smith and Mizrahi, 2013; Pierrehumbert, 2014). Reducing fossil fuel combustion will reduce aerosols levels, and thereby cause warming from removal of cooling effects (Myhre et al., 2013; Xu and Ramanathan, 2017; Samset et al., 2018). Recent studies have also found lower temperature effects of BC than what can be expected from the direct radiative forcing alone, thus questioning the effectiveness of targeted BC mitigation for climate change mitigation (Myhre et al., 2013; Baker et al., 2015; Stjern et al., 2017; Samset et al., 2018).

Table 4.5 provides an overview of three warming SLCFs and their emission sources, with examples of options for emission reductions and associated co-benefits.

Table 4.5: Overview of main characteristics of three warming Short-Lived Climate Forcers (SLCFs) (core information based on (Pierrehumbert, 2014) and (Schmale et al., 2014); rest of the details as referenced).

SLCF compound	**Atmospheric lifetime**	**Annual global emission**	**Main anthropogenic emission sources**	**Examples of options to reduce emissions consistent with 1.5°C**	**Examples of co-benefits based on** (Haines et al., 2017) **unless specified otherwise**
Methane	On the order of 10 years	0.3 $GtCH_4$ (2010) (Pierrehumbert, 2014)	Fossil fuel extraction and transportation Land-use change Livestock and rice cultivation Waste and wastewater	Managing manure from livestock Intermittent irrigation of rice Capture and usage of fugitive methane Dietary change For more: see Sections 4.3.2 and 4.3.3.	Reduction of tropospheric ozone (Shindell et al., 2017a) Health benefits of dietary changes Increased crop yields Improved access to drinking water
HFCs	Months to decades, depending on the gas	0.35 $GtCO_2$-eq (2010) (Velders et al., 2015)	Air conditioning Refrigeration Construction material	Alternatives to HFCs in air-conditioning and refrigeration applications	Greater energy efficiency (Mota-Babiloni et al., 2017)
Black carbon	Days	~7 Mt (2010) (Klimont et al., 2017)	Incomplete combustion of fossil fuels or biomass in vehicles (esp. diesel), cook stoves or kerosene lamps Field and biomass burning	Fewer and cleaner vehicles Reducing agricultural biomass burning Cleaner cook stoves, gas-based or electric cooking Replacing brick and coke ovens Solar lamps For more see Section 4.3.4	Health benefits of better air quality Increased education opportunities Reduced coal consumption for modern brick kilns Reduced deforestation

A wide range of options to reduce SLCF emissions was extensively discussed in AR5 (IPCC, 2014b). Fossil fuel and waste sector methane mitigation options have high cost-effectiveness, producing a net profit over a few years, considering market costs only. Moreover, reducing roughly one-third to one-half of all human-caused emissions has societal benefits greater than mitigation costs when considering environmental impacts only (UNEP, 2011; Höglund-Isaksson, 2012; IEA, 2017b; Shindell et al., 2017a). Since AR5, new options for methane, such as those related to shale gas, have been included in mitigation portfolios (e.g., Shindell et al. 2017b).

Reducing BC emissions and co-emissions has sustainable development co-benefits, especially around human health (Stohl et al., 2015; Haines et al., 2017; Aakre et al., 2018), avoiding premature deaths and increasing crop yields (Scovronick et al., 2015; Peng et al., 2016). Additional benefits include lower likelihood of non-linear climate changes and feedbacks (Shindell et al., 2017a) and temporarily slowing down the rate of sea level rise (Hu et al., 2013). Interventions to reduce BC offer tangible local air quality benefits, increasing the likelihood of local public support (Eliasson, 2014; Venkataraman et al., 2016) (see Section 5.4.1.2). Limited interagency co-ordination, poor science-policy interactions (Zusman et al., 2015), and weak policy and absence of inspections and enforcement (Kholod and Evans, 2016) are among barriers that reduce the institutional feasibility of options to reduce vehicle-induced BC emissions. A case study for India shows that switching from biomass cook stoves to cleaner gas stoves (based on liquefied petroleum gas or natural gas) or to electric cooking stoves is technically and economically feasible in most areas, but faces barriers in user preferences, costs and the organisation of supply chains (Jeuland et al., 2015). Similar feasibility considerations emerge in switching in lighting from kerosene wick lamps to solar lanterns, from current low-efficiency brick kilns and coke ovens to cleaner production technologies; and from field burning of crop residues to agricultural practices using deep-sowing and mulching technologies (Williams et al., 2011; Wong, 2012).

The radiative forcing from HFCs are currently small but have been growing rapidly (Myhre et al., 2013). The Kigali amendment (from 2016) to the Montreal Protocol set out a global accord for phasing out these compounds (Höglund-Isaksson et al., 2017). HFC mitigation options include alternatives with reduced warming effects, ideally combined with improved energy efficiency so as to simultaneously reduce CO_2 and co-emissions (Shah et al., 2015). Costs for most of HFC's mitigation potential are estimated to be below USD_{2010} 60 tCO_2-eq^{-1}, and the remainder below roughly double that number (Höglund-Isaksson et al., 2017).

Reductions in SLCFs can provide large benefits towards sustainable development, beneficial for social, institutional and economic feasibility. Strategies that reduce SLCFs can provide benefits that include improved air quality (for example (Anenberg et al., 2012)) and crop yields (for example (Shindell et al., 2012)), energy access, gender equality and poverty eradication (for example (Shindell et al., 2012; Haines et al., 2017)). Institutional feasibility can be negatively affected by an information deficit, with the absence of international frameworks for integrating SLCFs into emissions accounting and reporting mechanisms being a barrier for policy-making to address SLCF emissions (Venkataraman et al., 2016). The incentives for reducing SLCFs are particularly strong for small groups of countries, and such a collaboration could increase feasibility and effectiveness of SLCF mitigation options (Aakre et al., 2018).

4.3.7 Carbon Dioxide Removal (CDR)

CDR methods refer to a set of techniques for removing CO_2 from the atmosphere. In the context of 1.5°C-consistent pathways (Chapter 2), they serve to offset residual emissions that take longer to abate or to compensate for emissions occurring after running out of the 1.5°C carbon budget. See Cross-Chapter Box 7 in Chapter 3 for a synthesis of land-based CDR options. Cross-cutting issues and uncertainties are summarised in Table 4.6.

4.3.7.1 Bioenergy with carbon capture and storage (BECCS)

BECCS has been assessed in previous IPCC reports (IPCC, 2005; P. Smith et al., 2014; Minx et al., 2017) and has been incorporated into integrated assessment models (Clarke et al., 2014). In the meantime, 1.5°C pathways without BECCS have emerged (Bauer et al., 2018; Grübler, 2018; Mousavi and Blesl, 2018; van Vuuren et al., 2018). Still, models indicate that 3.7–8 $GtCO_2\ yr^{-1}$ (interquartile range) and 14 $GtCO_2\ yr^{-1}$ (median) would be removed by BECCS by 2050 and 2100, respectively, with some models starting BECCS in 2030 already (Section 2.3.4). BECCS is constrained by sustainable bioenergy potentials (Sections 4.3.1.2, 5.4.3 and Cross-Chapter Box 6 in Chapter 3), and availability of safe storage for CO_2 (Section 4.3.1.6). Literature estimates for BECCS mitigation potentials in 2050 range from 1-85 $GtCO_2$[4]. Fuss et al. (2018) narrow this range to 0.5–5 $GtCO_2\ yr^{-1}$ (*medium agreement, high evidence*) (Figure 4.3), thus falling below

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[4] FOOTNOTE: As more bottom-up literature exists on bioenergy potentials, this exercise explored the bioenergy literature and converted those estimates to BECCS potential with 1EJ of bioenergy yielding 0.02–0.05 $GtCO_2$ emission reduction. For the bottom-up literature references for the potentials range, please refer to Supplementary Material C Table 1.

the upper end of 1.5°C pathways. This is, among other things, related to sustainability concerns (Boysen et al., 2017; Heck et al., 2018; Henry et al., 2018).

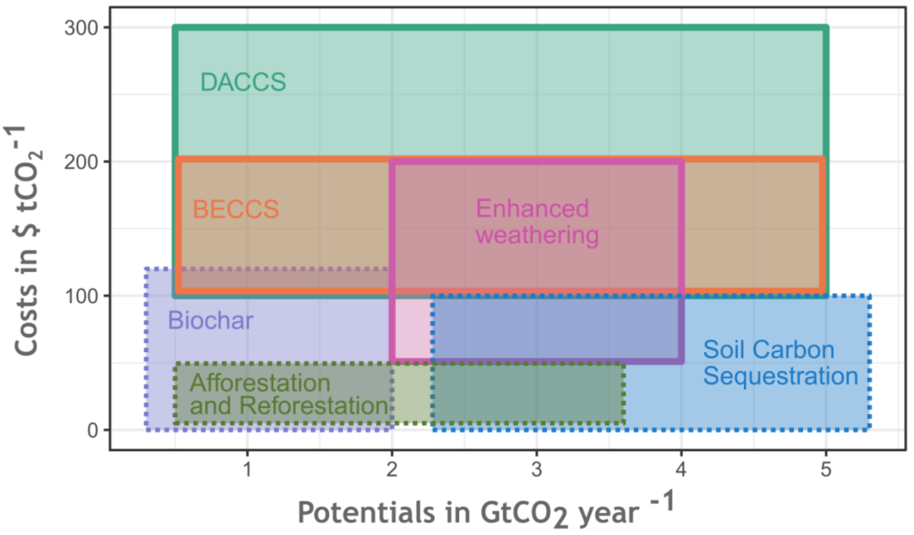
Assessing BECCS deployment in 2°C pathways (of about 12 $GtCO_2$-eq yr^{-1}, here considered as a lower deployment limit for 1.5°C, Smith et al. (2016b) estimate a land-use intensity of 0.3–0.5 ha tCO_2-eq^{-1} yr^{-1} using forest residues, 0.16 ha CO_2-eq^{-1} yr^{-1} for agricultural residues, and 0.03–0.1 ha tCO_2-eq^{-1} yr^{-1} for purpose-grown energy crops. The average amount of BECCS in these pathways requires 25–46% of arable and permanent crop area in 2100. Land area estimates differ in scale and are not necessarily a good indicator of competition with, e.g., food production, because requiring a smaller land area for the same potential could indicate that high-productivity agricultural land is used . In general, the literature shows *low agreement* on the availability of land (Fritz et al., 2011); see (Erb et al., 2016b) for recent advances. Productivity, food production and competition with other ecosystem services and land use by local communities are important factors for the design of regulation. These potentials and trade-offs are not homogenously distributed across regions. However, (Robledo-Abad et al., 2017) find that regions with higher potentials are understudied, given their potential contribution. Researchers have expressed the need to complement global assessments with regional, geographically explicit bottom-up studies of biomass potentials and socio-economic impacts (e.g., de Wit and Faaij 2010; Kraxner et al., 2014; Baik et al., 2018).

Energy production, land and water footprints show wide ranges in bottom-up assessments due to differences in technology, feedstock and other parameters (–1–150 EJ yr^{-1} of energy, 109–990 Mha, 6–79 MtN, 218–4758 km^3 yr^{-1} of water per $GtCO_2$ yr^{-1} (Smith and Torn, 2013; Smith et al., 2016b; Fajardy and Mac Dowell, 2017) and are not comparable to IAM pathways which consider system effects (Bauer et al., 2018). Global impacts on nutrients and albedo are difficult to quantify (Smith et al., 2016b). BECCS competes with other land-based CDR and mitigation measures for resources (Chapter 2).

There is uncertainty about the feasibility of timely upscaling. CCS (see Section 4.3.1) is largely absent from the nationally determined contributions (Spencer et al., 2015) and lowly ranked in investment priorities (Fridahl, 2017). Although there are dozens of small-scale BECCS demonstrations (Kemper, 2015) and a full scale project capturing 1 $MtCO_2$ exists (Finley, 2014)**,** this is well below the numbers associated with 1.5°C or 2°C-compatible pathways (IEA, 2016a; Peters et al., 2017). Although the majority of BECCS cost estimates are below 200 USD tCO_2^{-1} (Figure 4.3), estimates vary widely. Economic incentives for ramping up large CCS or BECCS infrastructure are weak (Bhave et al., 2017). The 2050 average investment costs for such a BECCS infrastructure for bio-electricity and biofuels are estimated at 138 and 123 billion USD yr^{-1}, respectively (Smith et al., 2016b).

BECCS deployment is further constrained by bioenergy’s carbon accounting, land, water and nutrient requirements (Section 4.3.1), its compatibility with other policy goals and limited public acceptance of both bioenergy and CCS (Section 4.3.1). Current pathways are believed to have inadequate assumptions on the development of societal support and governance structures (Vaughan and Gough, 2016).
However, removing BECCS and CCS from the portfolio of available options significantly raises mitigation costs (Kriegler et al., 2013) (Bauer et al., 2018).

Panel A - Estimated costs and 2050 potentials



Panel B - Literature estimates on costs, potentials (2050) and side effects

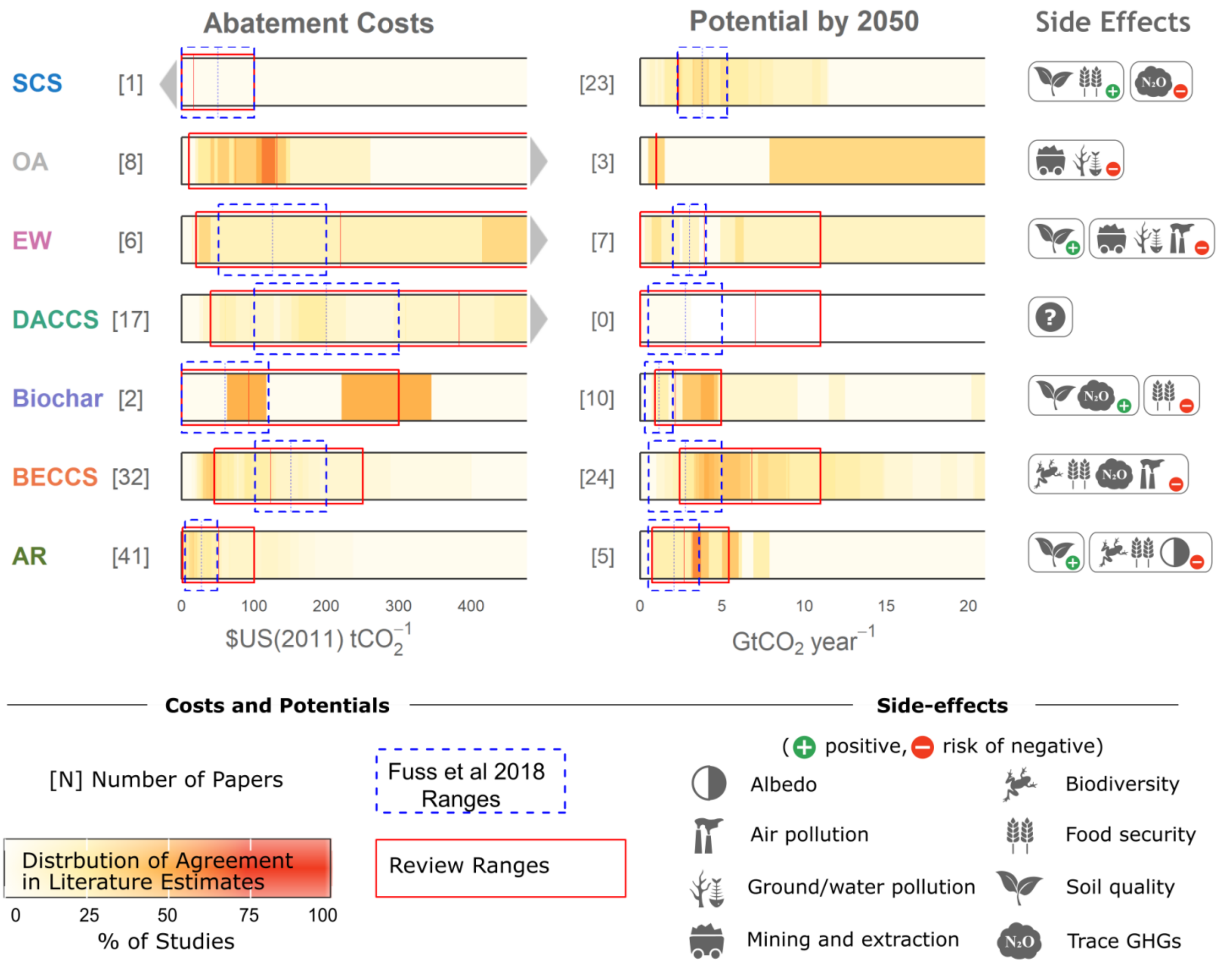


Figure 4.2: Evidence on Carbon Dioxide Removal (CDR) abatement costs, 2050 deployment potentials, and key side effects. Panel A presents estimates based on a systematic review of the bottom up literature (Fuss et al., 2018), corresponding to dashed blue boxes in Panel B. Dashed lines represent saturation limits for the corresponding technology. Panel B shows the percentage of papers at a given cost or potential estimate. Reference year for all potential estimates is 2050, while all cost estimates preceding 2050 have been

included (as early as 2030, older estimates are excluded if they lack a base year and thus cannot be made comparable). Ranges have been trimmed to show detail (see Fuss et al., 2018) for the full range). Costs refer only to abatement costs. Icons for side-effects are allocated only if a critical mass of papers corroborates their occurrence

Notes: For references please see Supplementary Material C, Table 1. Direct Air Carbon Dioxide Capture and Storage (DACCS) is theoretically only constrained by geological storage capacity, estimates presented are considering upscaling and cost challenges. BECCS potential estimates are based on bioenergy estimates in the literature (EJ yr^{-1}), converted to GtCO$_2$ following footnote 3. Potentials cannot be added up, as CDR options would compete for resources (e.g., land). SCS - Soil Carbon Sequestration; OA - Ocean Alkalinisation; EW- Enhanced Weathering; DACCS - Direct Air Carbon Dioxide Capture and Storage; BECCS - Bioenergy with Carbon Capture and Storage; AR - Afforestation

4.3.7.2 Afforestation and Reforestation (AR)

Afforestation implies planting trees on land not forested for a long time (e.g., over the last 50 years in the context of the Kyoto Protocol), while reforestation implies re-establishment of forest formations after a temporary condition with less than 10% canopy cover due to human-induced or natural perturbations. Houghton et al. (2015) estimate about 500 Mha could be available for the re-establishment of forests on lands previously forested, but not currently used productively. This could sequester at least 3.7 GtCO$_2$ yr^{-1} for decades. The full literature range gives 2050 potentials of 1–7 GtCO$_2$ yr^{-1} (*low evidence, medium agreement*), narrowed down to 0.5–3.6 GtCO$_2$ yr^{-1} based on a number of constraints (Fuss et al., 2018). Abatement costs are estimated to be low compared to other CDR options, 5–50 USD tCO$_2$-eq^{-1} (*robust evidence, high agreement*). Yet, realising such large potentials comes at higher land and water footprints than BECCS, although there would be a positive impact on nutrients, and the energy requirement would be negligible (Smith et al., 2016b; Cross-Chapter Box 7 in Chapter 3). The 2030 estimate by Griscom et al. (2017) is up to 17.9 GtCO$_2$ yr^{-1} for reforestation with significant co-benefits (Cross-Chapter Box 7 in Chapter 3).

Biogenic storage is not as permanent as emission reductions of geological storage. In addition, forest sinks saturate, a process which typically occurs in decades to centuries compared to the thousands of years of residence time of CO$_2$ stored geologically (Smith et al., 2016a) and is subject to disturbances that can be exacerbated by climate change (e.g. drought, forest fires and pests) (Seidl et al., 2017). Handling this requires careful forest management. There is much practical experience with AR, facilitating upscaling but with two caveats: AR potentials are heterogeneously distributed (Bala et al., 2007), partly because the planting of less reflective forests results in higher net-absorbed radiation and localised surface warming in higher latitudes (Bright et al., 2015; Jones et al., 2015), and forest governance structures and monitoring capacities can be bottlenecks and are usually not considered in models (Wang et al., 2016; Wehkamp et al., 2018b). There is *medium agreement* on the positive impacts of AR on ecosystems and biodiversity due to different forms of afforestation discussed in the literature: afforestation of grassland ecosystems or diversified agricultural landscapes with monocultures or invasive alien species can have significant negative impacts on biodiversity, water resources, etc. (P. Smith et al., 2014), while forest ecosystem restoration (forestry and agroforestry) with native species have positive social and environmental impacts (Cunningham et al., 2015; Locatelli et al., 2015; Paul et al., 2016); See Section 4.3.2).

Synergies with other policy goals are possible (see also Section 4.5.4); for example land spared by diet shifts could be afforested (Röös et al., 2017) or used for energy crops (Grübler, 2018). Such land-sparing strategies could also benefit other land-based CDR options.

4.3.7.3 Soil Carbon Sequestration and Biochar

At local scales there is *robust evidence* that Soil Carbon Sequestration (SCS, e.g., agroforestry, De Stefano and Jacobson, 2018), restoration of degraded land (Griscom et al., 2017), or conservation agriculture management practices (Aguilera et al., 2013; Poeplau and Don, 2015; Vicente-Vicente et al., 2016) have co-benefits in agriculture and that many measures are cost-effective even without supportive climate policy.

Evidence at global scale for potentials and especially costs is much lower. The literature spans cost ranges of –40–100 USD tCO_2^{-1} (negative costs relating to the multiple co-benefits of SCS, such as increased productivity and resilience of soils (P. Smith et al., 2014) and 2050 potentials are estimated between 1–11 $GtCO_2$ yr^{-1}, narrowed down to 2–5 $GtCO_2$ yr^{-1} considering that studies above 5 $GtCO_2$ yr^{-1} often do not apply constraints, while estimates lower than 2 $GtCO_2$ yr^{-1} mostly focus on single practices (Fuss et al., 2018).

SCS has negligible water and energy requirements (Smith, 2016), affects nutrients and food security favourably (*high agreement, robust evidence*) and can be applied without changing current land use thus making it socially more acceptable than CDR options with a high land footprint. However, soil sinks saturate after 10–100 years, depending on the SCS option, soil type and climate zone (Smith, 2016).

Biochar is formed by recalcitrant (i.e., very stable) organic carbon obtained from pyrolysis which applied to soil can increase soil carbon sequestration leading to improved soil fertility properties.[5] Looking at the full literature range, the global potential in 2050 lies between 1–35 Gt CO_2 yr^{-1} (*low agreement, low evidence*), but considering limitations in biomass availability and uncertainties due to a lack of large-scale trials of biochar application to agricultural soils under field conditions, Fuss et al. (2018) lower the 2050 range to 0.3–2 $GtCO_2$ yr^{-1}. This potential is below previous estimates (e.g., Woolf et al., 2010), which additionally consider the displacement of fossil fuels through biochar. Permanence depends on soil type and biochar production temperatures, varying between a few decades and several centuries (Fang et al., 2014). Costs are 30– 120 USD tCO_2^{-1} (*medium agreement, medium evidence*) (McCarl et al., 2009; McGlashan et al., 2012; McLaren, 2012; Smith, 2016).

Water requirements are low and at full theoretical deployment, up to 65 EJ yr^{-1} of energy could be generated as a side product (Smith, 2016). Positive side effects include a favourable effect on nutrients and reduced N_2O emissions(Cayuela et al., 2014; Kammann et al., 2017). However, 40–260 Mha are needed to grow the biomass for biochar for implementation at 0.3 $GtCO_2$-eq yr^{-1} (Smith, 2016), even though it is also possible to use residues (e.g., Windeatt et al., 2014). Biochar is further constrained by the maximum safe holding capacity of soils (Lenton, 2010) and the labile nature of carbon sequestrated in plants and soil at higher temperatures (Wang et al., 2013).

4.3.7.4 Enhanced Weathering (EW) and Ocean Alkalinisation

Weathering is the natural process of rock decomposition via chemical and physical processes in which CO_2 is spontaneously consumed and converted to solid or dissolved alkaline bicarbonates and/or carbonates (IPCC 2005). The process is controlled by temperature, reactive surface area, interactions with biota and, in particular, water solution composition. CDR can be achieved by accelerating mineral weathering through the distribution of ground-up rock material over land (Hartmann and Kempe, 2008; Wilson et al., 2009; Köhler et al., 2010; Renforth, 2012; ten Berge et al., 2012; Manning and Renforth, 2013; Taylor et al., 2016), shorelines (Hangx and Spiers, 2009; Montserrat et al., 2017) or the open ocean (House et al., 2007; Harvey, 2008; Köhler et al., 2013; Hauck et al., 2016). Ocean alkalinisation adds alkalinity to marine areas to locally increase the CO_2 buffering capacity of the ocean (González and Ilyina, 2016; Renforth and Henderson, 2017).

In the case of land application of ground minerals, the estimated CDR potential range is 0.72–95 $GtCO_2$ yr^{-1} (Hartmann and Kempe, 2008; Köhler et al., 2010; Hartmann et al., 2013; Taylor et al., 2016; Strefler et al., 2018) *(low evidence, low agreement*). Marine application of ground minerals is limited by feasible rates of mineral extraction, grinding and delivery, with estimates of 1–6 $GtCO_2$ yr^{-1} (Köhler et al., 2013; Hauck et al., 2016; Renforth and Henderson, 2017) (*low evidence, low agreement*). Agreement is low due to a variety of assumptions and unknown parameter ranges in the applied modelling procedures that would need to be verified by field experiments (Fuss et al., 2018). As with other CDR options, scaling and maturity are

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[5] FOOTNOTE: Other pyrolysis products that can achieve net CO_2 removals are bio-oil (pumped into geological storages) and permanent-pyrogas (capture and storage of CO_2 from gas combustion) (Werner et al., 2018)

challenges, with deployment at scale potentially requiring decades (NRC, 2015a), considerable costs in transport and disposal (Hangx and Spiers, 2009; Strefler et al., 2018) and mining (NRC, 2015a; Strefler et al., 2018)[6].

Site-specific cost estimates vary depending on the chosen technology for rock grinding – an energy-intensive process (Köhler et al., 2013; Hauck et al., 2016) – material transport and rock source (Renforth, 2012; Hartmann et al., 2013), ranging from 15–40 USD tCO_2^{-1} to 3,460 USD tCO_2^{-1} (Schuiling and Krijgsman, 2006; Köhler et al., 2010; Taylor et al., 2016, *limited evidence, low agreement*; Figure 4.2). The evidence base for costs of ocean alkalinisation and marine enhanced weathering is sparser than the land applications. The ocean alkalinisation potential is assessed to be 0.1–10 $GtCO_2$ yr^{-1} with costs of 14– >500 USD tCO_2^{-1} (Renforth and Henderson, 2017).

The main side effects of terrestrial EW are an increase in water pH (Taylor et al., 2016), the release of heavy metals like Ni and Cr, and plant nutrients like K, Ca, Mg, P and Si (Hartmann et al., 2013), and changes in hydrological soil properties. Respirable particle sizes, though resulting in higher potentials, can have impacts on health (Schuiling and Krijgsman, 2006; Taylor et al., 2016); utilisation of wave-assisted decomposition through deployment on coasts could avert the need for fine grinding (Hangx and Spiers, 2009; Schuiling and de Boer, 2010). Side effects of marine EW and ocean alkalinisation are the potential release of heavy metals like Ni and Cr (Montserrat et al., 2017). Increasing ocean alkalinity helps counter ocean acidification (Albright et al., 2016; Feng et al., 2016). Ocean alkalinisation could affect ocean biogeochemical functioning (González and Ilyina, 2016). A further caveat of relates to saturation state and the potential to trigger spontaneous carbonate precipitation.[7] While the geochemical potential to remove and store CO_2 is quite large, *limited evidence* on the preceding topics makes it difficult to assess the true capacity, net benefits and desirability of EW and ocean alkalinity addition in the context of CDR.

4.3.7.5 Direct Air Carbon Dioxide Capture and Storage (DACCS)

Capturing CO_2 from ambient air through chemical processes with subsequent storage of the CO_2 in geological formations is independent of source and timing of emissions, and can avoid competition for land. Yet, this is also the main challenge: while the theoretical potential for DACCS is mainly limited by the availability of safe and accessible geological storage, the CO_2 concentration in ambient air is 100–300 times lower than at gas- or coal-fired power plants (Sanz-Pérez et al., 2016) thus requiring more energy than flue gas CO_2 capture (Pritchard et al., 2015). This appears to be the main challenge to DACCS (Sanz-Pérez et al., 2016; Barkakaty et al., 2017).

Studies explore alternative techniques to reduce the energy penalty of DACCS (van der Giesen et al., 2017). Energy consumption could be up to 12.9 GJ tCO_2-eq^{-1}; translating into an average of 156 EJ yr^{-1} by 2100 (current annual global primary energy supply is 600 EJ); water requirements are estimated to average 0.8–24.8 km^3 $GtCO_2$-eq^{-1} yr^{-1} (Smith et al., 2016, based on Socolow et al., 2011).

However, the literature shows *low agreement* and is fragmented (Broehm et al., 2015). This fragmentation is reflected in a large range of cost estimates: from 20–1,000 USD tCO_2^{-1} (Keith et al., 2006; Pielke, 2009; House et al., 2011; Ranjan and Herzog, 2011; Simon et al., 2011; Goeppert et al., 2012; Holmes and Keith, 2012; Zeman, 2014; Sanz-Pérez et al., 2016; Sinha et al., 2017). The interquartile range (see Figure 4.2) is 40–449 USD tCO_2^{-1}; there is lower agreement and a smaller evidence base at the lower end of the cost range.

Research and efforts by small-scale commercialisation projects focus on utilisation of captured CO_2 (Wilcox

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[6] FOOTNOTE: It has also been suggested that ocean alkalinity can be increased through accelerated weathering of limestone (Rau and Caldeira, 1999; Rau, 2011; Chou et al., 2015) or electrochemical processes (House et al., 2007; Rau, 2008; Rau et al., 2013b; Lu et al., 2015). However, these techniques have not been proven at large scale either (Renforth and Henderson, 2017).

[7] FOOTNOTE: This analysis relies on the assessment in Fuss et al. (2018b), which provides more detail on saturation and permanence.

et al., 2018). Given that only a few IAM scenarios incorporate DACCS (e.g., Chen and Tavoni 2013; Strefler et al. 2018a) its possible role in cost-optimised 1.5°C scenarios is not yet fully explored. Given the technology's early stage of development (McLaren, 2012; NRC, 2015a; Nemet et al., 2018) and few demonstrations (Holmes et al., 2013; Rau et al., 2013; Agee et al., 2016), deploying the technology at scale is still a considerable challenge though both optimistic (Lackner et al., 2012) and pessimistic outlooks exist (Pritchard et al., 2015).

4.3.7.6 Ocean Fertilisation

Nutrients can be added to the ocean resulting in increased biologic production, leading to carbon fixation in the sunlit ocean and subsequent sequestration in the deep ocean or sea floor sediments. The added nutrients can be either micronutrients (such as iron) or macronutrients (such as nitrogen and/or phosphorous) (Harrison 2017). There is *limited evidence* and *low agreement* on the readiness of this technology to contribute to rapid decarbonisation (Williamson et al. 2012). Only small-scale field experiments and theoretical modelling have been conducted (e.g., McLaren (2012)). The full range of CDR potential estimates is 15.2 $ktCO_2$ yr^{-1} (Bakker et al. 2001) for a spatially constrained field experiment to 4.4 $GtCO_2$ yr^{-1} (Sarmiento and Orr 1991) following a modelling approach, but Fuss et al. (2018b) consider the potential to be extremely limited given the evidence and existing barriers. Due to scavenging of iron, the iron addition only leads to inefficient use of the nitrogen in exporting carbon (Aumont and Bopp 2006; Zahariev et al. 2008; Zeebe 2005).

Cost estimates range from 2 USD tCO_2^{-1} (for iron fertilization) (Boyd and Denman 2008) to 457 USD tCO_2^{-1} (Harrison 2013). Jones (2014) proposed values greater than 20 USD tCO_2^{-1} for nitrogen fertilisation. Fertilisation is expected to impact food webs by stimulating its base organisms (Matear 2004), and extensive algal blooms may cause anoxia (Matear 2004; Russell et al. 2012; Sarmiento and Orr 1991) and deep water oxygen decline (Matear 2004), with negative impacts on biodiversity. Nutrient inputs can shift ecosystem production from an iron-limited system to a P, N-, or Si-limited system depending on the location (Bertram 2010; Matear 2004) and non-CO_2 GHGs may increase (Bertram 2010; Sarmiento and Orr 1991; Matear 2004). The greatest theoretical potential for this practice is the Southern Ocean, posing challenges for monitoring and governance (Robinson et al. 2014). The London Protocol of the International Maritime Organization has asserted authority for regulation of ocean fertilisation (Strong et al. 2009), which is widely viewed as a, de facto moratorium' on commercial ocean fertilisation activities.

There is *low agreement* in the technical literature on the permanence of CO_2 in the ocean, with estimated residence times of 1,600 years to millennia, especially if injected or buried in or below the sea floor (Williams and Druffel, 1987; Jones, 2014). Storage at the surface would mean that the carbon would be rapidly released after cessation (Aumont and Bopp 2006; Zeebe 2005).

Table 4.6: Cross-cutting issues and uncertainties across Carbon Dioxide Removal (CDR) options aspects and uncertainties

Area of uncertainty	***Cross-cutting issues and uncertainties***
Technology upscaling	• CDR options are at different stages of technological readiness (McLaren, 2012) and differ with respect to scalability. • Nemet et al. (2018) find >50% of the CDR innovation literature concerned with the earliest stages of the innovation process (R&D) identifying a dissonance between the large CO_2 removals needed in 1.5°C pathways and the long-time periods involved in scaling up novel technologies. • Lack of post-R&D literature, including incentives for early deployment, niche markets, scale-up, demand, and public acceptance.
Emerging and niche technologies	• For BECCS, there are niche opportunities with high efficiencies and fewer trade-offs (e.g., sugar and paper processing facilities (Möllersten et al., 2003), district heating (Kärki et al., 2013; Ericsson and Werner, 2016), industrial and municipal waste (Sanna et al., 2012). Turner et al. (2018) constrain potential using

	sustainability considerations and overlap with storage basins to avoid the CO_2 transportation challenge, providing a possible, though limited entry point for BECCS. • The impacts on land use, water, nutrients and albedo of BECCS could be alleviated using marine sources of biomass that could include aqua-cultured micro and macro flora (Hughes et al., 2012; Lenton, 2014) • Regarding captured CO_2 as a resource is discussed as an entry point for CDR. However, this does not necessarily lead to carbon removals, particularly if the CO_2 is sourced from fossil fuels and/or if the products do not store the CO_2 for climate-relevant horizons (von der Assen et al. 2013) (see also Section 4.3.4.5). • Methane[8] is a much more potent GHG than CO_2 (Montzka et al., 2011), associated with difficult-to-abate emissions in industry and agriculture, outgassing from lakes, wetlands, and oceans (Lockley, 2012; Stolaroff et al., 2012). Enhancing processes that naturally remove methane, either by chemical or biological decomposition (Sundqvist et al., 2012), has been proposed to remove CH_4. There is low confidence that existing technologies for methane removal are economically or energetically suitable for large-scale air capture (Boucher and Folberth, 2010). Methane removal potentials are limited due to its low atmospheric concentration and its low chemical reactivity at ambient conditions.
Ethical aspects	• Preston (2013) identifies distributive and procedural justice, permissibility, moral hazard (Shue, 2018), and hubris as ethical aspects that could apply to large-scale CDR deployment. • There is a lack of reflection on the climate futures produced by recent modelling and implying very different ethical costs/risks and benefits (Minx et al., 2018).
Governance	• Existing governance mechanisms are scarce and either targeted at particular CDR options (e.g., ocean-based) or aspects (e.g., concerning indirect land-use change (iLUC) associated with bioenergy upscaling) and often the mechanisms are at national or regional scale (e.g., EU). Regulation accounting for iLUC by formulating sustainability criteria (e.g., the EU Renewable Energy Directive) has been assessed as insufficient in avoiding leakage (e.g., Frank et al., 2013) • An international governance mechanism is only in place for R&D of Ocean Fertilisation within the Convention on Biological Diversity (IMO, 1972, 1996, CBD, 2008, 2010). • Burns and Nicholson (2017) propose a human rights-based approach to protect those potentially adversely impacted by CDR options.
Policy	• The CDR potentials that can be realised are constrained by the lack of policy portfolios incentivising large-scale CDR (Peters and Geden, 2017). • Near-term opportunities could be supported through modifying existing policy mechanisms (Lomax et al., 2015). • Scott and Geden (2018) sketch three possible routes for limited progress, (1) at EU-level, (2) at EU Member State level, and (3) at private sector level, noting the implied paradigm shift this would entail. • EU may struggle to adopt policies for CDR deployment on the scale or time-frame envisioned by IAMs (Geden et al., 2018). • Social impacts of large-scale CDR deployment (Buck, 2016) require policies taking these into account.
Carbon cycle	• On long time scales, natural sinks could reverse (C.D. Jones et al., 2016) • No robust assessments yet of the effectiveness of CDR in reverting climate change (Tokarska and Zickfeld, 2015; Wu et al., 2015; Keller et al., 2018), see also Section 2.2.2 and 2.6.2.

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[8] FOOTNOTE: Current work (e.g.de Richter et al. 2017) examines other technologies considering non-CO_2 GHGs like N_2O.

4.3.8 Solar Radiation Modification (SRM)

This report refrains from using the term ‘geoengineering’ and separates SRM from CDR and other mitigation options (see Section 1.4.1 and Glossary).

Table 4.6 gives an overview of SRM methods and characteristics. For a more comprehensive discussion of currently proposed SRM methods, and their implications for geophysical quantities and sustainable development, see Cross-Chapter Box 10 in this Chapter. This section assesses the feasibility, from an institutional, technological, economic and social-cultural viewpoint, focusing on Stratospheric Aerosol Injection (SAI) unless otherwise indicated, as most available literature is about SAI.

Some of the literature on SRM appears in the forms of commentaries, policy briefs, viewpoints and opinions (e.g., (Horton et al., 2016; Keith et al., 2017; Parson, 2017). This assessment covers original research rather than viewpoints, even if the latter appear in peer-reviewed journals.

Table 4.7: Overview of the main characteristics of the most-studied SRM methods

	Stratospheric aerosol injection (SAI)	**Marine cloud brightening (MCB)**	**Cirrus cloud thinning (CCT)**	**Ground-based albedo modification (GBAM)**
Description of SRM method	Injection of a gas in the stratosphere, which then converts to aerosols. Injection of other particles also considered.	Spraying sea salt or other particles into marine clouds, making them more reflective.	Seeding to promote nucleation, reducing optical thickness and cloud lifetime, to allow more outgoing longwave radiation to escape into space.	Whitening roofs, changes in land use management (e.g., no-till farming), change of albedo at a larger scale (covering glaciers or deserts with reflective sheeting and changes in ocean albedo).
Radiative forcing efficiencies	1–4 TgS W^{-1} m^2 yr^{-1}	100–295 Tg dry sea salt W^{-1} m^2 yr^{-1}	Not known	Small on global scale, up to 1–3°C on regional scale
Amount needed for 1°C overshoot	2–8 TgS yr^{-1}	70 Tg dry sea salt yr^{-1}	Not known	0.04–0.1 albedo change in agricultural and urban areas
SRM specific impacts on climate variables	Changes in precipitation patterns and circulation regimes; in case of SO_2 injection disruption to stratospheric chemistry (for instance NOx depletion and changes in methane lifetime); increase in stratospheric water vapour and tropospheric-stratospheric ice formation affecting cloud microphysics.	Regional rainfall responses; reduction in hurricane intensity	Low-level cloud changes; tropospheric drying; intensification of the hydrological cycle	Impacts on precipitation in monsoon areas; could target hot extremes
SRM specific impacts on human/natural systems	In case of SO_2 injection - stratospheric ozone loss (which could also have a positive effect	Reduction in the number of mild crop failures		

	– a net reduction in global mortality due to competing health impact pathways) and significant increase of surface UV			
Maturity of science	Volcanic analogues *High agreement* amongst simulations *Robust evidence* on ethical, governance and sustainable development limitations	Observed in ships tracks Several simulations confirm mechanism Regionally limited	No clear physical mechanism *Limited evidence* and *low agreement* several simulations	Natural and land-use analogues Several simulations confirm mechanism *High agreement* to influence on regional temperature Land use costly
Key references	(Robock et al., 2008; Heckendorn et al., 2009; Tilmes et al., 2012, 2016; Pitari et al., 2014; Crook et al., 2015; C.J. Smith et al., 2017; Visioni et al., 2017a, b; Eastham et al., 2018; Plazzotta et al., 2018)	(Salter et al., 2008; Alterskjær et al., 2012; Jones and Haywood, 2012; Latham et al., 2012, 2013; Kravitz et al., 2013; Crook et al., 2015; Parkes et al., 2015; Ahlm et al., 2017)	(Storelvmo et al., 2014; Kristjánsson et al., 2015; Jackson et al., 2016; Kärcher, 2017; Lohmann and Gasparini, 2017)	(Irvine et al., 2011; Akbari et al., 2012; Jacobson and Ten Hoeve, 2012; Davin et al., 2014; Crook et al., 2015, 2016; Seneviratne et al., 2018)

SRM could reduce some of the global risks of climate change related to temperature rise (Izrael et al., 2014; MacMartin et al., 2014), rate of sea level rise (Moore et al., 2010), sea-ice loss (Berdahl et al., 2014) and frequency of extreme storms in the North Atlantic and heatwaves in Europe (Jones et al., 2018). SRM also holds risks of changing precipitation and ozone concentrations and potentially reductions in biodiversity (Pitari et al., 2014; Visioni et al., 2017a; Trisos et al., 2018). Literature only supports SRM as a supplement to deep mitigation, for example in overshoot scenarios (Smith and Rasch, 2013; MacMartin et al., 2018).

4.3.8.1 Governance and Institutional Feasibility

There is *robust evidence* but *medium agreement* for unilateral action potentially becoming a serious SRM governance issue (Weitzman, 2015; Rabitz, 2016), as some argue that enhanced collaboration might emerge around SRM (Horton, 2011). An equitable institutional or governance arrangement around SRM would have to reflect views of different countries (Heyen et al., 2015; Robock, 2016) and be multilateral because of the risk of termination, and risks that implementation or unilateral action by one country or organisation will produce negative precipitation or extreme weather effects across borders (Lempert and Prosnitz, 2011; Dilling and Hauser, 2013; NRC, 2015b). Some have suggested that the governance of research and field experimentation can help clarify uncertainties surrounding deployment of SRM (Long and Shepherd, 2014; Parker, 2014; NRC, 2015c; Caldeira and Bala, 2017; Lawrence and Crutzen, 2017), and that SRM is compatible with democratic processes (Horton et al., 2018) or not (Szerszynski et al., 2013; Owen, 2014).

Several possible institutional arrangements have been considered for SRM governance: under the UNFCCC (in particular under the Subsidiary Body on Scientific and Technological Advice (SBSTA)) or the United Nations Convention on Biological Diversity (UNCBD) (Honegger et al., 2013; Nicholson et al., 2018), or through a consortium of states (Bodansky, 2013; Sandler, 2017). Voice in SRM diplomacy, prevention of unilateral action by others and benefits from research collaboration might be reasons for states to join an international governance framework for SRM (Lloyd and Oppenheimer, 2014).

Alongside SBSTA, the WMO, UNESCO and UN Environment could play a role in governance of SRM (Nicholson et al., 2018). Each of these organisations has relevance with respect to the regulatory framework (Bodle et al., 2012; Williamson and Bodle, 2016). The UNCBD gives guidance that ‘that no climate-related geo-engineering activities that may affect biodiversity take place’ (UNCBD, 2010).

4.3.8.2 Economic and Technological Feasibility

The literature on engineering cost of SRM is limited and may be unreliable in the absence of testing or deployment. There is *high agreement* that cost of SAI (not taking into account indirect and social costs, research and development costs and monitoring expenses) may be in the range of 1–10 billion USD yr^{-1} for injection of 1–5 MtS to achieve cooling of 1–2 W m^{-2} (Robock et al., 2009; McClellan et al., 2012; Ryaboshapko and Revokatova, 2015; Moriyama et al., 2016), suggesting that cost-effectiveness may be high if side-effects are low or neglected (McClellan et al., 2012). The overall economic feasibility of SRM also depends on externalities and social costs (Moreno-Cruz and Keith, 2013; Mackerron, 2014), climate sensitivity (Kosugi, 2013), option value (Arino et al., 2016), presence of climate tipping points (Eric Bickel, 2013) and damage costs as a function of the level of SRM (Bahn et al., 2015; Heutel et al., 2018). Modelling of game-theoretic, strategic interactions of states under heterogeneous climatic impacts shows *low agreement* on the outcome and viability of a cost-benefit analysis for SRM (Ricke et al., 2015; Weitzman, 2015).

For SAI, there is *high agreement* that aircrafts after some modifications could inject millions of tons of SO_2 in the lower stratosphere (~20 km; (Davidson et al., 2012; McClellan et al., 2012; Irvine et al., 2016).

4.3.8.3 Social Acceptability and Ethics

Ethical questions around SRM include those of international responsibilities for implementation, financing, compensation for negative effects, the procedural justice questions of who is involved in decisions, privatisation and patenting, welfare, informed consent by affected publics, intergenerational ethics (because SRM requires sustained action in order to avoid termination hazards), and the so-called ‘moral hazard’ (Burns, 2011; Whyte, 2012; Gardiner, 2013; Lin, 2013; Buck et al., 2014; Klepper and Rickels, 2014; Morrow, 2014; Wong, 2014; Reynolds, 2015; Lockley and Coffman, 2016; McLaren, 2016; Suarez and van Aalst, 2017; Reynolds et al., 2018). The literature shows *low agreement* on whether SRM research and deployment may lead policy-makers to reduce mitigation efforts and thus imply a moral hazard (Linnér and Wibeck, 2015). SRM might motivate individuals (as opposed to policymakers) to reduce their GHG emissions (Merk et al., 2016), but even a subtle difference in the articulation of information about SRM can influence subsequent judgements of favourability (Corner and Pidgeon, 2014). The argument that SRM research increases the likelihood of deployment (the ‘slippery slope’ argument), is also made (Parker, 2014; Quaas et al., 2017; Bellamy and Healey, 2018).

Unequal representation and deliberate exclusion are plausible in decision-making on SRM, given diverging regional interests and the anticipated low resource requirements to deploy SRM (Ricke et al., 2013). Whyte (2012) argues that the concerns, sovereignties, and experiences of Indigenous peoples may particularly be at risk.

The general public can be characterised as ignorant and worried about SRM (Carr et al., 2013; Parkhill et al., 2013; Wibeck et al., 2017). An emerging literature discusses public perception of SRM, showing a lack of knowledge and unstable opinions (Scheer and Renn, 2014). The perception of controllability affects legitimacy and public acceptability of SRM experiments (Bellamy et al., 2017). In Germany, laboratory work on SRM is generally approved of, field research much less so, and immediate deployment is largely rejected (Merk et al., 2015; Braun et al., 2017). Various factors could explain variations in the degree of rejection of SRM between Canada, China, Germany, Switzerland, the United Kingdom, and the United States (Visschers et al., 2017).

[START CROSS-CHAPTER BOX 10 HERE]

Cross-Chapter Box 10: Solar Radiation Modification in the Context of 1.5°C Mitigation Pathways

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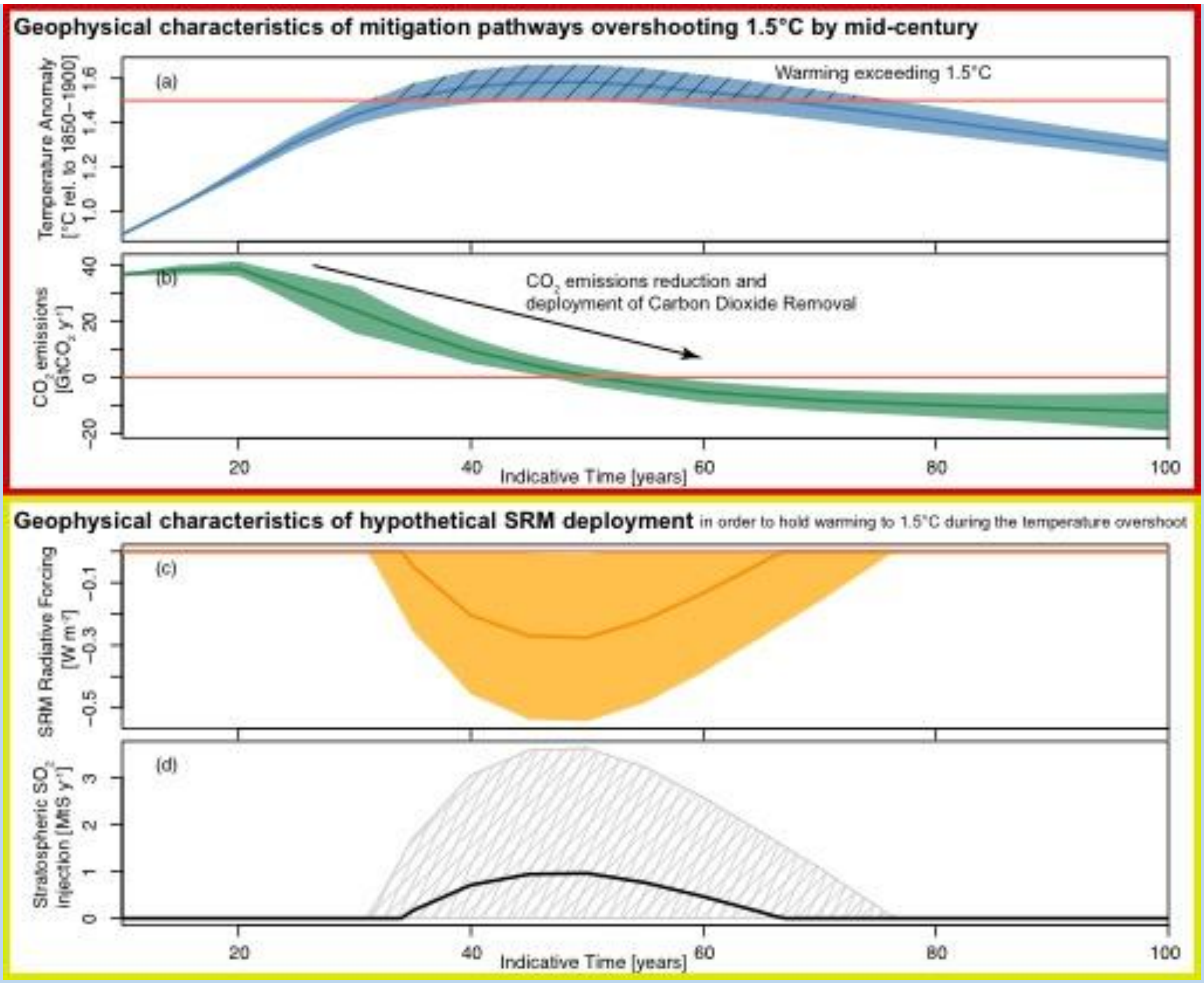
Solar Radiation Modification (SRM) refers to a range of radiation modification measures not related to Greenhouse Gas (GHG) mitigation, which seek to limit global warming (see Section 1.4.1). Most methods involve reducing the solar incoming radiation reaching the surface, but others also act on the longwave radiation budget reducing optical thickness and cloud lifetime (see Table 4.6). In the context of this report, SRM is assessed in terms of its potential to limiting warming below 1.5°C in temporary overshoot scenarios as a way to reduce elevated temperatures and associated impacts (Irvine et al., 2016; Keith and Irvine, 2016; Chen and Xin, 2017; Sugiyama et al., 2017a; Visioni et al., 2017a; MacMartin et al., 2018). The inherent variability of the climate system would make it difficult to detect the efficacy or side-effects of SRM intervention when deployed in such a temporary scenario (Jackson et al., 2015).

A. Potential SRM timing and magnitude

Published SRM approaches are summarised in Table 4.6. The timing and magnitude of potential SRM deployment depends on the temperature overshoot associated with mitigation pathways. All overshooting pathways make use of carbon dioxide removal. Therefore, if considered, SRM would only be deployed as a supplement measure to large-scale carbon dioxide removal (Section 2.3).

Cross-Chapter Box 10, Figure 1 below illustrates an example of how a hypothetical SRM deployment based on Stratospheric Aerosols Injection (SAI) could be used to limit warming below 1.5°C using an ‘adaptive SRM’ approach (e.g., Kravitz et al. 2011; Tilmes et al., 2016), where global mean temperature exceeds 1.5°C compared to pre-industrial level by mid-century and returns below before 2100 with a 66% likelihood (see Chapter 2). In all such limited adaptive deployment scenarios, deployment of SRM only commences under conditions in which CO_2 emissions have already fallen substantially below their peak level and are continuing to fall. In order to hold warming to 1.5°C, a hypothetical SRM deployment could span from one to several decades with the earliest possible threshold exceedance occurring before mid-century. Over this duration, SRM has to compensate for warming that exceeds 1.5°C (displayed with hatching on panel a) with a decrease in radiative forcing (panel b) which could be achieved with a rate of SAI varying between 0–5.9 $MtSO_2$ yr^{-1} (panel c) (Robock et al., 2008; Heckendorn et al., 2009).



Cross-Chapter Box CB10, Figure 1: Evolution of hypothetical SRM deployment (based on SAI) in the context of 1.5°C-consistent pathways. (a) Range of median temperature outcomes as simulated by MAGICC (see in Section 2.2) given the range of CO_2 emissions (b) and other climate forcers for mitigation pathways exceeding 1.5°C at mid-century and returning below by 2100 with a 66% likelihood. Geophysical characteristics are represented by the magnitude of radiative forcing (c) and the amount of stratospheric SO_2 injection (d) that are required to keep the global median temperature below 1.5°C during the temperature overshoot (given by the blue hatching on panel a). SRM surface radiative forcing has been diagnosed using a mean cooling efficiency of 0.3°C (W^{-1} m^2) of Plazzotta et al. (2018). Magnitude and timing of SO_2 injection have been derived from published estimates of Heckendorn et al. (2009) and Robock et al. (2008).

SAI is the most researched SRM method with *high agreement* that it could limit warming to below 1.5°C (Tilmes et al., 2016; Jones et al., 2018). The response of global temperature to SO_2 injection, however, is uncertain and varies depending on the model parametrisation and emission scenarios (Jones et al., 2011; Kravitz et al., 2011; Izrael et al., 2014; Crook et al., 2015; Niemeier and Timmreck, 2015; Tilmes et al., 2016; Kashimura et al., 2017). Uncertainty also arises due to the nature and the optical properties of injected aerosols.

Other approaches are less well researched but the literature suggests that Ground-Based Albedo Modification (GBAM), Marine Cloud Brightening (MCB) or Cirrus Cloud Thinning (CCT) are not assessed to be able to substantially reduce overall global temperature (Irvine et al., 2011; Seneviratne et al., 2018). However, these SRM approaches are known to create spatially heterogeneous forcing and potentially more spatially heterogeneous climate effects, which may be used to mitigate regional climate impacts. This may be of most relevance in the case of GBAM when applied to crop and urban areas (Seneviratne et al. 2018). Most of the literature on regional mitigation has focused on GBAM in relationship with land-use land cover changes scenarios. Both models and observations suggest that there is a *high agreement* that GBAM would result in cooling over the region of changed albedo, and in particular reduce hot extremes (Irvine et al., 2011; Akbari et al., 2012; Jacobson and Ten Hoeve, 2012; Davin et al., 2014; Crook et al., 2015, 2016; Alkama and Cescatti, 2016; Seneviratne et al., 2018). In comparison, there is a *limited evidence* on the ability of MCB or CCT to mitigate regional climate impacts of 1.5°C warming because the magnitude of the climate response to MCB or CCT remains uncertain and the processes are not fully understood (Lohmann and Gasparini, 2017).

B. General consequence and impacts of solar radiation modification

It has been proposed that deploying SRM as a supplement to mitigation may reduce increases in global temperature-related extremes and rainfall intensity, and lessen the loss of coral reefs from increasing sea-surface temperatures (Keith and Irvine, 2016), but it would not address or even worsen (Tjiputra et al., 2016) negative effects from continued ocean acidification.

Another concern with SRM is the risk of a 'termination shock' or 'termination effect' when suddenly stopping SRM, which might cause rapid temperature rise and associated impacts (Jones et al., 2013; Izrael et al., 2014; McCusker et al., 2014; Robock, 2016), most noticeably biodiversity loss (Trisos et al., 2018). The severity of the termination effect has recently been debated (Parker and Irvine, 2018) and depends on the degree of SRM cooling. This report only considers limited SRM in the context of mitigation pathways to 1.5°C. Other risks of SRM deployment could be associated with the lack of testing of the proposed deployment schemes (*e.g.* (Schäfer et al., 2013)). Ethical aspects and issues related to the governance and economics are discussed in Section 4.3.8.

C. Consequences and impacts of SRM on the carbon budget

Because of its effects on surface temperature, precipitation and surface shortwave radiation, SRM would also alter the carbon budget pathways to 1.5°C or 2°C (Eliseev, 2012; Keller et al., 2014; Keith et al., 2017; Lauvset et al., 2017).

Despite the large uncertainties in the simulated climate response to SRM, current model simulations suggest that SRM would lead to altered carbon budgets compatible with 1.5°C or 2°C. The 6 CMIP5 models investigated simulated an increase of natural carbon uptake by land biosphere and, to a smaller extent, by the oceans (*high agreement*). The multi-model mean of this response suggests an increase of the RCP4.5 carbon budget of about 150 $GtCO_2$ after 50 years of SO_2 injection with a rate of 4 TgS yr^{-1}, which represents about 4 years of CO_2 emissions at the current rate (36 $GtCO_2$ yr^{-1}). However, there is uncertainty around quantitative determination of the effects that SRM or its cessation has on the carbon budget due to a lack of understanding of the radiative processes driving the global carbon cycle response to SRM (Ramachandran et al., 2000; Mercado et al., 2009; Eliseev, 2012; Xia et al., 2016), uncertainties about how the carbon cycle will respond to termination effects of SRM, and uncertainties in climate-carbon cycle feedbacks (Friedlingstein et al., 2014).

D. Sustainable development and SRM

There are few studies investigating potential implications of SRM for sustainable development. These are based on a limited number of scenarios and hypothetical considerations, mainly referring to benefits from lower temperatures (Irvine et al., 2011; Nicholson, 2013; Anshelm and Hansson, 2014; Harding and Moreno-Cruz, 2016). Other studies suggest negative impacts from SRM implementation concerning issues related to regional disparities (Heyen et al., 2015), equity (Buck, 2012), fisheries, ecosystems, agriculture, and termination effects (Robock, 2012; Morrow, 2014; Wong, 2014). If SRM is initiated by the richer nations, there might be issues with local agency, and possibly worsening conditions for those suffering most under climate change (Buck et al., 2014). In addition, ethical issues related to testing SRM have been raised (e.g., (Lenferna et al., 2017)). Overall, there is *high agreement* that SRM would affect many development issues but *limited evidence* on the degree of influence, and how it manifests itself across regions and different levels of society.

E. Overall feasibility of SRM

If mitigation efforts do not keep global mean temperature below 1.5°C, SRM can potentially reduce the climate impacts of a temporary temperature overshoot, in particular extreme temperatures, rate of sea level rise and intensity of tropical cyclones, alongside intense mitigation and adaptation efforts. While theoretical developments show that SRM is technically feasible (see Section 4.3.8.2), global field experiments have not been conducted and most of the knowledge about SRM is based on imperfect model simulations and some natural analogues. There are also considerable challenges to the implementation of SRM associated with disagreements over the governance, ethics, public perception, and distributional development impacts (Boyd, 2016; Preston, 2016; Asayama et al., 2017; Sugiyama et al., 2017b; Svoboda, 2017; McKinnon, 2018; Talberg et al., 2018) (see Section 4.3.8). Overall, the combined uncertainties surrounding the various SRM approaches, including technological maturity, physical understanding, potential impacts, and challenges of governance, constrain the ability to implement SRM in the near future.

[END CROSS-CHAPTER BOX 10 HERE]

4.4 Implementing Far-Reaching and Rapid Change

The feasibility of 1.5°C-compatible pathways is contingent upon enabling conditions for systemic change (see Cross Chapter Box 3 in Chapter 1). Section 4.3 identifies the major systems, and options within those systems, that offer the potential for change to align with 1.5°C pathways.

AR5 identifies enabling conditions as influencing the feasibility of climate responses (Kolstad et al., 2014). This section draws on 1.5°C-specific and related literature on rapid and scale-up change, to identify the enabling conditions that influence the feasibility of adaptation and mitigation options assessed in Section 4.5. Examples from diverse regions and sectors are provided to illustrate how these conditions could enable or constrain the implementation of incremental, rapid, disruptive and transformative mitigation and adaptation consistent with 1.5°C pathways.

Coherence between the enabling conditions holds potential to enhance feasibility of 1.5°C-consistent pathways and adapting to the consequences. This includes better alignment across governance scales (OECD/IEA/NEA/ITF, 2015; Geels et al., 2017), enabling multi-level governance (Cheshmehzangi, 2016; Revi, 2017; Tait and Euston-Brown, 2017) and nested institutions (Abbott, 2012). It also includes inter-disciplinary actions, combined adaptation and mitigation action (Göpfert et al., 2018) and science-policy partnerships (Vogel et al., 2007; Hering et al., 2014; Roberts, 2016; Figueres et al., 2017; Leal Filho et al., 2018). These partnerships are difficult to establish and sustain, but can generate trust (Cole, 2015; Jordan et al., 2015) and inclusivity that ultimatley can provide durability and the realisation of co-benefits for sustained rapid change (Blanchet, 2015; Ziervogel et al., 2016a).

4.4.1 Enhancing Multi-Level Governance

Addressing climate change and implementing responses to 1.5°C-consistent pathways will need to engage with various levels and types of governance (Betsill and Bulkeley, 2006; Kern and Alber, 2009; Christoforidis et al., 2013; Romero-Lankao et al., 2018). AR5 highlighted the significance of governance as a means of strengthening adaptation and mitigation and advancing sustainable development (Fleurbaey et al., 2014). Governance is defined in the broadest sense as the ‘processes of interaction and decision making among actors involved in a common problem’ (Kooiman 2003, Hufty 2011) (Fleurbaey et al., 2014). This definition goes beyond notions of formal government or political authority and integrates other actors, networks, informal institutions and communities.

4.4.1.1 Institutions and their Capacity to Invoke Far-Reaching and Rapid Change

Institutions, the rules and norms that guide human interactions (Section 4.4.2), enable or impede the structures, mechanisms and measures that guide mitigation and adaptation. Institutions, understood as the ‘rules of the game’ (North, 1990), exert direct and indirect influence over the viability of 1.5°C-consistent pathways (Munck et al., 2014; Willis, 2017). Governance would be needed to support wide-scale and effective adoption of mitigation and adaptation options. Institutions and governance structures are strengthened when the principle of the 'commons' is explored as a way of sharing management and responsibilities (Ostrom et al., 1999; Chaffin et al., 2014; Young, 2016). Institutions would need to be strengthened to interact amongst themselves, and to share responsibilities for the development and implementation of rules, regulations and policies (Ostrom et al., 1999; Wejs et al., 2014; Craig et al., 2017), with the goal of ensuring that these embrace equity, justice, poverty alleviation and sustainable development, enabling a 1.5°C world (Reckien et al., 2017; Wood et al., 2017).

Several authors have identified different modes of cross-stakeholder interaction in climate policy, including the role played by large multinational corporations, small enterprises, civil society and non-state actors. Ciplet et al. (2015) argue that civil society is to a great extent the only reliable motor for driving institutions to change at the pace required. Kern and Alber (2009) recognise different forms of collaboration relevant to successful climate policies beyond the local level. Horizontal collaboration (e.g., transnational city networks) and vertical collaboration within nation-states can play an enabling role (Ringel, 2017). Vertical and horizontal collaboration requires synergistic relationships between stakeholders (Ingold and Fischer, 2014; Hsu et al., 2017). The importance of community participation is emphasised in literature, and in particular the need to take into account equity and gender considerations (Chapter 5) (Graham et al., 2015; Bryan et al., 2017; Wangui and Smucker, 2017). Participation often faces implementation challenges and may not always result in better policy outcomes. Stakeholders, for example, may not view climate change as a priority and may not share the same preferences, potentially creating a policy deadlock (Preston et al., 2013, 2015; Ford et al., 2016).

4.4.1.2 International Governance

International treaties help strengthen policy implementation, providing a medium and long-term vision (Obergassel et al., 2016). International climate governance is organised via many mechanisms, including international organisations, treaties and conventions, for example, UNFCCC, the Paris Agreement and the Montreal Protocol. Other multilateral and bilateral agreements, such as trade agreements, also have a bearing on climate change.

There are significant differences between global mitigation and adaptation governance frames. Mitigation tends to be global by its nature and it is based on the principle of the climate system as a global commons (Ostrom et al., 1999). Adaptation has traditionally been viewed as a local process, involving local authorities, communities, and stakeholders (Khan, 2013; Preston et al., 2015), although is now recognised to be a multi-scaled, multi-actor process that transcends from local and sub-national, to national and international scales (Mimura et al., 2014; UNEP, 2017a). National governments provide a central pivot for coordination, planning, determining policy (Section 4.4.5) priorities and distributing resources. National governments are accountable to the international community through international agreements. Yet, many of the impacts of climate change are transboundary, so that bilateral and multilateral cooperation are needed (Nalau et al., 2015; Donner et al., 2016; Magnan and Ribera, 2016; Tilleard and Ford, 2016; Lesnikowski et al., 2017). The Kigali Amendment to the Montreal Protocol demonstrates that a global environmental agreement facilitating common but differentiated responsibilities is possible (Sharadin, 2018). This was operationalised by developed countries acting first, with developing countries following and benefiting from leap-frogging the trial-and-error stages of innovative technology development.

Work on international climate governance has focused on the nature of 'climate regimes' and coordinating the action of nation-states (Aykut, 2016) organised around a diverse set of intruments: i) binding limits allocated by principles of historical responsibility and equity, ii) carbon prices, emissions quotas, iii) pledges and review of policies and measures or iv) a combination of these options (Stavins, 1988; Grubb, 1990; Pizer, 2002; Newell and Pizer, 2003).

Literature on the Kyoto Protocol provides two important insights for 1.5°C transition: the challenge of agreeing on rules to allocate emissions quotas (Shukla, 2005; Caney, 2012; Winkler et al., 2013; Gupta, 2014; Méjean et al., 2015) and a climate-centric vision (Shukla, 2005; Winkler et al., 2011), separated from development issues which drove resistance from many developing nations (Roberts and Parks, 2006). For the former, a burden sharing approach led to an adversarial process among nations to decide who shall be allocated 'how much' of the remainder of the emissions budget (Caney, 2014; Ohndorf et al., 2015; Roser et al., 2015; Giménez-Gómez et al., 2016). Industry group lobbying, further contributed to reducing space for maneuvre of some major emitting nations (Newell and Paterson, 1998; Levy and Egan, 2003; Dunlap and McCright, 2011; Michaelowa, 2013; Geels, 2014).

Given the political unwillingness to continue with the Kyoto Protocol approach a new approach was introduced in the Copenhagen Accord, the Cancun Agreements, and finally in the Paris Agreement. The transition to 1.5°C requires carbon neutrality and thus going beyond the traditional framing of climate as a 'tragedy of the commons' to be addressed via cost-optimal allocation rules, which demonstrated a low probability of enabling a transition to 1.5°C consistent pathways (Patt, 2017). The Paris Agreement, built on a 'pledge and review'-system is thought be more effective in securing trust (Dagnet et al., 2016), enables effective monitoring and timely reporting on national actions (including adaptation), allowing for international scrutiny and persistent efforts of civil society and non-state actors to encourage action in both national and international contexts (Allan and Hadden, 2017; Bäckstrand and Kuyper, 2017; Höhne et al., 2017; Lesnikowski et al., 2017; Maor et al., 2017; UNEP, 2017a), with some limitations (Nieto et al., 2018).

The paradigm shift enabled at Cancun succeeded by focusing on the objective of 'equitable access to sustainable development' (Hourcade et al., 2015). The use of 'pledge and review' now underpins the Paris Agreement. This consolidates multiple attempts to define a governance approach that relies on National Determined Contributions (NDCs) and on means for a 'facilitative model' (Bodansky and Diringer, 2014) to reinforce them. This enables a regular, iterative, review of NDCs allowing countries to set their own ambitions after a global stocktake and more flexible, experimental forms of climate governance, which may provide room for higher ambition, and be consistent with the needs of governing for a rapid transition to close the emission gap (Clémençon, 2016; Falkner, 2016) (Cross-Chapter Box11 in this Chapter). Beyond a general consensus on the necessity of Measurement, Reporting and Verification (MRV) mechanisms as a key element of a climate regime (Ford et al., 2015b; van Asselt et al., 2015), some authors emphasise different governance approaches to implement the Paris Agreement. Through market mechanisms under Article 6 of the Paris Agreement and the new proposed sustainable development mechanism, it allows the space to harness the lowest cost mitigation options worldwide. This may incentivise policymakers to enhance mitigation ambition by speeding up climate action as part of 'climate regime complex' (Keohane and Victor, 2011) of loosely interrelated global governance institutions. In the Paris Agreement, the Common But Differentiated Responsibilities and Respective Capabilities (CBDR-RC) principle could be expanded and revisited under a 'sharing the pie' paradigm (Ji and Sha, 2015) as a tool to open innovation processes towards alternative development pathways (Chapter 5).

COP16 in Cancun was also the first time in the UNFCCC that adaptation was recognised to have similar priority as mitigation. The Paris Agreement recognises the importance of adaptation action and cooperation to enhance such action. (Chung Tiam Fook, 2017; Lesnikowski et al., 2017) suggest that the Paris Agreement is explicit about multilevel adaptation governance, outlines stronger transparency mechanisms, links adaptation to development and climate justice, and is hence, suggestive of greater inclusiveness of non-state voices and the broader contexts of social change.

1.5°C-consistent pathways require further exploration of conditions of trust and reciprocity amongst nation states (Schelling, 1991; Ostrom and Walker, 2005). Some authors (Colman et al., 2011; Courtois et al., 2015) suggest a departure from the vision of actors acting individually in the pursuit of self-interest to that of iterated games with actors interacting over time showing that reciprocity, with occasional forgiveness and initial good faith, can lead to win-win outcomes and to cooperation as a stable strategy (Axelrod and Hamilton, 1981).

Regional cooperation plays an important role in the context of global governance. Literature on climate regimes has only started exploring innovative governance arrangements including: coalitions of transnational actors including state, market and non-state actors (Bulkeley et al., 2012; Hovi et al., 2016; Hagen et al., 2017; Hermwille et al., 2017; Roelfsema et al., 2018) and groupings of countries, as a complement to the

UNFCCC (Abbott and Snidal, 2009; Biermann, 2010; Zelli, 2011; Nordhaus, 2015). Climate action requires multi-level governance from the local and community level to national, regional and international levels. Box 4.1 shows the role of sub-national authorities, e.g. regions and provinces in facilitating urban climate action, while Box 4.2 shows that climate governance can be organised across hydrological and not only political units as well.

4.4.1.3 Sub-National Governance

Local governments can play a key role (Melica et al., 2018; Romero-Lankao et al., 2018) in influencing mitigation and adaptation strategies. It is important to understand how rural and urban areas, small islands, informal settlements and communities might intervene to reduce climate impacts (Bulkeley et al., 2011), either by implementing climate objectives defined at higher government levels, taking initiative autonomously or collectively (Aall et al., 2007; Reckien et al., 2014; Araos et al., 2016a; Heidrich et al., 2016). Local governance faces the challenge of reconciling local concerns with global objectives. Local governments could coordinate and develop effective local responses, and could pursue procedural justice in ensuring community engagement and more effective policies around energy and vulnerability reduction (Moss et al., 2013; Fudge et al., 2016). They can enable more participative decision-making (Barrett, 2015; Hesse, 2016). Fudge et al. (2016) argue that local authorities are well-positioned to involve the wider community in: designing and implementing climate policies, engaging with sustainable energy generation, e.g., by supporting energy communities (Slee, 2015), and the delivery of demand-side measures and adaptation implementation.

By 2050, it is estimated three billion people will be living in slums and informal settlements: neighbourhoods without formal governance, on un-zoned land developments and in places that are exposed to climate-related hazards (Bai et al., 2018). Emerging research is examining how citizens can contribute informally to governance with rapid urbanisation and weaker government regulation (Sarmiento and Tilly, 2018). It remains to be seen how the possibilities and consequences of alternative urban governance models for large, complex problems and addressing inequality and urban adaptation will be managed (Amin and Cirolia, 2018; Bai et al., 2018; Sarmiento and Tilly, 2018).

Expanding networks of cities sharing experiences on coping with climate change and drawing economic and development benefits from climate change responses represent a recent institutional innovation. This could be complemented by efforts of national governments through national urban policies to enhance local climate action (Broekhoff et al., 2018). Over the years, non-state actors have set up several transnational climate governance initiatives to accelerate the climate response, for example ICLEI (1990), C–40 (2005), the Global Island Partnership (2006) and the Covenant of Mayors (2008) (Gordon and Johnson, 2017; Hsu et al., 2017; Ringel, 2017; Kona et al., 2018; Melica et al., 2018) and to exert influence on national governments and the UNFCCC (Bulkeley, 2005). However, (Michaelowa and Michaelowa, 2017) find low effectiveness of over 100 of such mitigation initiatives.

4.4.1.4 Interactions and Processes for Multi-Level Governance

Literature has proposed multi-level governance in climate change as an enabler for systemic transformation and effective governance, as the concept is thought to allow for combining decisions across levels, sectors and institutional types at the same level (Romero-Lankao et al., 2018) with multi-level reinforcement and the mobilisation of economic interests at different levels of governance (Janicke and Quitzow, 2017). These governance mechanisms are based on accountability and transparency rules and participation and coordination across and within these levels.

A study of 29 European countries showed that the rapid adoption and diffusion of adaptation policymaking is largely driven by internal factors, at the national and sub-national levels (Massey et al., 2014). An assessment of national level adaptation in 117 countries (Berrang-Ford et al., 2014), find good governance to be the one of the strongest predictors of national adaptation policy. An analysis of climate response by 200 large and medium-sized cities across eleven European countries find that factors such as membership of climate networks, population size, Gross Domestic Product (GDP) per capita and adaptive capacity act as drivers of mitigation and adaptation plans (Reckien et al., 2015).

Adaptation policy has seen growth in some areas (Massey et al., 2014; Lesnikowski et al., 2016), although efforts to track adaptation progress are constrained by an absence of data sources on adaptation (Berrang-Ford et al. 2011; Ford and Berrang-Ford 2016; Magnan and Ribera 2016; Magnan 2016). Many developing countries have made progress in formulating national policies, plans and strategies on responding to climate change. The NDCs have been identified as one such institutional mechanism (Magnan et al., 2015; Kato and Ellis, 2016; Peters et al., 2017) (Cross-Chapter Box11 in this Chapter).

To overcome barriers to policy implementation, local conflicts of interest or vested interests, strong leadership and agency is needed by political leaders. As shown by the Covenant of Mayors initiative (Box 4.1), political leaders with a vision for the future of the local community can succeed in reducing GHG emissions, when they are supported by civil society (Rivas et al., 2015; Croci et al., 2017; Kona et al., 2018). Any political vision would need to be translated into an action plan, of which elements could be describing policies and measures needed to achieve transition, the human and financial resources needed, milestones, and appropriate measurement and verification processes (Azevedo and Leal, 2017). Discussing the plan with stakeholders and civil society, including citizens and right of participation for minorities, and having them provide input and endorse it, is found to increase the likelihood of success (Rivas et al., 2015; Wamsler, 2017). However, as described by Nightingale (2017) and Green (2016), struggles over natural resources and adaptation governance both at the national and community levels would need to be addressed too, ‘in politically unstable contexts, where power and politics shape adaptation outcomes’.

[START BOX 4.1 HERE]

Box 4.1: Multi-Level Governance in the EU Covenant of Mayors: Example of the Provincia di Foggia

Since 2005, cities have emerged as a locus of institutional and governance climate innovation (Melica et al., 2018) and are driving responses to climate change (Roberts, 2016). Many cities have adopted more ambitious Greenhouse Gas (GHG) emission reduction targets than countries (Kona et al., 2018), with an overall commitment of GHG emission reduction targets by 2020 of 27%, almost 7 percentage points higher than the minimum target for 2020 (Kona et al., 2018). The Covenant of Mayors (CoM) is an initiative in which municipalities voluntarily commit to CO_2 emission reduction. The participation of small municipalities has been facilitated by the development and testing of a new multi-level governance model involving Covenant Territorial Coordinators (CTCs), i.e., provinces and regions, which commit to providing strategic guidance, financial and technical support to municipalities in their territories. Results from the 315 monitoring inventories submitted shows an achievement of 23% reduction in emissions (compared to an average year 2005) of more than half of the cities under a CTC schema (Kona et al., 2018).

The Province of Foggia, acting as a CTC, gave support to 36 municipalities to participate in the CoM and to prepare Sustainable Energy Action Plans (SEAPs). The Province developed a common approach to prepare SEAPs, provided data to compile municipal emission inventories (Bertoldi et al., 2018) and guided the signatory to identify an appropriate combination of measures to curb GHG emissions programme. The local Chamber of Commerce had a key role also in the implementation of these projects by the municipalities (Lombardi et al., 2016). The joint action by the province and the municipalities in collaboration with the local business community could be seen as an example of multi-level governance (Lombardi et al., 2016).

Researchers have investigated local forms of collaboration within local government, with the active involvement of citizens and stakeholders, and acknowledge that public acceptance is key to the successful implementation of policies (Larsen and Gunnarsson-Östling, 2009; Musall and Kuik, 2011; Pollak et al., 2011; Christoforidis et al., 2013; Pasimeni et al., 2014; Lee and Painter, 2015). Achieving ambitious targets would need leadership, enhanced multi-level governance, vision and widespread participation in transformative change (Castán Broto and Bulkeley, 2013; Rosenzweig et al., 2015; Castán Broto, 2017;

Fazey et al., 2017; Wamsler, 2017; Romero-Lankao et al., 2018). The Section 5.6.4 case studies of climate-resilient development pathways, at state and community scales, show that participation, social learning and iterative decision-making are governance features of strategies that deliver mitigation, adaptation, and sustainable development in a fair and equitable manner. Other insights include that incremental voluntary changes are amplified through community networking, poly-centric governance (Dorsch and Flachsland, 2017) and partnerships and long-term change to governance systems at multiple levels (Stevenson and Dryzek, 2014; Lövbrand et al., 2017; Pichler et al., 2017; Termeer et al., 2017).

[END BOX 4.1 HERE]

Multilevel governance includes adaptation across local, regional, and national scales (Adger et al., 2005). The whole-of-government approach to understanding and influencing climate change policy design and implementation puts analytical emphasis on how different levels of government and different types of actors (e.g., public and private) can constrain or support local adaptive capacity (Corfee-Morlot et al., 2011), including the role of the civil society. National governments, for example, have been associated with enhancing adaptive capacity through building awareness of climate impacts, encouraging economic growth, providing incentives, establishing legislative frameworks conducive to adaptation, and communicating climate change information (Berrang-Ford et al., 2014; Massey et al., 2014; Austin et al., 2015; Henstra, 2016; Massey and Huitema, 2016). Local governments, on the other hand, are responsible for delivering basic services and utilities to the urban population, and protecting their integrity from the impacts of extreme weather (Austin et al., 2015; Cloutier et al., 2015; Nalau et al., 2015; Araos et al., 2016b). National policies and transnational governance could be seen as complementary, rather than competitors, and strong national policies favour sub- and non-state actors to engage transnationally (Andonova et al., 2017). Local initiatives are complementary with higher level policies and can be integrated in the multi-level governance system (Fuhr et al., 2018).

A multilevel approach considers that adaptation planning is affected by scale mismatches between the local manifestation of climate impacts and the diverse scales at which the problem is driven (Shi et al., 2016). Multilevel approaches may be relevant in low-income countries where limited financial resources and human capabilities within local governments often lead to greater dependency on national governments and other (donor) organisations, to strengthen adaptation responses (Donner et al., 2016; Adenle et al., 2017). National governments or international organisations may motivate urban adaptation externally through broad policy directives or projects by international donors. Municipal governments on the other hand work within the city to spur progress on adaptation. Individual political leadership in municipal government, for example, has been cited as a factor driving adaptation policy of early adapters in Quito, Ecuador, and Durban, South Africa (Anguelovski et al., 2014), and for adaptation more generally (Smith et al., 2009). Adaptation pathways can help identify maladaptive actions (Juhola et al., 2016; Magnan et al., 2016; Gajjar et al., 2018) and encourage social learning approaches across multiple levels of stakeholders in sectors such as marine biodiversity and water supply (Bosomworth et al., 2015; Butler et al., 2015; van der Brugge and Roosjen, 2015).

Box 4.2 exemplifies how multilevel governance has been used for watershed management in different basins, given the impacts on water sources (Section 3.4.2).

[START BOX 4.2 HERE]

Box 4.2: Watershed Management in a 1.5˚C World

Water management is necessary if the global community would adapt to 1.5°C-consistent pathways. Cohesive planning that includes numerous stakeholders will be required to improve access, utilisation and efficiency of water use and ensure hydrologic viability.

Response to drought and El Niño Southern Oscillation (ENSO) in Southern Guatemala

Hydro-meteorological events, including the ENSO, have impacted Central America (Steinhoff et al., 2014; Chang et al., 2015; Maggioni et al., 2016) and are projected to increase in frequency during a 1.5°C transition (Wang et al., 2017). The 2014–2016 ENSO damaged agriculture, seriously impacting rural communities.

In 2016, the Climate Change Institute, in conjunction with local governments, the private sector, communities and human rights organisations, established dialogue tables for different watersheds to discuss water usage amongst stakeholders and plans to mitigate the effects of drought, ameliorate social tension, and map water use of watersheds at risk. The goal was to encourage better water resource management and to enhance ecological flow through improved communication, transparency, and coordination amongst users. These goals were achieved in 2017 when each previously affected river reached the Pacific Ocean with at least its minimum ecological flow (Guerra, 2017).

Drought management through the Limpopo Watercourse Commission

The governments sharing the Limpopo river basin (Botswana, Mozambique, South Africa and Zimbabwe) formed the Limpopo Watercourse Commission in 2003 (Nyagwambo et al., 2008; Mitchell, 2013). It has an advisory body comprised of working groups that assess water use and sustainability, decides national level distribution of water access, and supports disaster and emergency planning. The Limpopo basin delta is highly vulnerable (Tessler et al., 2015), and is associated with a lack of infrastructure and investment capacity, requiring increased economic development together with plans for vulnerability reduction (Tessler et al., 2015) and water rights (Swatuk, 2015). The high vulnerability is influenced by gender inequality, limited stakeholder participation and institutions to address unequal water access (Mehta et al., 2014). The implementation of Integrated Water Resources Management (IWRM) would need to consider pre-existing social, economic, historical and cultural contexts (Merrey, 2009; Mehta et al., 2014). The Commission therefore could play a role in improving participation and in providing an adaptable and equitable strategy for cross-border water sharing (Ekblom et al., 2017).

Flood management in the Danube

The Danube River Protection Convention is the official instrument for cooperation on transboundary water governance between the countries that share the Danube Basin. The International Commission for the Protection of the Danube River (ICPDR) provides a strong science-policy link through expert working groups dealing with issues including governance, monitoring and assessment and flood protection (Schmeier, 2014). The Trans-National Monitoring Network (TNMN) was developed to undertake comprehensive monitoring of water quality (Schmeier, 2014). Monitoring of water quality constitutes almost 50% of ICPDR's scientific publications, which also works on governance, basin planning, monitoring, and IWRM, indicating the importance. The ICPDR is an example of IWRM ‘coordinating groundwater, surface water abstractions, flood management, energy production, navigation, and water quality’ (Hering et al., 2014).

[END BOX 4.2 HERE]

[START CROSS-CHAPTER BOX 11 HERE]

Cross-Chapter Box 11: Consistency Between Nationally Determined Contributions and 1.5°C Scenarios

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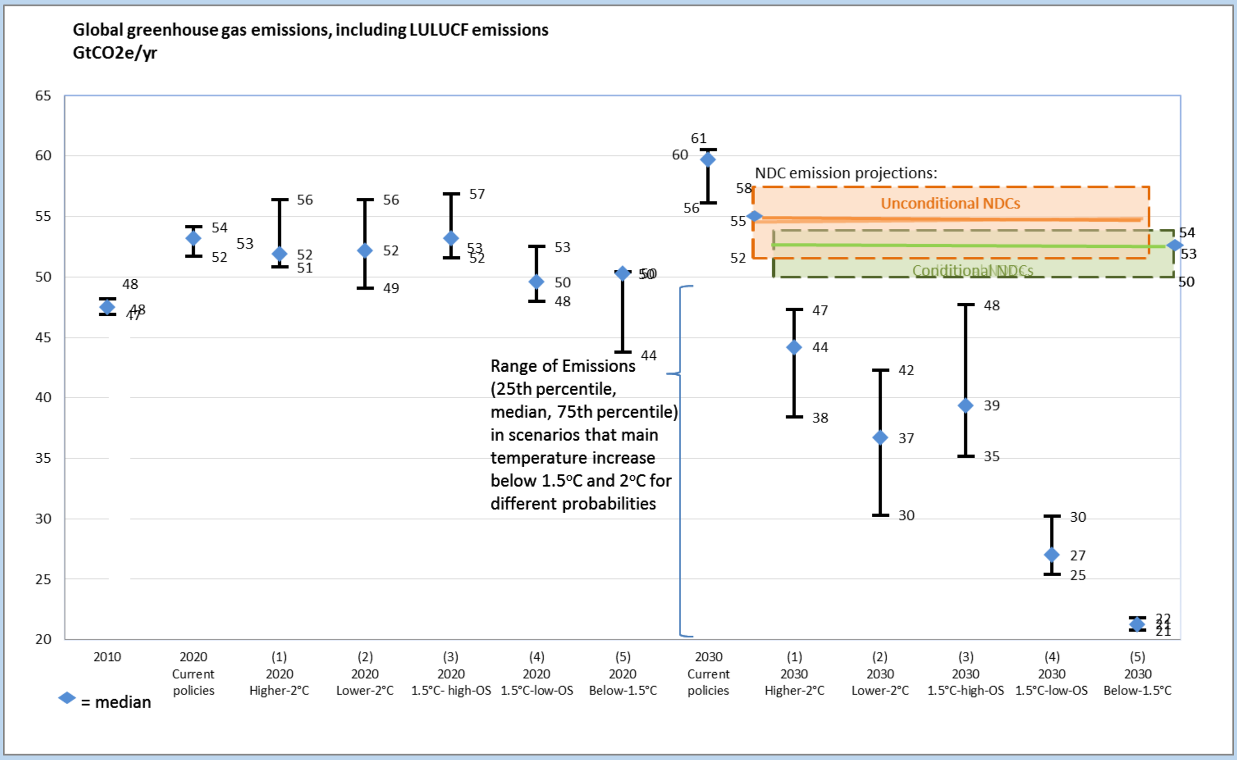
Mitigation

1. Introduction

There is *high agreement* that Nationally Determined Contributions (NDCs) are important for the global response to climate change and represent an innovative bottom-up instrument in climate change governance (Section 4.4.1), with contributions from all signatory countries (den Elzen et al., 2016; Rogelj et al., 2016; Vandyck et al., 2016; Luderer et al., 2018; Vrontisi et al., 2018). The global emission projection resulting from full implementation of the NDCs represent an improvement compared to business as usual (Rogelj et al., 2016) and current policies scenarios to 2030 (den Elzen et al., 2016; Vrontisi et al., 2018). Most G20 economies would require new policies and actions to achieve their NDC targets (den Elzen et al., 2016; Vandyck et al., 2016; Kuramochi et al., 2017; UNEP, 2017b).

2. The effect of NDCs on global Greenhouse Gas (GHG) emissions

Several studies estimate global emission levels that would be achieved under the NDCs (e.g., den Elzen et al., 2016; Luderer et al., 2016; Rogelj et al., 2016, 2017; Vandyck et al., 2016; Rose et al., 2017; Vrontisi et al., 2018). Rogelj et al. (2016) and (UNEP, 2017b) concluded that the full implementation of the unconditional and conditional NDCs are expected to result in global GHG emissions of about 55 (52–58) and 53 (50–54) $GtCO_2$-eq yr^{-1}, respectively (Cross-Chapter Box 11, Figure 1 below).



Cross-Chapter Box 11, Figure 1: GHG emissions are all expressed in units of CO_2-equivalence computed with 100-year Global Warming Potentials (GWPs) reported in IPCC SAR, while the emissions of the 1.5°C and 2°C scenarios in Table 2.4 are reported using the 100-year GWPs reported in IPCC AR4, and are hence about 3% higher. Using IPCC AR4 instead of SAR GWP values is estimated to result in a 2-3% increase in estimated 1.5°C and 2°C emissions levels in 2030. Source: based on Rogelj et al. (2016) and UNEP (2017b).

3. The effect of NDCs on temperature increase and carbon budget

Estimates of global average temperature increase are 2.9–3.4°C above preindustrial levels with a greater than 66% probability by 2100 (Rogelj et al., 2016; UNEP, 2017b), under a full implementation of unconditional NDCs and a continuation of climate action similar to that of the NDCs. Full implementation of the conditional NDCs would lower the estimates by about 0.2°C by 2100. As an indication of the carbon budget implications of NDC scenarios, Rogelj et al. (2016) estimated cumulative emissions in the range of 690 to 850 $GtCO_2$ for the period 2011–2030 if the NDCs are successfully implemented. The carbon budget for post-2010 till 2100 emissions compatible with staying below 1.5°C with a 50–66% probability was estimated at 550–600 $GtCO_2$ (Clarke et al., 2014; Rogelj et al., 2016), which will be well exceeded by 2030 at full implementation of the NDCs. This estimate has been updated (Section 2.2 and Section 2.3.1).

4. The 2030 emissions gap with 1.5ºC and urgency of action

As the 1.5°C pathways require reaching carbon neutrality by mid-century, the NDCs alone are not sufficient, as they have a time horizon until 2030. (Rogelj et al., 2016; Hof et al., 2017) have used results or compared NDC pathways with emissions pathways produced by Integrated Assessment Models (IAMs) assessing the contribution of NDCs to achieve the 1.5°C targets. There is *high agreement* that current NDC emission levels are not in line with pathways that limit warming to 1.5°C by the end of the century (Rogelj et al., 2016, 2017; Hof et al., 2017; UNEP, 2017b; Vrontisi et al., 2018). The median 1.5°C emissions gap (>66% chance) for the full implementation of both the conditional and unconditional NDCs for 2030 is 26 (19–29) to 28 (22–33) $GtCO_2$-eq (Cross-Chapter Box 11, Figure 1 above).

Studies indicate important trade-offs of delaying global emissions reductions (Sections 2.3.5 and 2.5.1). AR5 identified flexibility in 2030 emission levels when pursuing a 2°C objective (Clarke et al., 2014) indicating that strongest trade-offs for 2°C pathways could be avoided if emissions are limited to below 50 $GtCO_2$-eq yr^{-1} in 2030 (here computed with the GWP–100 metric of the IPCC SAR). New scenario studies show that full implementation of the NDCs by 2030 would imply much deeper and faster emission reductions beyond 2030 in order to meet 2ºC, and also higher costs and efforts of negative emissions (Fujimori et al., 2016; Sanderson et al., 2016; Rose et al., 2017; van Soest et al., 2017; Luderer et al., 2018). However, no flexibility has been found for 1.5°C pathways (Luderer et al., 2016; Rogelj et al., 2017) indicating that post–2030 emissions reductions required to remain within a 1.5°C compatible carbon budget during the 21st century (Section 2.2) are not within the feasible operating space of IAMs. This indicates that failing to reach a 1.5°C pathway are significantly increased (Riahi et al., 2015), if near-term ambition is not strengthened beyond the level implied by current NDCs.

Accelerated and stronger short-term action and enhanced longer-term national ambition going beyond the NDCs would be needed for 1.5°C-consistent pathways. Implementing deeper emissions reduction than current NDCs would imply action towards levels identified in Section 2.3.3, either as part of or over-delivering on NDCs.

5. *The impact of uncertainties on NDC emission levels*

The measures proposed in NDCs are not legally binding (Nemet et al., 2017), further impacting estimates of anticipated 2030 emission levels. The aggregation of targets results in high uncertainty (Rogelj et al., 2017), which could be reduced with clearer guidelines for compiling future NDCs focused more on energy accounting (Rogelj et al., 2017) and increased transparency and comparability (Pauw et al., 2018).

Many factors would influence NDCs global aggregated effects, including: (1) variations in socioeconomic conditions, (Gross Domestic Product, GDP, and population growth), (2) uncertainties in historical emission inventories, (3) conditionality of certain NDCs, (4) definition of NDC targets as ranges instead of single values, (5) the way in which renewable energy targets are expressed, and (6) the way in which traditional biomass use is accounted for. Additionally, there are land-use mitigation uncertainties (Forsell et al., 2016; Grassi et al., 2017). Land-use options play a key role in many country NDCs, however, many analyses on NDCs do not use country estimates on land-use emissions, but use model estimates, mainly because of the large difference in estimating the "anthropogenic" forest sink between countries and models (Grassi et al., 2017).

7. Comparing countries' NDC ambition (equity, cost optimal allocation and other indicators)

Various assessment frameworks have been proposed to analyse, benchmark and compare NDCs, and indicate possible strengthening, based on equity and other indicators (Aldy et al., 2016; den Elzen et al., 2016; Höhne et al., 2017; Jiang et al., 2017; Holz et al., 2018).There is large variation in conformity/fulfillment with equity principles across NDCs and countries. Studies use assessment frameworks based on six effort sharing categories in the AR5 (Clarke et al., 2014) with the principles of 'responsibility', 'capability' and 'equity' (Höhne et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017). There is an important methodological gap in the assessment of the NDCs' fairness and equity implications, partly due to lack of information on countries' own assessment (Winkler et al., 2017). Implementation of Article 2.2 of the Paris Agreement could reflect equity and the principle of common but differentiated responsibilities and respective capabilities, due to different national circumstances and different interpretations of equity principles (Lahn, 2017; Lahn and Sundqvist, 2017).

Adaptation

The Paris Agreement recognises adaptation by establishing a global goal for adaptation (Kato and Ellis, 2016; Rajamani, 2016; Kinley, 2017; Lesnikowski et al., 2017; UNEP, 2017a). This is assessed qualitatively, as achieve a temperature goal, would determine the level of ambition of addressing adaptation to consequent risks and impacts (Rajamani, 2016). Countries can include domestic adaptation goals in their NDCs, which together with National Adaptation Plans (NAPs) give countries flexibility to design and adjust their adaptation trajectories as their needs evolve and as progress is evaluated over time. A challenge for assessing progress on adaptation globally is the aggregation of many national adaptation actions and approaches. Knowledge gaps still remain about how to design measurement frameworks that generate and integrate national adaptation data without placing undue burdens on countries (UNEP, 2017a).

The Paris Agreement stipulates that adaptation communications shall be submitted as a component of or in conjunction with other communications, such as an NDC, a NAP, or a National Communication. Of the 197 Parties to the UNFCCC, 140 NDCs have an adaptation component, almost exclusively from developing countries. NDC adaptation components could be an opportunity for enhancing adaptation planning and implementation by highlighting priorities and goals (Kato and Ellis, 2016). At the national level they provide momentum for the development of NAPs and raise the profile of adaptation (Pauw et al., 2016b, 2018). The Paris Agreement's transparency framework includes adaptation, through which 'adaptation communication' and accelerated adaptation actions are submitted and reviewed every five years (Hermwille, 2016; Kato and Ellis, 2016). This framework, unlike others used in the past, is applicable to all countries taking into account differing capacities amongst Parties (Rajamani, 2016).

Adaptation measures presented in qualitative terms include sectors, risks and vulnerabilities that are seen as priorities by the Parties. Sectoral coverage of adaptation actions identified in NDCs is uneven, with adaptation primarily reported to focus on the water sector (71% of NDCs with adaptation component), agriculture (63%), and health (54%), and biodiversity/ecosystems (50%) (Pauw et al., 2016b, 2018).

[END CROSS-CHAPTER BOX 11 HERE]

4.4.2 Enhancing Institutional Capacities

The implementation of sound responses and strategies to enable a transition to 1.5°C world would require strengthening governance and scaling up institutional capacities, particularly in developing countries (Adenle et al., 2017; Rosenbloom, 2017). Building on the characterisation of governance in Section 4.4.1, this section examines the necessary institutional capacity to implement actions to limit warming to 1.5°C and adapt to the consequences. This takes into account a plurality of regional and local responses, as institutional capacity is highly context-dependent (North, 1990; Lustick et al., 2011).

Institutions would need to interact with one another and align across scales to ensure that rules and regulations are followed (Chaffin and Gunderson, 2016; Young, 2016). The institutional architecture required for a 1.5°C world would include the growing proportion of the world's population that live in peri-urban and informal settlements and engage in informal economic activity (Simone and Pieterse, 2017). This population, amongst the most exposed to perturbed climates in the world (Hallegatte et al., 2017), is also beyond the direct reach of some policy instruments (Jaglin, 2014; Thieme, 2017). Strategies that accommodate the informal rules of the game adopted by these populations have large chances of success (McGranahan et al., 2016; Kaika, 2017).

The goal for strengthening implementation is to ensure that these rules and regulations embrace equity, equality and poverty alleviation along 1.5°C-consistent pathways (mitigation) and enables the building of adaptive capacity that together, will enable sustainable development and poverty reduction.

Rising to the challenge of a transition to a 1.5°C world would require enhancing institutional climate change capacities along multiple dimensions presented below.

4.4.2.1 Capacity for Policy Design and Implementation

The enhancement of institutional capacity for integrated policy design and implementation has long been among the top items on the UN agenda of addressing global environmental problems and sustainable development (UNEP, 2005) (see Section 5.5).

Political stability, an effective regulatory and enforcement framework (e.g., institutions to impose sanctions, collect taxes and to verify building codes), access to a knowledge base and the availability of resources, would be needed at various governance levels, to address a wide range of stakeholders, and their concerns. The strengthening of the global response would need to support these with different interventions, in the context of sustainable development(Pasquini et al., 2015) (Section 5.5.1).

Given the scale of change needed to achieve 1.5°C, strengthening the response capacity of relevant institutions are best addressed in ways that take advantage of existing decision-making processes in local and regional governments and within cities and communities (Romero-Lankao et al., 2013), and draw upon diverse knowledge sources including Indigenous and local knowledge (Nakashima et al., 2012; Smith and Sharp, 2012; Mistry and Berardi, 2016; Tschakert et al., 2017). Examples of successful local institutional processes and the integration of local knowledge in climate-related decisions making are provided in Box 4.3 and Box 4.4.

Implementing 1.5°C-relevant strategies would require well-functioning legal frameworks to be in place, in conjunction with clearly defined mandates, rights and responsibilities to enable the institutional capacity to deliver (Romero-Lankao et al., 2013). As an example, current rates of urbanisation occurring in cities with a lack of institutional capacity for effective land-use planning, zoning and infrastructure development, result in unplanned, informal urban settlements which are vulnerable to climate impacts. It is common for 30–50% of urban populations in low-income nations to live in informal settlements with no regulatory infrastructure (Revi et al., 2014b). For example, in Huambo (Angola), a classified ‘urban’ area extends 20km west of the city and is predominantly made up of ‘unplanned’ urban settlements (Smith and Jenkins, 2015).

Internationally, the Paris Agreement process has aimed at enhancing the capacity of decision-making institutions in developing countries to support effective implementation. These efforts are particularly reflected in Article 11 of the Paris Agreement on capacity building (the creation of the Paris Committee on Capacity Building), Article 13 (the creation of the Capacity Building Initiative on Transparency), as well as Article 15 on compliance (UNFCCC, 2015).

[START BOX 4.3 HERE]

Box 4.3: Indigenous Knowledge and Community Adaptation

Indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings (UNESCO, 2017). This knowledge can underpin the development of adaptation and mitigation strategies (Ford et al., 2014b; Green and Minchin, 2014; Pearce et al., 2015; Savo et al., 2016).

Climate change is an important concern for the Maya, who depend on climate knowledge for their livelihood. In Guatemala, the collaboration between the Mayan K'iché population of the Nahualate river basin and the Climate Change Institute has resulted in a catalogue of Indigenous knowledge, used to identify indicators for watershed meteorological forecasts (Yax L. and Álvarez, 2016). These indicators are relevant but would need continuous assessment if their continued reliability is to be confirmed (Nyong et al., 2007;

Alexander et al., 2011; Mistry and Berardi, 2016). For more than ten years, Guatemala has maintained an 'Indigenous Table for Climate Change', to enable the consideration of indigenous knowledge in disaster management and adaptation development.

In Tanzania, increased variability of rainfall is challenging Indigenous and local communities(Mahoo et al., 2015; Sewando et al., 2016). The majority of agro-pastoralists use Indigenous knowledge to forecast seasonal rainfall, relying on observations of plant phenology, bird, animal, and insect behaviour, the sun and moon, and wind (Chang'a et al., 2010; Elia et al., 2014; Shaffer, 2014). Increased climate variability has raised concerns about the reliability of these indicators (Shaffer, 2014), therefore, initiatives have focused on the co-production of knowledge, through involving local communities in monitoring and discussing the implications of indigenous knowledge and meteorological forecasts (Shaffer, 2014), and creating local forecasts by utilising the two sources of knowledge (Mahoo et al., 2013). This has resulted in increased documentation of Indigenous knowledge, understanding of relevant climate information amongst stakeholders, and adaptive capacity at the community-level (Mahoo et al., 2013, 2015; Shaffer, 2014).

The Pacific Islands and Small Island Develiping States (SIDS) are vulnerable to the effects of climate change, but the cultural resilience of Pacific Island inhabitants is also recognized (Nunn et al., 2017). In Fiji and Vanuatu, strategies used to prepare for cyclones include building reserve emergency supplies, and utilising farming techniques to ensure adequate crop yield to combat potential losses from a cyclone or drought (McNamara and Prasad, 2014; Granderson, 2017; Pearce et al., 2017). Social cohesion and kinship are important in responding and preparing for climate-related hazards, including the role of resource sharing, communal labour, and remittances (McMillen et al., 2014; Gawith et al., 2016; Granderson, 2017). There is a concern that Indigenous knowledge will weaken, a process driven by westernisation and disruptions in established bioclimatic indicators and traditional planning calendars (Granderson, 2017). In some urban settlements, it has been noted that cultural practices (e.g., prioritising the quantity of food over the quality of food) can lower food security through dispersing limited resources and by encouraging the consumption of cheap but nutrient-poor foods (Mccubbin et al., 2017) (See Cross-Chapter Box 6 on Food Security in Chapter 3). Indigenous practices also encounter limitations, particularly in-relating to sea level rise (Nunn et al., 2017).

[END BOX 4.3 HERE]

[START BOX 4.4 HERE]

Box 4.4: Manizales, Colombia: Supportive National Government and Localised Planning and Integration as an Enabling Condition for Managing Climate and Development Risks

Institutional reform in the city of Manizales, Colombia helps identify three important features of an enabling environment: integrating climate change adaptation, mitigation and disaster risk management at the city-scale; the importance of decentralised planning and policy formulation within a supportive national policy environment; and the role of a multi-sectoral framework in mainstreaming climate action in development activities.

Manizales is exposed to risks caused by rapid development and expansion in a mountainous terrain exposed to seismic activity and periodic wet and dry spells. Local assessments expect climate change to amplify the risk of disasters (Carreño et al., 2017). The city is widely recognised for its longstanding urban environmental policy (Biomanizales) and local environmental action plan (Bioplan), and has been integrating environmental planning in its development agenda for nearly two decades (Velásquez Barrero, 1998; Hardoy and Velásquez Barrero, 2014). When the city's environmental agenda was updated in 2014 to reflect climate change risks, assessments were conducted in a participatory manner at the street and neighbourhood level (Hardoy and Velásquez Barrero, 2016).

The creation of a new Environmental Secretariat assisted in coordination and integration of environmental policies, disaster risk management, development and climate change (Leck and Roberts, 2015).
Planning in Manizales remains mindful of steep gradients, through its longstanding Slope Guardian

programme that trains women and keeps records of vulnerable households. Planning also looks to include mitigation opportunities and enhance local capacity through participatory engagement (Hardoy and Velásquez Barrero, 2016).

Manizales' mayors were identified as important champions for much of these early integration and innovation efforts. Their role may have been enabled by Colombia's history of decentralised approaches to planning and policy formulation, including establishing environmental observatories (for continuous environmental assessment) and participatory tracking of environmental indicators. Multi-stakeholder involvement has both enabled and driven progress, and has enabled the integration of climate risks in development planning (Hardoy and Velásquez Barrero, 2016).

[END BOX 4.4 HERE]

4.4.2.2 Monitoring, Reporting, and Review Institutions

One of the novel features of the new climate governance architecture emerging from the 2015 Paris Agreement is the transparency framework in Article 13 committing countries, based on capacity, to provide regular progress reports on national pledges to address climate change (UNFCCC, 2015). Many countries will rely on public policies and existing national reporting channels to deliver on their NDCs under the Paris Agreement. Scaling up the mitigation and adaptation efforts in these countries to be consistent with 1.5°C would put significant pressure on the need to develop, enhance and streamline local, national and international climate change reporting and monitoring methodologies and institutional capacity in relation to mitigation, adaptation, finance, and Greenhouse Gases (GHGs) inventories (Ford et al., 2015b; Lesnikowski et al., 2015; Schoenefeld et al., 2016). Consistent with this direction, the provision of the information to the stocktake under Article 14 of the Paris Agreement would contribute to enhancing reporting and transparency (UNFCCC, 2015). Nonetheless, approaches, reporting procedures, reference points, and data sources to assess progress on implementation across and within nations are still largely underdeveloped (Ford et al., 2015b; Araos et al., 2016b; Magnan and Ribera, 2016; Lesnikowski et al., 2017). The availability of independent private and public reporting and statistical institutions is integral to oversight, effective monitoring, reporting and review. The creation and enhancement of these institutions would be an important contribution to an effective transition to a low-emission world.

4.4.2.3 Financial Institutions

IPCC AR5 assessed that to enable a transition to a 2°C pathway, the volume of climate investments would need to be transformed along with changes in the pattern of general investment behaviour towards low-emissions. The report argued that, compared to 2012, annually up to a trillion dollars in additional investment in low-emission energy and energy efficiency measures may be required until 2050 (Blanco et al., 2014; IEA, 2014a). Financing of 1.5°C would present an even greater challenge, addressing financing of both existing and new assets, which would require significant transitions to the type and structure of financial institutions as well as to the method of financing (Cochrani et al., 2014; Ma, 2014). Both public and private financial institutions would be needed to contribute to the large resource mobilisation needed for 1.5°C, yet, in the ordinary course of business, these transitions may not be expected. On one hand, private financial institutions could face the scale-up risk, for example the risks associated with commercialisation and scaling up of renewable technologies to accelerate mitigation (Wilson, 2012; Hartley and Medlock, 2013) and/or price risk, such as carbon price volatility that carbon markets could face. In contrast, traditional public financial institutions are limited by both structure and instruments, while concessional financing would require taxpayer support for subsidisation. Special efforts and innovative approaches would be needed to address these challenges, for example the creation of special institutions that underwrite the value of emission reductions using auctioned price floors (Bodnar et al., 2018) to deal with price volatility.

Financial institutions are equally important for adaptation. Linnerooth-Bayer and Hochrainer-Stigler (2015) discuss the benefits of financial instruments in adaptation, including the provision of post-disaster finances for recovery and pre-disaster security necessary for climate adaptation and poverty reduction. Pre-disaster financial instruments and options include insurance, such as index-based weather insurance schemes, catastrophe bonds, and laws to encourage insurance purchasing. The development and enhancement of microfinance institutions to ensure social resilience and smooth transitions in the adaptation to climate change impacts could be an important local institutional innovation (Hammill et al., 2008).

4.4.2.4 Co-Operative Institutions and Social Safety Nets

Effective co-operative institutions and social safety nets may help address energy access, adaptation, as well as distributional impacts during the transition to 1.5°C-consistent pathways and enabling sustainable development. Not all countries have the institutional capabilities to design and manage these. Social capital for adaptation in the form of bonding, bridging, and linking social institutions has proved to be effective in dealing with climate crises at the local, regional, and national levels (Aldrich et al., 2016).

The shift towards sustainable energy systems in transitioning economies could impact the livelihoods of large populations, in traditional and legacy employment sectors. The transition of selected EU Member States to biofuels, for example, caused anxiety among farmers, who lacked confidence in the biofuel crop market. Enabling contracts between farmers and energy companies, involving local governments, helped create an atmosphere of confidence during the transition (McCormick and Kåberger, 2007).

How do broader socio-economic processes influence urban vulnerabilities and thereby underpin climate change adaptation? This is a systemic challenge originating from a lack of collective societal ownership of the responsibility for climate risk management. Numerous explanations, help explain this from competing time-horizons due to self-interest of stakeholders to a more ‘rational’ conception of risk assessment, measured across a risk-tolerance spectrum (Moffatt, 2014).

Self-governing and self-organised institutional settings where equipment and resource systems are commonly owned and managed can potentially generate a much higher diversity of administration solutions, than other institutional arrangements where energy technology and resource systems are either owned and administered individually in market settings or via a central authority (e.g., the state). They can also increase the adaptability of technological systems, while reducing their burden on the environment (Labanca, 2017). Educational, learning and awareness-building institutions can help strengthen the societal response to climate change (Butler et al., 2016; Thi Hong Phuong et al., 2017).

4.4.3 Enabling Lifestyle and Behavioural Change

Humans are at the centre of global climate change: their actions cause anthropogenic climate change, and social change is key to effectively respond to climate change (Vlek and Steg, 2007; Dietz et al., 2013; ISSC and UNESCO, 2013; Hackmann et al., 2014). Chapter 2 shows that 1.5°C-consistent pathways assume substantial changes in behaviour. This section assesses the potential of behaviour change, as the Integrated Assessment Models (IAMs) applied in Chapter 2 do not comprehensively asses this potential.

Table 4.8 shows examples of mitigation and adaption actions relevant for 1.5ºC-consistent pathways. Reductions in population growth can reduce overall carbon demand and mitigate climate change (Bridgeman, 2017), particularly when population growth is accompanied with increases in affluence and carbon-intensive consumption (Rosa and Dietz, 2012; Clayton et al., 2017). Mitigation actions with a substantial carbon emission reduction potential (see Figure 4.3) that individuals may readily adopt would have the most climate impact (Dietz et al., 2009).

Table 4.8: Examples of mitigation and adaptation behaviours relevant for 1.5ºC (Dietz et al., 2009; Jabeen, 2014; Taylor et al., 2014; Araos et al., 2016b; Steg, 2016; Stern et al., 2016b; Creutzig et al., 2018)

Climate action	Type of action	Examples
Mitigation	Implementing resource efficiency in building	Insulation Low-carbon building materials
	Adopting low-emission innovations	Electric vehicles Heat pumps, district heating and cooling
	Adopting energy efficient appliances	Energy-efficient heating or cooling Energy-efficient appliances
	Energy-saving behaviour	Walking or cycling rather than drive short distances Using mass transit rather than flying Lower temperature for space heating Line drying of laundry Reducing food waste
	Buying products and materials with low GHG emissions during production and transport	Reducing meat and dairy consumption Buying local, seasonal food Replacing aluminium products by low-GHG alternatives
	Organisational behaviour	Designing low-emission products and procedures Replacing business travel by videoconferencing
Adaptation	Growing different crops and raising different animal varieties	Using crops with higher tolerance for higher temperatures or CO_2 elevation
	Flood protective behaviour	Elevating barriers between rooms Building elevated storage spaces Building drainage channels outside the home
	Heat protective behaviour	Staying hydrated Moving to cooler places Installing green roofs
	Efficient water use during water shortage crisis	Rationing water Constructing wells or rainwater tanks
Mitigation & adaptation	Adoption of renewable energy sources	Solar PV Solar water heaters
	Citizenship behaviour	Engage through civic channels to encourage or support planning for low-carbon climate-resilient development

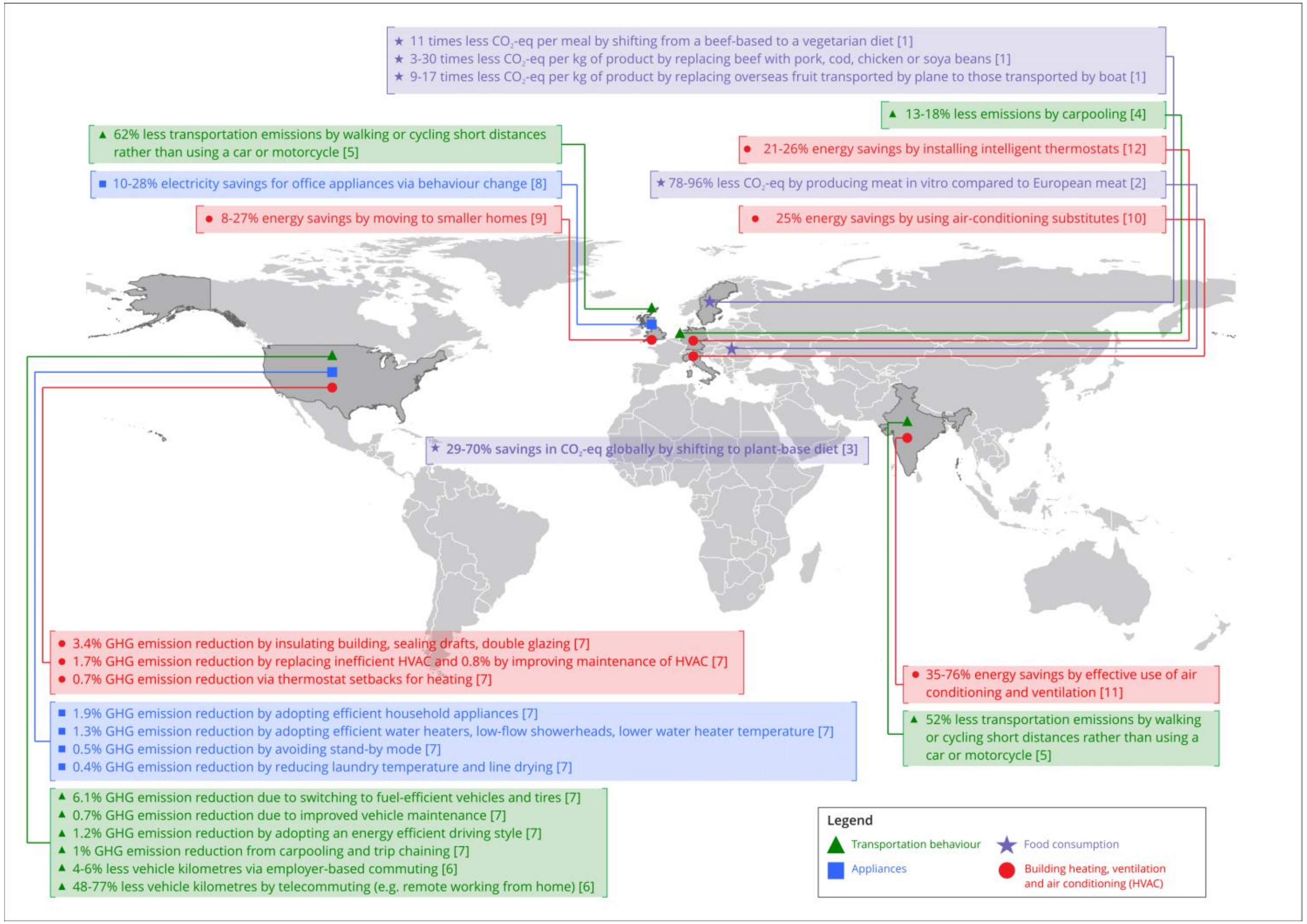


Figure 4.3: Examples of mitigation behaviour and their GHG emission reduction potential. Mitigation potential assessments are printed in different units. Based on [1] Carlsson-Kanyama and González (2009); [2] Tuomisto and Teixeira de Mattos (2011); [3] Springmann et al. (2016); [4] Nijland and Meerkerk (2017); [5] Woodcock et al. (2009); [6] Salon et al. (2012); [7] Dietz et al. (2009); [8] Mulville et al. (2017); [9] Huebner and Shipworth (2017); [10] Jaboyedoff et al. (2004); [11] Pellegrino et al. (2016); [12] Nägele et al. (2017).

Various policy approaches and strategies can encourage and enable climate actions by individuals and organisations. Policy approaches would be more effective when they address key contextual and psycho-social factors influencing climate actions, which differ across contexts and individuals (Steg and Vlek, 2009; Stern, 2011). This suggests that diverse policy approaches would be needed in 1.5ºC-consistent pathways in different contexts and regions. Combinations of policies that target multiple barriers and enabling factors simultaneously can be more effective (Nissinen et al., 2015).

In the US and Europe, GHG emissions are lower when legislators have strong environmental records (Jensen and Spoon, 2011; Dietz et al., 2015). Political elites affect public concern about climate change: pro-climate action statements increased concern, while anti-climate action statements and anti-environment voting reduced public concern about climate change (Brulle et al., 2012). In the European Union, individuals worry more about climate change and engage more in climate actions in countries where political party elites are united rather than divided in their support for environmental issues (Sohlberg, 2017).

This section discusses how to enable and encourage behaviour and lifestyle changes that strengthen implementation of 1.5ºC-consistent pathways by assessing psycho-social factors related to climate action, as well as the effects and acceptability of policy approaches targeting climate actions that are consistent with 1.5ºC. Box 4.5 and Box 4.6 illustrate how these have worked in practice.

4.4.3.1 Factors Related to Climate Actions

Mitigation and adaptation behaviour is affected by many factors that shape which options are feasible and considered by individuals. Besides contextual factors (see other sub-sections in Section 4.4), these include abilities and different types of motivation to engage in behaviour.

4.4.3.1.1 Ability to engage in climate action

Individuals more often engage in adaptation (Gebrehiwot and van der Veen, 2015; Koerth et al., 2017) and mitigation behaviour (Pisano and Lubell, 2017) when they are or feel more capable to do so. Hence, it is important to enhance ability to act on climate change, which depends on income and knowledge, among other things. A higher income is related to higher CO_2 emissions; higher income groups can afford more carbon-intensive lifestyles (Lamb et al., 2014; Dietz et al., 2015; Wang et al., 2015). Yet, low-income groups may lack resources to invest in energy efficient technology and refurbishments (Andrews-Speed and Ma, 2016) and adaptation options (Wamsler, 2007; Fleming et al., 2015b; Takahashi et al., 2016). Adaptive capacity further depends on gender roles (Jabeen, 2014; Bunce and Ford, 2015), technical capacities and knowledge (Feola et al., 2015; Eakin et al., 2016; Singh et al., 2016b).

Knowledge of the causes and consequences of climate change and on ways to reduce GHG emissions is not always accurate (Bord et al., 2000; Whitmarsh et al., 2011; Tobler et al., 2012), which can inhibit climate actions, even when people would be motivated to act. For example, people overestimate savings from low-energy activities, and underestimate savings from high-energy activities (Attari et al., 2010). They know little about ‘embodied’ energy (i.e., energy needed to produce products; Tobler et al., 2011), including meat (de Boer et al., 2016b). Some people mistake weather for climate (Reynolds et al., 2010), or conflate climate risks with other hazards, which can inhibit adequate adaptation (Taylor et al., 2014).

More knowledge on adaptation is related to higher engagement in adaptation actions in some circumstances (Bates et al., 2009; van Kasteren, 2014; Hagen et al., 2016). How adaptation is framed in the media can influence the types of options viewed as important in different contexts (Boykoff et al., 2013; Moser, 2014; Ford and King, 2015).

Knowledge is important, but is often not sufficient to motivate action (Trenberth et al., 2016). Climate change knowledge and perceptions are not strongly related to mitigation actions (Hornsey et al., 2016). Direct experience of events related to climate change influences climate concerns and actions (Blennow et al., 2012; Taylor et al., 2014), more so than second-hand information (Spence et al., 2011; Myers et al., 2012; Demski et al., 2017); high impact events with low frequency are remembered more than low impact regular events (Meze-Hausken, 2004; Singh et al., 2016b; Sullivan-Wiley and Short Gianotti, 2017). Personal experience with climate hazards strengthens motivation to protect oneself (Jabeen, 2014) and enhances adaptation actions (Bryan et al., 2009; Berrang-Ford et al., 2011; Demski et al., 2017), although this does not always translate into proactive adaptation (Taylor et al., 2014). Collectively constructed notions of risk and expectations of future climate variability shape risk perception and adaptation behaviour (Singh et al., 2016b). People with particular political views and those who emphasise individual autonomy may reject climate science knowledge and believe that there is widespread scientific disagreement about climate change (Kahan, 2010; O'Neill et al., 2013), inhibiting support for climate policy (Ding et al., 2011; McCright et al., 2013). This may explain why extreme weather experiences enhances preparedness to reduce energy use among left- but not right-leaning voters (Ogunbode et al., 2017).

4.4.3.1.2 Motivation to engage in climate action

Climate actions are more strongly related to motivational factors, reflecting individuals' reasons for actions, such as values, ideology and worldviews than to knowledge (Hornsey et al., 2016). People consider various types of costs and benefits of actions (Gölz and Hahnel, 2016), and focus on consequences that have implications for the values they find most important (Dietz et al., 2013; Hahnel et al., 2015; Steg, 2016). This implies that different individuals consider different consequences when making choices. People who strongly value protecting the environment and other people generally more strongly consider climate impact and act more on climate change than those who strongly endorse hedonic and egoistic values (Taylor et al., 2014; Steg, 2016). People are more prone to adopt sustainable innovations when they are more open to new ideas (Jansson, 2011; Wolske et al., 2017). Further, a free-market ideology is associated with weaker climate change beliefs (McCright and Dunlap, 2011; Hornsey et al., 2016), and a capital-oriented culture tends to promote activity associated with GHG emissions (Kasser et al., 2007).

Some Indigenous populations believe it is arrogant to predict the future, and some cultures have belief systems that interpret natural phenomena as sentient, where thoughts and words are believed to influence the future, with people reluctant to talk about negative future possibilities (Natcher et al., 2007; Flynn et al., 2018). Integrating these considerations into the design of adaptation and mitigation policy is important (Cochran et al., 2013; Chapin et al., 2016; Brugnach et al., 2017; Flynn et al., 2018).

People are more prone to act on climate change when individual benefits of actions exceed costs (Steg and Vlek, 2009; Kardooni et al., 2016; Wolske et al., 2017). For this reason, people generally prefer adoption of energy-efficient appliances above energy consumption reductions; the latter is perceived as more costly (Poortinga et al., 2003; Steg et al., 2006), although transaction costs can inhibit the uptake of mitigation technology (Mundaca, 2007). Decentralised renewable energy systems are evaluated most favourably when they guarantee independence, autonomy, control and supply security (Ecker, 2017).

Besides, social costs and benefits affect climate action (Farrow et al., 2017). People engage more in climate actions when they think others expect them to do so and when others act as well (Nolan et al., 2008; Le Dang et al., 2014; Truelove et al., 2015; Rai et al., 2016), and when they experience social support (Singh et al., 2016a; Burnham and Ma, 2017; Wolske et al., 2017). Discussing effective actions with peers also encourages climate action (Esham and Garforth, 2013), particularly when individuals strongly identify with their peers (Biddau et al., 2012; Fielding and Hornsey, 2016). Further, individuals may engage in mitigation actions when they think doing so would enhance their reputation (Milinski et al., 2006; Noppers et al., 2014; Kastner and Stern, 2015). Such social costs and benefits can be addressed in climate policy (see Section 4.4.3.2).

Feelings affect climate action (Brosch et al., 2014). Negative feelings related to climate change can encourage adaptation action (Kerstholt et al., 2017; Zhang et al., 2017), while positive feelings associated with climate risks may inhibit protective behaviour (Lefevre et al., 2015). Individuals are more prone to engage in mitigation actions when they worry about climate change (Verplanken and Roy, 2013), and when they expect to derive positive feelings from such actions (Pelletier et al., 1998; Taufik et al., 2016).

Furthermore, collective consequences affect climate actions (Balcombe et al., 2013; Dóci and Vasileiadou, 2015; Kastner and Stern, 2015). People are motivated to see themselves as morally right, which encourages mitigation actions (Steg et al., 2015), particularly when long-term goals are salient (Zaval et al., 2015) and behavioural costs are not too high (Diekmann and Preisendörfer, 2003). Individuals are more prone to engage in climate actions when they believe climate change is occurring, when they are aware of threats caused by climate change and by their inaction, and when they think they can engage in actions that will reduce these threats (Esham and Garforth, 2013; Arunrat et al., 2017; Chatrchyan et al., 2017). The more individuals are concerned about climate change and aware of the negative climate impact of their behaviour, the more they feel responsible for and think their actions can help reduce such negative impacts, which can strengthen their moral norms to act accordingly (Steg and de Groot, 2010; Jakovcevic and Steg, 2013; Chen, 2015; Ray et al., 2017; Wolske et al., 2017; Woods et al., 2017). Individuals may engage in mitigation actions when they see themselves as supportive of the environment (i.e. strong environmental self-identity) (Fielding et al., 2008; van der Werff et al., 2013b; Kashima et al., 2014; Barbarossa et al., 2017); a strong environmental identity strengthens intrinsic motivation to engage in mitigation actions both at home (van der Werff et al., 2013a) and at work (Ruepert et al., 2016). Environmental self-identity is strengthened when people realise they engaged in mitigation actions, which can in turn promote further mitigation actions (van der Werff et al., 2014b).

Individuals are less prone to engage in adaptation behaviour themselves when they rely on external measures such as government interventions (Grothmann and Reusswig, 2006; Wamsler and Brink, 2014a; Armah et al., 2015; Burnham and Ma, 2017) or perceive themselves as protected by god (Gandure et al., 2013; Dang et al., 2014; Cannon, 2015).

4.4.3.1.3 Habits, heuristics and biases

Decisions are often not based on weighing costs and benefits, but on habit or automaticity, both of individuals (Aarts and Dijksterhuis, 2000; Kloeckner et al., 2003) and within organisations (Dooley, 2017) and institutions (Munck et al., 2014). When habits are strong, individuals are less perceptive of information (Verplanken et al., 1997; Aarts et al., 1998), and may not consider alternatives as long as outcomes are good enough (Maréchal, 2010). Habits are mostly only reconsidered when the situation changed significantly (Fujii and Kitamura, 2003; Maréchal, 2010; Verplanken and Roy, 2016). Hence, strategies that create the opportunity for reflection and encourage active decisions can break habits (Steg et al., 2017).

Individuals can follow heuristics, or ‘rules of thumb’, in making inferences rather than thinking through all implications of actions, which demands less cognitive resources, knowledge and time (Preston et al., 2013; Frederiks et al., 2015; Gillingham and Palmer, 2017). For example, people tend to think that larger and visible appliances use more energy, which is not always accurate (Cowen and Gatersleben, 2017). They underestimate energy used for water heating and overestimate energy used for lighting (Stern, 2014). When facing choice overload, people may choose the easiest or first available option, which can inhibit energy saving behaviour (Stern and Gardner, 1981; Frederiks et al., 2015). As a result, individuals and firms often strive for satisficing (‘good enough’) outcomes with regard to energy decisions (Wilson and Dowlatabadi, 2007; Klotz, 2011), which can inhibit investments in energy efficiency (Decanio, 1993; Frederiks et al., 2015).

Besides, biases play a role. In Mozambique, farmers displayed omission biases (unwillingness to take adaptation actions with potentially negative consequences to avoid personal responsibility for losses), while policymakers displayed action biases (wanting to demonstrate positive action despite potential negative consequences; Patt and Schröter, 2008). People tend to place greater value on relative losses than gains (Kahneman, 2003). Perceived gains and losses depend on the reference point or status-quo (Kahneman, 2003). Loss aversion and the status-quo bias prevent consumers from switching electricity suppliers (Ek and Söderholm, 2008), to time-of-use electricity tariffs (Nicolson et al., 2017), and to accept new energy systems (Leijten et al., 2014).

Owned inefficient appliances and fossil fuel-based electricity can act as endowments, increasing their value compared to alternatives (Pichert and Katsikopoulos, 2008; Dinner et al., 2011). Uncertainty and loss aversion lead consumers to undervalue future energy savings (Greene, 2011) and savings from energy efficient technologies (Kolstad et al., 2014). Uncertainties about the performance of products and illiquidity of investments can drive consumers to postpone (profitable) energy efficient investments (Sutherland, 1991; van Soest and Bulte, 2001). People with a higher tendency to delay decisions may engage less in energy saving actions (Lillemo, 2014). Training energy auditors in loss-aversion increased their clients' investments in energy efficiency improvements (Gonzales et al., 1988). Engagement in energy saving and renewable energy programmes can be enhanced if participation is set as a default option (Pichert and Katsikopoulos, 2008; Ölander and Thøgersen, 2014; Ebeling and Lotz, 2015).

4.4.3.2 Strategies and Policies to Promote Actions on Climate Change

Policy can enable and strengthen motivation to act on climate change via top-down or bottom-up approaches, through informational campaigns, regulatory measures, financial (dis)incentives, and infrastructural and technological changes (Adger et al., 2003; Steg and Vlek, 2009; Henstra, 2016).

Adaptation efforts tend to focus on infrastructural and technological solutions (Ford and King, 2015) with lower emphasis on socio-cognitive and finance aspects of adaptation. For example, flooding policies in cities focus on infrastructure projects and regulation such as building codes, and hardly target individual or household behaviour (Araos et al., 2016b; Georgeson et al., 2016).

Current mitigation policies emphasise infrastructural and technology development, regulation, financial incentives and information provision (Mundaca and Markandya, 2016) that can create conditions enabling climate action, but target only some of the many factors influencing climate actions (see Section 4.4.5.1). They fall short of their true potential if their social and psychological implications are overlooked (Stern et al., 2016a). For example, promising energy-saving or low carbon technology may not be adopted or not be used as intended (Pritoni et al., 2015) when people lack resources and trustworthy information (Stern, 2011; Balcombe et al., 2013).

Financial incentives or feedback on financial savings can encourage climate action (Santos, 2008; Bolderdijk et al., 2011; Maki et al., 2016) (see Box 4.5), but are not always effective (Delmas et al., 2013), and can be less effective than social rewards (Handgraaf et al., 2013) or emphasising benefits for people and the environment (Bolderdijk et al., 2013b; Asensio and Delmas, 2015; Schwartz et al., 2015). The latter can happen when financial incentives reduce a focus on environmental considerations and weaken intrinsic motivation to engage in climate action (Evans et al., 2012; Agrawal et al., 2015; Schwartz et al., 2015). Besides, pursuing small financial gains is perceived to be less worth the effort than pursuing equivalent CO_2 emission reductions (Bolderdijk et al., 2013b; Dogan et al., 2014). Also, people may not respond to financial incentives (e.g., to improve energy efficiency) because they do not trust the organisation sponsoring incentive programmes (Mundaca, 2007) or when it takes too much effort to receive the incentive (Stern et al., 2016a).

[START BOX 4.5 HERE]

Box 4.5: How Pricing Policy has Reduced Car Use in Singapore, Stockholm and London

In Singapore, Stockholm and London, car ownership, car use, and Greenhouse Gas (GHG) emissions have reduced because of pricing and regulatory policies and policies facilitating behaviour change. Notably, acceptability of these policies has increased as people experienced their positive effects.

Singapore implemented electronic road pricing in the central business district and at major expressways, a vehicle quota and registration fee system, and investments in mass transit. In the vehicle quota system introduced in 1990, registration of new vehicles is conditional upon a successful bid (via auctioning) (Chu, 2015), costing about 50,000 USD in 2014 (LTA, 2015). The registration tax incentivises purchases of low-emission vehicles via a feebate system. As a result, per capita transport emissions (approximately 1.25 tCO_2/yr^{-1}) and car ownership (107 vehicles per 1000 capita) (LTA, 2017) are substantially lower than in cities with comparable income levels. Modal share of public transport was 63% during peak hours in 2013 (LTA, 2013).

The Stockholm congestion charge implemented in 2007 (after a trial in 2006) reduced kilometres driven in the inner city by 16%, and outside the city by 5%; traffic volumes reduced by 20% and remained constant across time despite economic and population growth (Eliasson, 2014). CO_2 emissions from traffic reduced by 2–3% in Stockholm county. Vehicles entering or leaving the city centre were charged during weekdays (except for holidays). Charges were 1–2€ (maximum 6€ per day), being higher during peak hours; taxis, emergency vehicles and busses were exempted. Before introducing the charge, public transport and parking places near mass transit stations were extended. The aim and effects of the charge were extensively communicated to the public. Acceptability of the congestion charge was initially low, but gained support of about two-thirds of the population and all political parties after the scheme was implemented (Eliasson, 2014), which may be related to earmarking the revenues to constructing a motorway tunnel. After the trial, people believed that the charge had more positive effects on environmental, congestion and parking problems while costs increased less than they anticipated beforehand (Schuitema et al., 2010a). The initially hostile media eventually declared the scheme to be a success.

In 2003, a congestion charge was implemented in the Greater London area, with an enforcement and compliance scheme and an information campaign on the functioning of the scheme. Vehicles entering, leaving, driving or parking on a public road in the zone at weekdays at daytime pay a congestion charge of 8£ (until 2005 5£), with some exemptions. Revenues were invested in London's bus network (80%), cycling facilities, and road safety measures (Leape, 2006). The number of cars entering the zone decreased by 18% in 2003 and 2004. In the charging zone, vehicle kilometres driven decreased by 15% in the first year and a further 6% a year later, while CO_2 emissions from road traffic reduced by 20% (Santos, 2008).

[END BOX 4.5 HERE]

While providing information on the causes and consequences of climate change or on effective climate actions, generally increases knowledge, it often does not encourage engagement in climate actions by individuals (Abrahamse et al., 2005; Ünal et al., 2017) or organisations (Anderson and Newell, 2004). Similarly, media coverage on the UN Climate Summit slightly increased knowledge about the conference but did not enhance motivation to engage personally in climate protection (Brüggemann et al., 2017). Fear-inducing representations of climate change may inhibit action when they make people feel helpless and overwhelmed (O'Neill and Nicholson-Cole, 2009). Energy-related recommendations and feedback (e.g., via performance contracts, energy audits, smart metering) are more effective to promote energy conservation, load shifting in electricity use and sustainable travel choices when framed in terms of losses rather than gains (Gonzales et al., 1988; Wolak, 2011; Bradley et al., 2016; Bager and Mundaca, 2017).

Credible and targeted information at the point of decision can promote climate action (Stern et al., 2016a). For example, communicating the impacts of climate change is more effective when provided right before adaptation decisions are taken (e.g., before the agricultural season) and when bundled with information on potential actions to ameliorate impacts, rather than just providing information on climate projections with little meaning to end users (e.g., weather forecasts, seasonal forecasts, decadal climate trends) (Dorward et al., 2015; Singh et al., 2017). Similarly, heat action plans that provide early alerts and advisories combined with emergency public health measures can reduce heat-related morbidity and mortality (Benmarhnia et al., 2016).

Information provision is more effective when tailored to the personal situation of individuals, demonstrating clear impacts, and resonating with individuals' core values (Daamen et al., 2001; Abrahamse et al., 2007; Bolderdijk et al., 2013a; Dorward et al., 2015; Singh et al., 2017). Tailored information prevents information overload, and people are more motivated to consider and act upon information that aligns with their core values and beliefs (Campbell and Kay, 2014; Hornsey et al., 2016). Also, tailored information can remove barriers to receive and interpret information faced by vulnerable groups, such as the elderly during heat waves (Vandentorren et al., 2006; Keim, 2008). Further, prompts can be effective when they serve as reminders to perform a planned action (Osbaldiston and Schott, 2012).

Feedback provision is generally effective in promoting mitigation behaviour within households (Abrahamse et al., 2005; Delmas et al., 2013; Karlin et al., 2015) and at work (Young et al., 2015), particularly when provided in real-time or immediately after the action (Abrahamse et al., 2005), which makes the implications of one's behaviour more salient (Tiefenbeck et al., 2016). Simple information is more effective than detailed and technical data (Wilson and Dowlatabadi, 2007; Ek and Söderholm, 2010; Frederiks et al., 2015). Energy labels (Banerjee and Solomon, 2003; Stadelmann, 2017), visualisation techniques (Pahl et al., 2016), and ambient persuasive technology (Midden and Ham, 2012) can encourage mitigation actions by providing information and feedback in a format that immediately makes sense and hardly requires users' conscious attention.

Social influence approaches that emphasise what other people do or think can encourage climate action (Clayton et al., 2015), particularly when they involve face-to-face interaction (Abrahamse and Steg, 2013). For example, community approaches, where change is initiated from the bottom-up, can promote adaptation (see Box 4.6) and mitigation actions (Middlemiss, 2011; Seyfang and Haxeltine, 2012; Abrahamse and Steg, 2013), especially when community ties are strong (Weenig and Midden, 1991). Furthermore, providing social models of desired actions can encourage mitigation action (Osbaldiston and Schott, 2012; Abrahamse and Steg, 2013). Social influence approaches that do not involve social interaction, such as social norm, social comparison and group feedback, are less effective, but can be easily administered on a large scale at low costs (Allcott, 2011; Abrahamse and Steg, 2013).

[START BOX 4.6 HERE]

Box 4.6: Bottom-up Initiatives: Adaptation Responses Initiated by Individuals and Communities

To effectively adapt to climate change, bottom-up initiatives by individuals and communities are essential, in addition to efforts of governments, organisations, and institutions (Wamsler and Brink, 2014a). This box presents examples of bottom-up adaptation responses and behavioural change.

Fiji increasingly faces a lack of freshwater due to decreasing rainfall and rising temperatures (Deo, 2011; IPCC, 2014a). While some villages have access to boreholes, these are not sufficient to supply the population with freshwater. Villagers are adapting by rationing water, changing diets, and setting up inter-village sharing networks (Pearce et al., 2017). Some villagers take up wage employment to buy food instead of growing it themselves (Pearce et al., 2017). In Kiribati, residents adapt to drought by purchasing rainwater tanks and constructing additional wells (Kuruppu and Liverman, 2011). An important factor that motivated residents of Kiribati to adapt to drought was the perception that they could effectively adapt to the negative consequences of climate change (Kuruppu and Liverman, 2011).

In the Philippines, seismic activity has caused some islands to flood during high tide. While the municipal government offered affected island communities the possibility to relocate to the mainland, residents preferred to stay and implement measures themselves in their local community to reduce flood damage (Laurice Jamero et al., 2017). Migration is perceived as undesirable because island communities have strong place-based identities (Mortreux and Barnett, 2009), Instead, these island communities have adapted to flooding by constructing stilted houses and raising floors, furniture, and roads to prevent water damage (Laurice Jamero et al., 2017). While inundation was in this case caused by seismic activity, this example indicates how island-based communities may respond to rising sea levels caused by climate change.

Adaptation initiatives by individuals may temporarily reduce the impacts of climate change and enable residents to cope with changing environmental circumstances. However, they may not be sufficient to sustain communities' way of life in the long term. For instance, in Fiji and Kiribati, freshwater and food are projected to become even scarcer in the future, rendering individual adaptations ineffective. Moreover, individuals can sometimes engage in behaviour that may be maladaptive over larger spatio-temporal scales. For example, in the Philippines, many islanders adapt to flooding by elevating their floors using coral stone (Laurice Jamero et al., 2017). Over time, this can harm the survivability of their community, as coral reefs are critical for reducing flood vulnerability (Ferrario et al., 2014). In Maharashtra, India, on-farm ponds are promoted as rainwater harvesting structures to adapt to dry spells during the monsoon season. However, some individuals fill these ponds with groundwater, leading to depletion of water tables and potentially maladaptive outcomes in the long run (Kale, 2015).

Integration of individuals' adaptation initiatives with top-down adaptation policy is critical (Butler et al., 2015), as failing to do so may lead individual actors to mistrust authority and can discourage them from undertaking adequate adaptive actions (Wamsler and Brink, 2014a).

[END BOX 4.6 HERE]

Goal setting can promote mitigation action, when goals are not set too low or too high (Loock et al., 2013). Commitment strategies where people make a pledge to engage in climate actions can encourage mitigation behaviour (Abrahamse and Steg, 2013; Lokhorst et al., 2013), particularly when individuals also indicate how and when they will perform the relevant action and anticipate how to cope with possible barriers (i.e., implementation intentions) (Bamberg, 2000, 2002). Such strategies take advantage of individuals' desire to be consistent (Steg, 2016). Similarly, hypocrisy strategies that make people aware of inconsistencies between their attitudes and behaviour can encourage mitigation actions (Osbaldiston and Schott, 2012).

Actions that reduce climate risks can be rewarded and facilitated, while actions that increase climate risks can be punished and inhibited, and behaviour change can be voluntary (e.g., information provision) or imposed (e.g., by law); voluntary changes that involve rewards are more acceptable than imposed changes that restrict choices (Eriksson et al., 2006, 2008; Steg et al., 2006; Dietz et al., 2007). Policies punishing maladaptive behaviour can increase vulnerability when they reinforce socio-economic inequalities that typically produce the maladaptive behaviour in the first place (W.N. Adger et al., 2003). Change can be initiated by governments at various levels, but also by individuals, communities, profit-making organisations, trade organisations, and other non-governmental actors (Lindenberg and Steg, 2013; Robertson and Barling, 2015; Stern et al., 2016b).

Strategies can target intrinsic versus extrinsic motivation. It may be particularly important to enhance intrinsic motivation so that people voluntarily engage in climate action over and again (Steg, 2016). Endorsement of mitigation and adaptation actions are positively related (Brügger et al., 2015; Carrico et al., 2015); both are positively related to concern about climate change (Brügger et al., 2015). Strategies that target general antecedents that affect a wide range of actions, such as values, identities, worldviews, climate change beliefs, awareness of climate impacts of one's actions and feelings of responsibility to act on climate change, can encourage consistent actions on climate change (van Der Werff and Steg, 2015; Hornsey et al., 2016; Steg, 2016). Initial climate actions can lead to further commitment to climate action (Juhl et al., 2017), when people learn that such actions are easy and effective (Lauren et al., 2016), when they engaged in the initial behaviour for environmental reasons (Peters et al., 2018), hold strong pro-environmental values and norms (Thøgersen, J., Ölander, 2003), and when initial actions make them realise they are an environmentally-sensitive person, motivating them to act on climate change in subsequent situations so as to be consistent (van der Werff et al., 2014a; Lacasse, 2015, 2016). Yet, some studies suggest that people may feel licensed not to engage in further mitigation actions when they believe they already did their bit (Truelove et al., 2014).

4.4.3.3 Acceptability of Policy and System Changes

Public acceptability can shape, enable or prevent policy and system changes. Acceptability reflects the extent to which policy or system changes are evaluated (un)favourably. Acceptability is higher when people expect more positive and less negative effects of policy and system changes (Perlaviciute and Steg, 2014; Demski et al., 2015; Drews and Van den Bergh, 2016), including climate impacts (Schuitema et al., 2010b). Because of this, policy 'rewarding' climate actions is more acceptable than policy 'punishing' actions that increase climate risks (Steg et al., 2006; Eriksson et al., 2008). Pricing policy is more acceptable when revenues are earmarked for environmental purposes (Steg et al., 2006; Sælen and Kallbekken, 2011), or redistributed towards those affected (Schuitema and Steg, 2008). Acceptability can increase when people experience positive effects after a policy has been implemented (Schuitema et al., 2010a; Eliasson, 2014; Weber, 2015); effective policy trials can thus build public support for climate policy.

Climate policy and renewable energy systems are more acceptable when people strongly value other people and the environment, or support egalitarian worldviews, left-wing or green political ideologies (Drews and Van den Bergh, 2016), and less acceptable when people strongly endorse self-enhancement values, or support individualistic and hierarchical worldviews (Dietz et al., 2007; Perlaviciute and Steg, 2014; Drews and Van den Bergh, 2016). Solar radiation modification is more acceptable when people strongly endorse self-enhancement values, and less acceptable when they strongly value other people and the environment (Visschers et al., 2017). Climate policy is more acceptable when people believe climate change is real, when they are concerned about climate change (Hornsey et al., 2016), when they think their actions may reduce climate risks, and when they feel responsible to act on climate change (Steg et al., 2005; Eriksson et al., 2006; Jakovcevic and Steg, 2013; Drews and Van den Bergh, 2016; Kim and Shin, 2017). Stronger environmental awareness is associated with a preference for governmental regulation and behaviour change, rather than free market and technological solutions (Poortinga et al., 2002).

Climate policy is more acceptable when costs and benefits are distributed equally, when nature and future generations are protected (Sjöberg and Drottz-Sjöberg, 2001; Schuitema et al., 2011; Drews and Van den Bergh, 2016), and when fair procedures have been followed, including participation by the public (Dietz, 2013; Bernauer et al., 2016a; Bidwell, 2016) or public society organisations (Bernauer and Gampfer, 2013). Providing benefits to compensate affected communities for losses due to policy or systems changes enhanced public acceptability in some cases (Perlaviciute and Steg, 2014), although people may disagree on what would be a worthwhile compensation (Aitken, 2010; Cass et al., 2010), or feel they are being bribed (Cass et al., 2010; Perlaviciute and Steg, 2014).

Public support is higher when individuals trust responsible parties (Perlaviciute and Steg, 2014; Drews and Van den Bergh, 2016). Yet, public support for multilateral climate policy is not higher than for unilateral policy (Bernauer and Gampfer, 2015); public support for unilateral, non-reciprocal climate policy is rather strong and robust (Bernauer et al., 2016b). Public opposition may result from a culturally valued landscape being affected by adaptation or mitigation options, such as renewable energy development (Warren et al., 2005; Devine-wright and Howes, 2010) or coastal protection measures (Kimura, 2016), particularly when people have formed strong emotional bonds with the place (Devine-Wright, 2009, 2013).

Climate actions may reduce human wellbeing when such actions involve more costs, effort or discomfort. Yet, some climate actions enhance wellbeing, such as technology that improves daily comfort and nature-based solutions for climate adaptation (Wamsler and Brink, 2014b). Further, climate action may enhance wellbeing (Kasser and Sheldon, 2002; Xiao et al., 2011; Schmitt et al., 2018) because pursuing meaning by acting on climate change can make people feel good (Venhoeven et al., 2013, 2016; Taufik et al., 2015), more so than merely pursuing pleasure.

4.4.4 Enabling Technological Innovation

This section focuses on the role of technological innovation in limiting warming to 1.5ºC, and how innovation can contribute to strengthening implementation to move towards or to adapt to 1.5ºC worlds. This assessment builds on information of technological innovation and related policy debates in and after AR5 (Somanathan et al., 2014).

4.4.4.1 The Nature of Technological Innovations

Technological systems have their own dynamics. New technologies have been described as emerging as part of a ‘socio-technical system’ that is integrated with social structures and that itself evolves over time (Geels and Schot, 2007). This progress is cumulative and accelerating (Kauffman, 2002; Arthur, 2009). To illustrate such a process of co-evolution: the progress of computer simulation enables us to understand climate, agriculture, and material sciences better, contributing to upgrading food production and quality, microscale manufacturing techniques, and leading to much faster computing technologies, resulting for instance in better performing Photovoltaic (PV) cells.

A variety of technological developments have and will, contribute to 1.5°C-consistent climate action or the lack of it. They can do this, e.g., in the form of applications such as smart lighting systems, more efficient drilling techniques making fossil fuels cheaper, or precision agriculture. As discussed in Section 4.3.1, costs of PV (IEA, 2017f) and batteries (Nykvist and Nilsson, 2015) have sharply dropped. In addition, costs of fuel cells (Iguma and Kidoshi, 2015; Wei et al., 2017) and shale gas and oil (Wang et al., 2014; Mills, 2015) have come down as a consequence of innovation.

4.4.4.2 Technologies as Enablers of Climate Action

Since AR5, literature has emerged as to how much future GHG emission reductions can be enabled by the rapid progress of General Purpose Technologies (GPTs), consisting of Information and Communication Technologies (ICT) including Artificial Intelligence (AI) and Internet-of-Things (IoT), nanotechnologies, biotechnologies, robotics, and so forth (World Economic Forum, 2015; OECD, 2017c). Although these may contribute to limiting warming to 1.5°C, the potential environmental, social and economic impacts of new technologies are uncertain.

Rapid improvement of performance and cost reduction is observed for many GPTs. They include AI, sensors, internet, memory storage and micro-electro mechanical systems. The latter GPTs are not usually categorised as climate technologies, but they can impact GHG emissions.

Progress of GPT could help reducing GHG emissions more cost-effectively. Examples are shown in Table 4.9. It may however, result in more emissions by increasing the volume of economic activities, with unintended negative consequence on sustainable development. While ICT increases electricity consumption (Aebischer and Hilty, 2015), the energy consumption of ICT is usually dwarfed by the energy saving by ICT (Koomey et al., 2013; Malmodin et al., 2014), but rebound effects and other sustainable development impacts may be significant. An appropriate policy framework that accommodates such impacts and their uncertainties could address the potential negative impacts by GPT (Jasanoff, 2007).

GHG emission reduction potentials in relation to GPTs were estimated for passenger cars using a combination of three emerging technologies: electric vehicles, car sharing, and self-driving. GHG emission reduction potential is reported, assuming generation of electricity with low GHG emissions (Greenblatt and Saxena, 2015; ITF, 2015; Viegas et al., 2016; Fulton et al., 2017). It is also possible that GHG emissions increase due to an incentive to car use. Appropriate policies such as urban planning and efficiency regulations could contain such rebound effects (Wadud et al., 2016).

Estimating emission reductions by GPT is difficult due to substantial uncertainties, including projections of future technological performance, costs, penetration rates, and induced human activity. Even if a technology is available, the establishment of business models might not be feasible (Linder and Williander, 2017). Indeed, studies show a wide range of estimates, ranging from deep emission reductions to possible increases in the emissions due to the rebound effect (Larson and Zhao, 2017).

GPT could also enable climate adaptation, in particular through more effective climate disaster risk management and improved weather forecasting.

Table 4.9: Examples of technological innovations relevant to 1.5°C enabled by General Purpose Technologies (GPT). Note: Lists of enabling GPT or adaptation/mitigation options are not exhaustive, and the GPTs by themselves do not reduce emissions or increase climate change resilience.

Sector	**Examples of mitigation/adaptation technological innovation**	**Enabling GPT**
Buildings	Energy and CO_2 efficiency of logistics, warehouse and shops (GeSI, 2015; IEA, 2017a)	IoT, AI
	Smart lighting and air conditioning (IEA, 2016b, 2017a)	IoT, AI, nanotechnology
Industry	Energy efficiency improvement by industrial process optimisation (IEA, 2017a)	Robots, IoT
	Bio-based plastic production by bio-refinery (OECD, 2017c)	Biotechnology
	New materials from bio-refineries (Fornell et al., 2013; McKay et al., 2016)	ICT, Biotechnology
Transport	Electric vehicles, car sharing, automation (Greenblatt and Saxena, 2015; Fulton et al., 2017)	IoT, AI, nanotechnology
	Bio-based diesel fuel by bio-refinery (OECD, 2017c)	Biotechnology
	Second Generation Bioethanol potentially coupled to Carbon Capture Systems (de Souza et al., 2014; Rochedo et al., 2016)	ICT, Biotechnology
	Logistical optimisation, and electrification of trucks by overhead line (IEA, 2017e)	IoT, AI
	Reduction of transport needs by remote education, health, and other services (GeSI, 2015; IEA, 2017a)	ICT
	Energy saving by lightweight aircraft components (Beyer, 2014; Faludi et al., 2015; Verhoef et al., 2018)	Additive manufacturing (3D printing)
Electricity	Solar PV manufacturing (Nemet, 2014)	Nanotechnology
	Smart grids and grid flexibility to accommodate intermittent renewables (Heard et al., 2017)	IoT, AI
	Plasma confinement for nuclear fusion (Baltz et al., 2017)	AI
Agriculture	Precision agriculture (improvement of energy and resource efficiency including reduction of fertiliser use and N_2O emissions) (Pierpaoli et al., 2013; Brown et al., 2016; Schimmelpfennig and Ebel, 2016)	Biotechnology ICT, AI
	Methane inhibitors (methanogenic vaccines) that reduce dairy livestock emissions (Wollenberg et al., 2016)	Biotechnology
	Engineering C3 into C4 photosynthesis to improve agricultural production and productivity (Schuler et al., 2016)	Biotechnology
	Genome editing using CRISPR to improve/adapt crops to a changing climate (Gao, 2018)	Biotechnology
Disaster reduction and adaptation	Weather forecasting and early warning systems, in combination with user knowledge (Hewitt et al., 2012; Lourenço et al., 2016)	ICT
	Climate risk reduction (Upadhyay and Bijalwan, 2015)	ICT
	Rapid assessment of disaster damage (Kryvasheyeu et al., 2016)	ICT

Government policy usually plays a role in promoting or limiting GPTs, or science and technology in general. It has impacts on climate action, because the performance of further climate technologies will partly depend on the progress of GPTs. Governments have established institutions for achieving many social, and sometimes conflicting goals, including economic growth and addressing climate change (OECD, 2017c), which include investment in basic R&D that can help develop game changing technologies (Shayegh et al., 2017). Governments are also needed to create an enabling environment for the growth of scientific and technological ecosystems necessary for GPT development (Tassey, 2014).

4.4.4.3 The Role of Government in 1.5°C-Consistent Climate Technology Policy

While literature on 1.5°C-specific innovation policy is absent, a growing body of literature indicates that governments aim to achieve social, economic and environmental goals by promoting science and a broad range of technologies through ‘mission-driven’ innovation policies, based on differentiated national priorities

(Edler and Fagerberg, 2017). Governments can play a role in advancing climate technology via a 'technology push' policy on the technology supply side (e.g., R&D subsidies), and by 'demand pull' policy on the demand side (e.g., energy efficiency regulation), and these policies can be complemented by enabling environments (Somanathan et al., 2014). Governments may also play a role in removing existent support for incumbents (Kivimaa and Kern, 2016). A growing literature indicates that policy mixes, rather than single policy instruments, are more effective in addressing climate innovation challenges ranging from technologies in the R&D phase to those ready for diffusion (Veugelers, 2012; Quitzow, 2015; Rogge et al., 2017; Rosenow et al., 2017). Such innovation policies can help address two kinds of externalities: environmental externalities and proprietary problems (GEA, 2012; IPCC, 2014b; Mazzucato and Semieniuk, 2017). To avoid 'picking winners', governments often maintain a broad portfolio of technological options (Kverndokk and Rosendahl, 2007) and work in close collaboration with the industrial sector and society in general. Some governments have achieved relative success in supporting innovation policies (Grubler et al., 2012; Mazzucato, 2013) that addressed climate-related R&D (see Box 4.7 on bioethanol in Brazil).

[START BOX 4.7 HERE]

Box 4.7: Bioethanol in Brazil: Innovation and Lessons for Technology Transfer

The use of sugarcane as a bioenergy source started in Brazil in the 1970s. Government and multinational car factories modified car engines nationwide so that vehicles running only on ethanol could be produced. As demand grew, production and distribution systems matured and costs came down (Soccol et al., 2010). After a transition period in which ethanol-only and gasoline-only cars were used, the flex-fuel era started in 2003, when all gasoline was blended with 25% ethanol (de Freitas and Kaneko, 2011). By 2010, around 80% of the car fleet in Brazil had been converted to use flex-fuel (Goldemberg, 2011; Su et al., 2015).

More than forty years of combining technology push and market pull measures led to the deployment of ethanol production, transportation and distribution systems across Brazil, leading to a significant decrease in CO_2 emissions (Macedo et al., 2008). Examples of innovations include: 1) the development of environmentally well-adapted varieties of sugarcane; 2) the development and scaling up of sugar fermentation in a non-sterile environment, and 3) the development of adaptations of car engines to use ethanol as a fuel isolated or in combination with gasoline (Amorim et al., 2011; de Freitas and Kaneko, 2011; de Souza et al., 2014). Public procurement, public investment in R&D and mandated fuel blends accompanying these innovations were also crucial (Hogarth, 2017). In the future, innovation could lead to viable partial carbon dioxide removal through deployment of BECCS associated with the bioethanol refineries (Fuss et al., 2014; Rochedo et al., 2016) (see Section 4.3.7).

Ethanol appears to reduce urban car emission of health-affecting ultrafine particles by 30% compared to gasoline-based cars, but increases ozone (Salvo et al., 2017). During the 1990s, when sugarcane burning was still prevalent, particulate pollution had negative consequences for human health and the environment (Ribeiro, 2008; Paraiso and Gouveia, 2015). While (Jaiswal et al., 2017) report bioethanol's limited impact on food production and forests in Brazil, despite the large scale, and attribute this to specific agro-ecological zoning legislation, various studies report adverse effects of bioenergy production through forest substitution by croplands (Searchinger et al., 2008), as well as impacts on biodiversity, water resources, and food security (Rathore et al., 2016). For new generation biofuels, feasibility and life cycle assessment studies can provide information on their impacts on environmental, economic, and social factors (Rathore et al., 2016).

Brazil and the European Union have tried to replicate Brazil's bioethanol experience in climatically suitable African countries. Although such technology transfer achieved relative success in Angola and Sudan, the attempts to set up bioethanol value chains did not pass the phase of political deliberations and feasibility studies elsewhere in Africa. Lessons learned include the need of political and economic stability of the donor country (Brazil) and the necessity of market creation to attract investments in first-generation biofuels alongside a safe legal and policy environment for improved technologies (Afionis et al., 2014; Favretto et al., 2017).

[END BOX 4.7 HERE]

Funding for R&D could come from various sources, including the general budget, energy or resource taxation, or emission trading schemes (see Section 4.4.5). Investing in climate-related R&D has as an additional benefit of building capabilities to implement climate mitigation and adaptation technologies (Ockwell et al., 2015). Countries regard innovation in general and climate technology specifically as a national interests issue, and addressing climate change primarily as in the global interest. Reframing part of climate policy as technology or industrial policy might therefore contribute to resolving the difficulties that continue to plague emission target negotiations (Faehn and Isaksen, 2016; Fischer et al., 2017; Lachapelle et al., 2017).

Climate technology transfer to emerging economies has happened regardless of international treaties, as these countries have been keen to acquire them, and companies have an incentive to access emerging markets to remain competitive (Glachant and Dechezleprêtre, 2016). However, the complexity of this transfer processes is high and they have to be conducted carefully by governments and institutions (Favretto et al., 2017). It is noticeable that the impact of the EU Emission Trading Scheme (EU ETS) on innovation is contested; recent work (based on lower carbon prices than anticipated for 1.5°C-consistent pathways) indicates that it is limited (Calel and Dechezleprêtre, 2016) but earlier assessments (Blanco et al., 2014) indicate otherwise.

4.4.4.4 Technology Transfer in the Paris Agreement

Technology development and transfer is recognised as an enabler of both mitigation and adaptation in Article 10 in the Paris Agreement (UNFCCC, 2015) as well as in Article 4.5 of the original text of the UNFCCC (UNFCCC, 1992). As previous sections have focussed on technology development and diffusion, this section focuses on technology transfer. Technology transfer can adapt technologies to local circumstances, reduce financing costs, develop indigenous technology, and build capabilities to operate, maintain, adapt and innovate on technology globally (Ockwell et al., 2015; de Coninck and Sagar, 2017). Technology cooperation could decrease global mitigation cost, and enhance developing countries' mitigation contributions (Huang et al., 2017a).

The international institutional landscape around technology development and transfer includes the UNFCCC (via its technology framework and technology mechanism including the Climate Technology Centre and Network (CTCN)), the United Nations (a technology facilitation mechanism for the SDGs) and a variety of non-UN multilateral and bilateral cooperation initiatives such as the Consultative Group on International Agricultural Research (CGIAR, founded in the 1970s), and numerous initiatives of companies, foundations, governments and non-governmental and academic organisations. Moreover, in 2015, twenty countries launched an initiative called 'Mission Innovation', seeking to double their energy R&D funding. At this point it is difficult to evaluate whether Mission Innovation achieved its objective (Sanchez and Sivaram, 2017). At the same time, the private sector started an initiative called the 'Breakthrough Energy Coalition'.

Most technology transfer is driven by through markets by the interests of technology seekers and technology holders, in particular in regions with well-developed institutional and technological capabilities such as developed and emerging nations (Glachant and Dechezleprêtre, 2016). However, the current international technology transfer landscape has gaps, in particular in reaching out to least-developed countries, where institutional and technology capabilities are limited (de Coninck and Puig, 2015; Ockwell and Byrne, 2016). On the one hand, literature suggests that the management or even monitoring of all these UN, bilateral, private and public initiatives may fail to lead to better results. On the other hand, it is probably more cost-effective to adopt a strategy of 'letting a thousand flowers bloom', by challenging and enticing researchers in the public and the private sector to direct innovation towards low-emission and adaptation options (Haselip et al., 2015). This can be done at the same time as mission-oriented research is adopted in parallel by the scientific community (Mazzucato, 2018).

At COP 21, the UNFCCC requested the Subsidiary Body for Scientific and Technological Advice (SBSTA) to initiate the elaboration of the technology framework established under the Paris Agreement (UNFCCC, 2015). Among other things, the technology framework would 'provide overarching guidance for the work of the Technology Mechanism in promoting and facilitating enhanced action on technology development and transfer in order to support the implementation of this Agreement' (this Agreement being the Paris Agreement). An enhanced guidance issued by the Technology Executive Committee (TEC) for preparing a Technology Action Plan (TAP) supports the new technology framework as well as Parties' long-term vision on technology development and transfer, reflected in the Paris Agreement (TEC, 2016).

4.4.5 Strengthening Policy Instruments and Enabling Climate Finance

Triggering rapid and far-reaching change in technical choices and institutional arrangements, consumption and lifestyles, infrastructure, land use and spatial patterns implies the ability to scale-up policy signals to enable the decoupling of GHGs emission, and economic growth and development (Section 4.2.2.3). Such a scale-up would also imply that potential short-term negative responses by populations and interest groups, that could block these changes from the outset, would need to be prevented or overcome. This section describes the size and nature of investment needs and the financial challenge over the coming two decades in the context of 1.5°C warmer worlds, assesses the potential and constraints of three categories of policy instruments that respond to the challenge, and explains the conditions for using them synergistically. The policy and finance instruments discussed in this section relate to Section 4.4.1 (on governance) and other Sections in 4.4.

4.4.5.1 The Core Challenge: Cost Efficiency, Coordination of Expectations and Distributive Effects

Box 4.8 shows that the average estimates by seven models of annual investments needs in the energy system is around 2.38 trillion USD_{2010} (1,38 to 3,25) between 2016 and 2035. This represents between 2.53% (1.6% to 4%) of the world GDP in Market Exchange Rates (MER) and 1.7% of the world GDP in purchasing power parity (PPP). OECD investment assessments for a 2°C-consistent transition suggest that including investments in transportation and in other infrastructure would increase the investment needs by a factor of three. Other studies not included in Box 4.8, in particular by the World Economic Forum (World Economic Forum, 2013) and the Global Commission on the Economy and Climate (GCEC, 2014) confirm these orders of magnitude of investment.

[START BOX 4.8 HERE]

Box 4.8: Investment Needs and the Financial Challenge of Limiting Warming to 1.5°C

The peer-reviewed literature that estimates the investment needs to scale up the response to limit warming to 1.5°C is limited (see Section 4.6). This box attempts to bring together available estimates of the order of magnitude of these investments to provide the context for global and national financial mobilisation policy and related institutional arrangements.

Table 1 in this box presents mean annual investments up to 2035, based on three studies (after clarifying their scope and harmonising their metrics): an ensemble of six integrated assessment models (See Chapter 2); an OECD (Organisation for Economic Co-operation and Development) scenario for a 2°C limit (OECD, 2017a) and scenarios from the International Energy Agency (IEA) (IEA, 2016c). All three sources provide estimates for the energy sector for various for mitigation scenarios. The OECD estimate also covers transportation and other infrastructure (water, sanitation, and telecommunication), which are essential to deliver the Sustainable Development Goals (SDGs), including SDG7 on clean energy access, and enhance the adaptive capacity to climate change.

Box 4.8, Table 1: Estimated annualised mitigation investment needed to stay well below 2°C (2015–2035 in trillion USD at market exchange rates)

	Energy investments	Of which demand side	Transport	Other infra-structures	Total	Ratio to MER GDP
IAM Baseline (mean)	1.96	0.24			1.96	1.8%
IAM NDC (mean)	2.04	0.28			2.04	1.9%
IAM 2°C (mean)	2.19	0.38			2.19	2.1%
IAM 1.5°C (mean)	2.32	0.45			2.32	2.2%
IEA NDC	*2.40*	*0.72*	*0.35*		*2.40*	2.3%
IEA 1.5°C	*2.76*	*1.13*	*0.55*		*2.76*	2.7%
Mean IAM-IEA, 1.5°C	**2.38**	**0.54**			**2.38**	**2.53%**
Min IAM-IEA, 1.5°C	1.38	0.38			1.38	1.6%
Max IAM-IEA, 1.5°C	3.25	1.13			3.25	4.0%
OECD Baseline	*1.91*	*0.36*	*2.46*	*1.37*	*5.74*	5.4%
OECD 2°C	*2.13*	*0.40*	*2.73*	*1.52*	*6.38*	6.0%

The mean incremental share of annual mitigation investments to stay well below 2°C is 0.36% (between 0.2–1%) of global Gross Domestic Product (GDP) over 2015–2035. Since Gross Fixed Capital Formation (GFCF) is about 24% of global GDP, the estimated incremental energy investments between a baseline and a 1.5°C transition would be approximately 1.5% (between 0.8–4.2%) of projected total world investments. Given the uncertainty in these estimates, decision-makers could lower the probability of the most pessimistic assumptions by implementing policies to accelerate technical change (Section 4.4.5).

While total incremental investment for a 2°C-consistent pathway, including for transportation and other infrastructure, is estimated at 2.5% of global GFCF, there is no comprehensive study or estimate of these investments for a 1.5°C limit. For a 1.5°C-consistent pathway, the anticipated incremental 'other investments' might be lower thanks to lower investment needs in adaptation.

The issue, from a macroeconomic perspective, is whether these investments would be funded by higher savings at the costs of lower consumption. This would mean a 0.5% reduction in consumption for the energy sector for 1.5°C. Note that for a 2°C scenario, this reduction would be 0.8% if we account for the investment needs of all infrastructure sectors . Assuming a constant saving ratio, this can be enabled by reallocating existing capital flows towards infrastructure. In addition to these incremental investments, the amount of redirected investments is relevant from a financial perspective. In the reported Integrated Assessment Model (IAM) energy sector scenarios, about three times the incremental investments is redirected. There is no such assessment for the other sectors. The OECD report suggests that these ratios might be higher.

These orders of magnitude of investment can be compared to the available statistics of the global stock of 386 trillion USD of financial capital, which consists of 100 trillion USD in bonds (SIFMA, 2017), around 60 trillion USD in equity (The World Bank Data, 2018), and 226 trillion USD of loans managed by the banking system (IIF, 2017)(World Bank, 2018a). The long term rate of return (interest plus increase of shareholder value) is about 3% on bonds, 5% on bank lending, 7% on equity, leading to a weighted mean cost of capital of 3.4% in real terms (5.4% in nominal terms). Using 3.4% as a lower bound and 5% as a higher bound (following (Piketty, 2014)) and taking a conservative assumption that global financial capital grows at the same rate as global GDP, the estimated financial capital revenues would be between 16.8 and 25.4 trillion USD.

Assuming that a quarter of these investments comes from public funds (as estimated by the World Bank (World Bank, 2018a)), the amount of private resources needed to enable an energy sector transition is between 3.3% and 5.3% of annual capital income and between 5.6% and 8.3% of these revenues for all infrastructure to meet the 2°C target and the SDGs.

Since the financial system has limited fungibility across budget lines, changing the partitioning of investments is not a zero-sum game. An effective policy regime could encourage investment managers to change their asset allocation. Part of the challenge may lie in increasing the pace of financing of low-emission assets to compensate for a possible 38% decrease, by 2035, in the value of fossil fuel assets (energy sector and indirect holdings in downstream uses like automobiles) (Mercure et al., 2018).

[END BOX 4.8 HERE]

The average increase of investment in the energy sector resulting from Box 4.8 represents a mean value of 1.5% of the global Gross Fixed Capital Formation (GFCF) compared with the baselines scenario in Market Exchange Rate (MER) and a little over 1% in Purchasing Power Parity (PPP). Including infrastructure investments would raise this to 2.5% and 1.7% respectively[9].

These incremental investments could be funded through a drain on consumption (Bowen et al., 2017) which would necessitate between 0.68% and 0.45% lower global consumption than in the baseline. But, consumption at constant savings/consumption ratio can alternatively be funded by shifting savings towards productive adaptation and mitigation investments, instead of real-estate sector and liquid financial products. This response depends upon whether it is possible to close the global investment funding gap for infrastructure that potentially inhibits growth, through structural changes in the global economy. In this case, investing more in infrastructures would not be an incremental cost in terms of development and welfare (IMF, 2014; Gurara et al., 2017)

Investments in other (non-energy system) infrastructure to meet development and poverty reduction goals can strengthen the adaptive capacity to address climate change, and is difficult to separate from overall sustainable development and poverty alleviation investments (Hallegatte and Rozenberg, 2017). The magnitude of potential climate change damages is related to pre-existing fragility of impacted societies (Hallegatte et al., 2007). Enhancing infrastructure and service provision would lower this fragility, for example through the provision of universal (water, sanitation, telecommunication) service access (Arezki et al., 2016).

The main challenge is thus not just a lack of mobilisation of aggregate resources but of redirection of savings towards infrastructure, and the further redirection of these infrastructure investments towards low-emission options. If emission-free assets emerge fast enough to compensate for the devaluation of high-emission assets, the sum of the required incremental and redirected investments in the energy sector would (up to 2035) be equivalent to between 3.3% and 5.3% of the average annual revenues of the private capital stock (see Box 4.8) and to 5.6% and 8.3%, including all infrastructure investments.

The interplay between mechanisms of financial intermediation and the private risk-return calculus is a major barrier to realising these investments (Sirkis et al., 2015). This obstacle is not specific to climate mitigation investments but also affects infrastructure and has been characterised as the gap between the ‘propensity to save’ and the ‘propensity to invest’ (Summers, 2016). The issue is whether new financial instruments could close this gap and inject liquidity into the low-emission transition, thereby unlocking new economic opportunities (GCEC, 2014; NCE, 2016). By offsetting the crowding-out of other private and public investments (Pollitt and Mercure, 2017) the ensuing ripple effect could reinforce growth and the sustainability of development (King, 2011; Teulings and Baldwin, 2014) and potentially triggering a new growth cycle (Stern, 2013, 2015). In this case, a massive mobilisation of low-emission investments would

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[9] FOOTNOTE: A calculation in MER tends indeed to underestimate the world GDP and its growth by giving a lower weight to fast growing developing countries whereas a calculation in PPP tends to overestimate it. The difference between the value of two currencies in PPP and MER should vanish as the gap of the income levels of the two concerned countries decreases. Accounting for this trend in modelling is challenging.

require a significant effort, but may be complementary to sustainable development investments.

This uncertain but potentially positive outcome might be constrained by the higher energy costs of low-emission options in the energy and transportation sectors. The price envelope of worldwide marginal abatement costs for 1.5°C-consistent pathways reported in Chapter 2 is 135–475 USD tCO_2^{-1} in 2030 and 245–1100 USD tCO_2^{-1} in 2050, which is between two or three times higher than for a 2°C limit.

These figures are consistent with the dramatic reduction in the unit costs of some low-emission technical options (for example solar PV, LED lighting) over the past decade (OECD, 2017c) (see Section 4.3.1). Yet, there are multiple constraints to a system-wide energy transition. Lower costs of some supply and demand-side options does not always result in a proportional decrease in energy system costs. The adoption of alternative options can be slowed down by increasing costs of decommissioning existing infrastructure, inertia of market structures, cultural habits and by risk-adverse user behaviour (see Sections 4.4.1 to 4.4.3). Learning-by-doing processes and R&D can accelerate the cost-efficiency of low-emission technology but often imply higher early-phase costs. The German energy transition resulted in high consumer prices for electricity in Germany (Kreuz and Müsgens, 2017) and needed strong accompanying measures to succeed.

One key issue is that energy costs can propagate across sectors amplifying overall production costs. During the early stage of a low-emission transition, an increase in the prices of non-energy goods could cause lower consumer purchasing power and final demand. A rise of energy prices has a proportionally greater impact in developing countries that are in a catch-up phase, with strong dependence on energy-intensive sectors (Crassous et al., 2006; Luderer et al., 2012) and a higher ratio of energy to labour cost (Waisman et al., 2012). This explains why with lower carbon prices, similar emission reductions are reached in South Africa (Altieri et al., 2016) and Brazil (La Rovere et al., 2017a) compared to developed countries. However, three distributional issues emerge.

First, in the absence of countervailing policies, higher energy costs have an adverse effect on the distribution of welfare (see also Chapter 5). The negative impact is inversely correlated with the level of income (Harberger, 1984; Fleurbaey and Hammond, 2004) and positively correlated with the share of energy in the households budget, which is high for low- and middle- income households (Proost and Van Regemorter, 1995; Barker and Kohler, 1998; West and Williams, 2004; Chiroleu-Assouline and Fodha, 2011). Moreover, climatic conditions and the geographical conditions of human settlements matter for heating and mobility needs (see Chapter 5). Medium-income populations in the suburbs, remote and low-density regions can be as vulnerable as residents of low-income urban areas. Poor households with low levels of energy consumption are also impacted by price increases of non-energy goods caused by the propagation of energy costs (Combet et al., 2010; Dubois, 2012). These impacts are generally not offset by non-market co-benefits of climate policies for the poor (Baumgärtner et al., 2017).

A second matter of concern is the distortion of international competition and employment implications in case of uneven carbon constraints, especially for energy-intensive industries (Demailly and Quirion, 2008). Some of these industries are not highly exposed to international competition because of their very high transportation costs per unit value added (Sartor, 2013; Branger et al., 2016), but other industries could suffer severe shocks, generate 'carbon leakage' through cheaper imports from countries with lower carbon constraints (Branger and Quirion, 2014) and weaken the surrounding regional industrial fabric with economy-wide and employment implications.

A third challenge is the depreciation of assets whose value is based on the valuation of fossil energy resources of which future revenues may decline precipitously with higher carbon prices (Waisman et al., 2013; Jakob and Hilaire, 2015; McGlade and Ekins, 2015) and on emission-intensive capital stocks (Guivarch and Hallegatte, 2011; OECD/IEA/NEA/ITF, 2015; Pfeiffer et al., 2016). This raises issues of changes in industrial structure, adaptation of worker skills and of stability of financial, insurance and social security systems. These systems are in part based on current holdings of carbon-based assets whose value might decrease by 38% by the mid-2030s (Mercure et al., 2018). This stranded asset challenge may be exacerbated by a decline of export revenues of fossil fuel producing countries and regions (Waisman et al., 2013; Jakob and Hilaire, 2015; McGlade and Ekins, 2015).

These distributional issues, if addressed carefully and expeditiously, could affect popular sensitivity towards climate policies. Addressing them could mitigate adverse macroeconomic effects on economic growth and employment that could undermine the potential benefits of a redirection of savings and investments towards 1.5°C-consistent pathways.

Strengthening policy instruments for a low-emission transition would thus need to reconcile three objectives: i) handling the short-term frictions inherent to this transition in an equitable way, ii) minimising these frictions by lowering the cost of avoided GHGs emissions, and iii) coordinating expectations of multiple stakeholders at various decision-making levels to accelerate the decline in costs of emission reduction, efficiency and decoupling options and maximising their co-benefits (see the practical example of lowering car use in cities in Box 4.9).

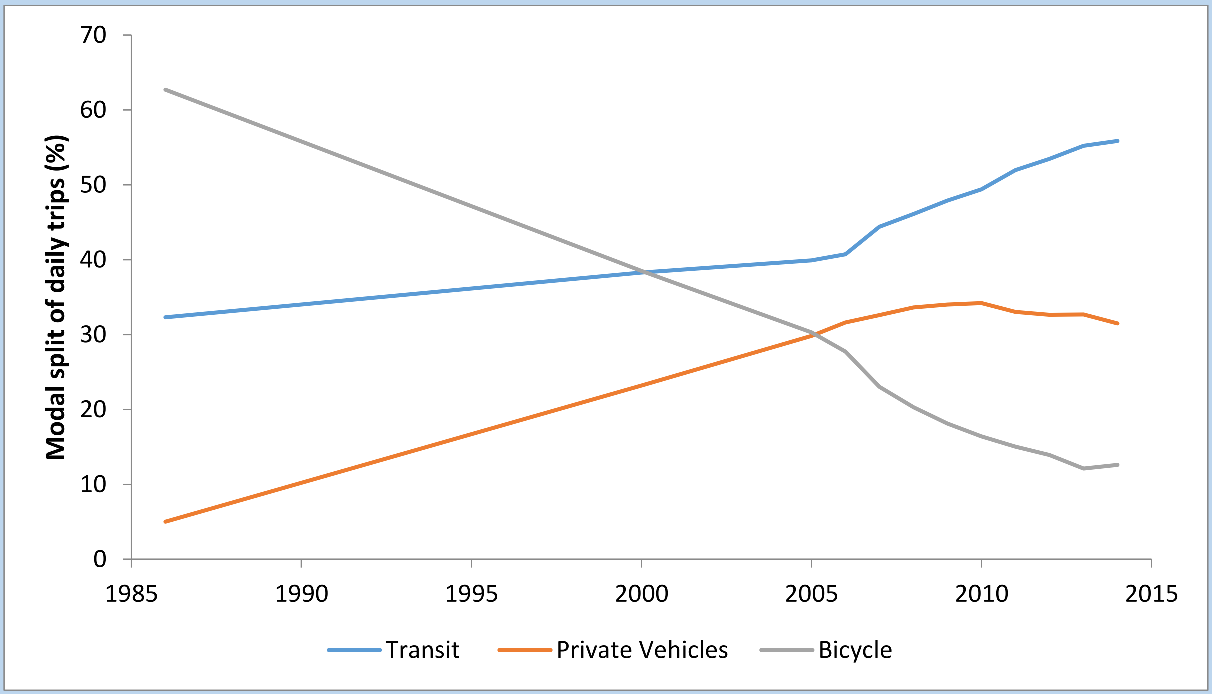
Three categories of policy tools would be available to meet the distributional challenges: carbon pricing, regulatory instruments and information and financial tools,. Each of them has its own strength and weaknesses, and in a 1.5°C perspective, policy tools would have to be both upscale and better coordinated in packages in a synergistic manner.

[START BOX 4.9 HERE]

Box 4.9: Emerging cities and 'peak car use': Evidence of decoupling in Beijing

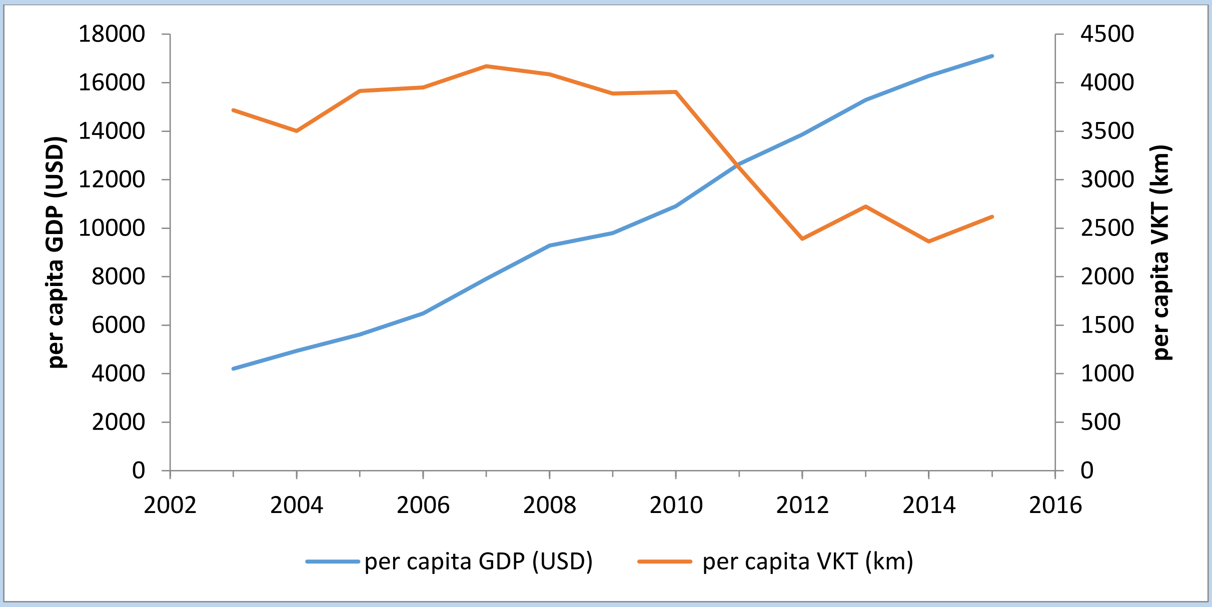
The phenomenon of 'peak car use', or reductions in per capita car use, provides hope for continuing reductions in greenhouse gas from oil consumption (Millard-Ball and Schipper, 2011; Newman and Kenworthy, 2011; Goodwin and Van Dender, 2013). The phenomenon has been mostly associated with developed cities apart from some early signs in Eastern Europe, Latin America and China (Newman and Kenworthy, 2015). New research indicates that peak car is now also underway in China (Gao and Newman, 2018).

China's rapid urban motorisation has resulted from strong economic growth, fast urban development and the prosperity of the Chinese automobile industry (Gao and Kenworthy, 2015). However, recent data (Gao and Newman, 2018) suggest the first signs of a break in the growth of car use expressed in percentage of daily trips as the growth in mass transit, primarily caused by the expansion of Metro systems, is becoming more significant (see Box 4.9, Figure 1).



Box 4.9, Figure 1: The modal split data in Beijing between 1986 and 2014. Source: (Gao and Newman, 2018).

Chinese urban fabrics, featuring traditional dense linear forms and mixed land use, favour mass transit systems over automobiles (Gao and Newman, 2018). The data show that the decline in car use did not impede economic development but Vehicle Kilometres of Travel (VKT) growth has decoupled absolutely from GDP as shown in Box 4.9, Figure 2 below.



Box 4.9, Figure 2: Peak car in Beijing: relationships between economic performance and private automobile use in Beijing from 1986 to 2014. VKT is Vehicle Kilometres of Travel. Source: (Gao and Newman, 2018).

[END BOX 4.9 HERE]

4.4.5.2 Carbon Pricing: Necessity and Constraints

For long, economic literature has argued that climate and energy policy only grounded in regulation, standards and public funding of R&D is at risk of being influenced by political and administrative arbitrariness, which could raise the costs of implementation. This literature has argued that it may be more efficient to make these costs explicit through carbon taxes and carbon trading, securing the abatement of emissions in places and sectors where it is cheapest (IPCC, 1995, 2001; Gupta et al., 2007; Somanathan et al., 2014).

In a frictionless world, a unique world carbon price could minimise the social costs of the low carbon transition by equating the marginal costs of abatement across all sources of emissions. This implies that investors will be able to make the right choices under perfect foresight and that domestic and international compensatory transfers offset the adverse distributional impacts of higher energy prices and their consequences on economic activity. In the absence of transfers targeted in function of countries market structures (Boeters, 2014), carbon prices are no longer optimal (Böhringer et al. 2009; Böhringer and Alexeeva-Talebi 2013) and need to be differentiated by jurisdiction (Chichilnisky and Heal, 2000; Sheeran, 2006) in function of the countries' social welfare function. This differentiation could in turn raise concerns of distortions in international competition (Hourcade et al., 2001; Stavins et al., 2014).

Obstacles to enforcing a unique world carbon price in the short-run would not necessarily crowd out explicit national carbon pricing, for three reasons. First, it could restrain an emissions rebound due to a higher consumption of energy services enabled by efficiency gains, if energy prices do not change (Greening et al., 2000; Fleurbaey and Hammond, 2004; Sorrell et al., 2009; Guivarch and Hallegatte, 2011; Chitnis and Sorrell, 2015; Freire-González, 2017). Second, it could hedge against the arbitrariness of regulatory policies. Third, 'revenue neutral' recycling, at a constant share of taxes on GDP, into lowering some existing taxes compensates at least part of the propagation effect of higher energy costs (Stiglitz et al., 2017). The substitution by carbon taxes of taxes that cause distortions on the economy can counteract the regressive effect of higher energy prices. For example, offsetting increased carbon prices with lower labour taxes can potentially decrease labour costs (without affecting salaries), enhance employment and reduce the attractiveness of informal economic activity (Goulder, 2013).

The conditions under which an economic gain along with climate benefit (a 'double dividend') can be expected are well documented (Goulder, 1995; Bovenberg, 1999; Mooij, 2000) . In the context of OECD countries, the literature examines how carbon taxation could substitute for other taxes to fund the social security system (Combet, 2013). The same general principles apply for countries that are building their social welfare system such as China (Li and Wang, 2012) or Brazil (La Rovere et al., 2017a) but an optimal recycling scheme could differ based on the structure of the economy (Lefèvre et al. 2018).

In every country the design of carbon pricing policy implies a balance between incentivising low-carbon behaviour and mitigating the adverse distributional consequences of higher energy prices (Combet et al., 2010). Carbon taxes can offset these effects if their revenues are redistributed through rebates to poor households. Other options include the reduction of value added taxes for basic products or direct benefit transfers to enable poverty reduction (see (Winkler et al., 2017) for South Africa and (Grottera et al., 2016) for Brazil). This is possible because higher income households pay more in absolute terms, even though their carbon tax burden is a relatively smaller share of their income (Arze del Granado et al., 2012).

Ultimately, the pace of increase of carbon prices would depend on the pace at which they can be embedded in a consistent set of fiscal and social policies. This is why, after a quarter century of academic debate and experimentation (see IPCC WGIII reports since the SAR), a gap persists with respect to 'switching carbon prices' needed to trigger rapid changes. In 2016, only 15% of global emissions are covered by carbon pricing, three-quarters of which with prices below 10 USD tCO_2^{-1} (World Bank, 2016). This is too low to outweigh the 'noise' from the volatility of oil markets (in the range of 100 USD tCO_2^{-1} over the past decade), of other price dynamics (interest rates, currency exchange rates and real estate prices) and of regulatory policies in energy, transportation and industry. For example, the dynamics of mobility depend upon a trade-off between housing prices and transportation costs in which the price of real estate and the inert endowments in public transport play as important a role as liquid fuel prices (Lampin et al., 2013).

These considerations apply to attempts to secure a minimum price in carbon trading systems (Wood and Jotzo, 2011; Fell et al., 2012; Fuss et al., 2018) and to the reduction of fossil fuel subsidies. Estimated at 650 billion USD in 2015 (Coady et al., 2017), they represent 25–30% of government revenues in forty (mostly developing) countries (IEA, 2014b). Reducing these subsidies would contribute to reaching 1.5°C-consistent pathways, but raises similar issues as carbon pricing around long-term benefits and short-term costs (Jakob et al., 2015; Zeng and Chen, 2016), as well as social impacts.

Explicit carbon prices are thus a necessary 'lubricant' to accommodate the general equilibrium effects of higher energy prices but may not suffice to trigger the low-carbon transition because of a persistent 'implementation gap' between the aspirational carbon prices and those that can practically be enforced. When systemic changes, such as those needed for 1.5°C-consistent pathways, are at play on many dimensions of development, price levels 'depend on the path and the path depends on political decisions' (Dréze and Stern, 1990).

4.4.5.3 Regulatory measures and information flows

Regulatory instruments are a common tool for improving energy efficiency and enhancing renewable energy in OECD countries (e.g., US, Japan, Korea, Australia, the EU) and, more recently, in developing countries (M.H. Scott et al., 2015; Brown et al., 2017) including constraints on the import of products banned in other countries (Knoop and Lechtenböhmer, 2017).

For energy efficiency, these instruments include end-use standards and labelling for domestic appliances, lighting, electric motors, water heaters and air-conditioners. They are often complemented by mandatory efficiency labels to attract consumers' attention and stimulate the manufacture of more efficient products (Girod et al., 2017). Experience shows that these policy instruments are effective only if they are regularly reviewed to follow technological developments, as in the 'Top Runner' programme for domestic appliances in Japan (Sunikka-Blank and Iwafune, 2011).

In four countries, efficiency standards (e.g. miles/gallon or level of CO_2 emission per km) have been used in the transport sector, for light and heavy-duty vehicles, which have spill-overs for the global car industry. In the EU (Ajanovic and Haas, 2017) and the US (Sen et al., 2017) vehicle manufacturers need to meet an annual CO_2 emission target for their entire new vehicle fleet. This allows them to compensate through the introduction of low-emission vehicles for the high-emission ones in the fleet. This leads to increasingly efficient fleets of vehicles over time, but does not necessarily limit the driven distance.

Building codes that prescribe efficiency requirements for new and existing buildings have been adopted in many OECD countries (Evans et al., 2017) and are regularly revised to increase their efficiency per unit of floor space. Building codes can avoid the lock-in of rapidly urbanising countries to poorly performing buildings that remain in use for the next 50–100 years (Ürge-Vorsatz et al., 2014). In OECD countries, however, their main role is to incentivise the retrofit of existing buildings. In addition of the convergence of these codes to Net Zero Energy Buildings (D′Agostino, 2015), a new focus should be placed, in the context of 1.5°C-consistent pathways, on public and private co-ordination to achieve better integration of building policies with the promotion of low-emission transportation modes (Bertoldi, 2017).

The efficacy of regulatory instruments can be reinforced by economic incentives, such as feed-in tariffs based on the quantity of renewable energy produced, subsidies or tax exemptions for energy savings (Bertoldi et al., 2013; Ritzenhofen and Spinler, 2016; García-Álvarez et al., 2017; Pablo-Romero et al., 2017), fee-bates, and 'bonus-malus' that foster the penetration of low-emission options (Butler and Neuhoff, 2008). Economic incentives can also be combined with direct use market-based instruments, for example combining, in the United States and, in some EU countries, carbon trading schemes with Energy Savings Obligations for energy retailers (Haoqi et al., 2017), or with Green Certificates for renewable energy portfolio standards (Upton and Snyder, 2017). Scholars have investigated caps on utilities' energy sales (Thomas et al., 2017) and emission caps at a personal level (Fawcett et al., 2010).

In combination with the funding of public research institutes, grants or subsidies also support R&D, where risk and the uncertainty about long-term perspectives can reduce the private sector's willingness to invest in low-emission innovation (see also Section 4.4.4). Subsidies can take the form of rebates on Value-Added Tax (VAT), of direct support to investments (e.g. renewable energy or refurbishment of buildings) or feed-in tariffs (Mir-Artigues and del Río, 2014). They can be provided by the public budget, via consumption levies, or via the revenues of carbon taxes or pricing. Fee-bates, introduced in some countries (for example for cars), have had a neutral impact on public budgets by incentivising low-emission products and penalising high-emission ones (de Haan et al., 2009).

All policy instruments can benefit from information campaigns (e.g., TV ads) tailored to specific end-users. A vast majority of public campaigns on energy and climate have been delivered through mass-media channels, and advertising-based approaches (Corner and Randall, 2011; Doyle, 2011). Although some authors report large savings obtained by such campaigns, most agree that the effects are short-lived and decrease over time (Bertoldi et al., 2016). Recently, focus has been placed on the use of social norms to motivate behavioural changes (Allcott, 2011; Alló and Loureiro, 2014). More on strategies to change behaviour can be found in section 4.4.3.

4.4.5.4 Scaling-up Climate Finance and De-Risking Low-Emission Investments

The redirection of savings towards low-emission investments may be constrained by enforceable carbon prices, implementation of technical standards and the short-term bias financial systems (Miles, 1993;

Bushee, 2001; Black and Fraser, 2002). The many causes of this bias are extensively analysed in economic literature (Tehranian and Waegelein, 1985; Shleifer and Vishny, 1990; Bikhchandani and Sharma, 2000) including their link with prevailing patterns of economic globalisation (Krugman, 2009; Rajan, 2011) and the chronic under-investment in long-term infrastructure (IMF, 2014). Emerging literature explores how to overcome this through reforms targeted to bridge the gap between short-term cash balances and long-term low-emission assets and to reduce the risk-weighted capital costs of climate-resilient investments. This gap was qualified by the Governor of the Bank of England as a Tragedy of the Horizons (Carney, 2016) that constitutes a threat to the stability of the financial system, is confirmed by the literature (Arezki et al., 2016; Christophers, 2017). This potential threat would encompass the impact of climate events on the value of assets (Battiston et al., 2017), liability risks (Heede, 2014) and the transition risk due to devaluation of certain classes of assets (Platinga and Scholtens, 2016).

The financial community's attention to climate change grew after COP 15 (ESRB ASC, 2016). This led to the introduction of climate-related risk disclosure in financial portfolios (UNEP, 2015) placing it on the agenda of G20 Green Finance Study Group and of the Financial Stability Board. This led to the creation of low-carbon financial indices that investors could consider as a 'free option on carbon' to hedge against risks of stranded carbon intensive assets (Andersson et al., 2016). This could also accelerate the emergence of climate-friendly financial products such as green or climate bonds, The estimated value of the Green bonds market in 2017 is USD 200 billion (BNEF, 2017). The bulk of these investments are in renewable energy, energy efficiency and low-emission transport (Lazurko and Venema, 2017), with only 4% for adaptation (OECD, 2017b). One major issue is whether individual strategies based on improved climate-related information alone will enable the financial system to allocate capital in an optimal way (Christophers, 2017) since climate change is a systemic risk (Schoenmaker and van Tilburg, 2016) (CISL, 2015).

The readiness of financial actors to reduce investments in fossil fuels is a real trend (Platinga and Scholtens, 2016; Ayling and Gunningham, 2017) but they may not resist the attractiveness of carbon-intensive investments in many regions. Hence, decarbonising an investment portfolio is not synonymous with investing massively in low-emission infrastructure. Scaling up climate-friendly financial products may depend upon a business context conducive to the reduction of the risk-weighted capital costs of low-emission projects. The typical leverage of public funding mechanisms for low-emission investment is low (2 to 4) compared with (10 to 15) in other sectors (Maclean et al., 2008; Ward et al., 2009; MDB, 2016). This is due to the interplay of the uncertainty of emerging low-emission technologies in the midst of their learning-by-doing cycle, and of uncertain future revenues due to volatility of fossil fuel prices (Roques et al., 2008; Gross et al., 2010) and of uncertainty around regulatory policies. This inhibits low-emission investments by corporations functioning under a 'shareholder value business regime' (Berle and Means, 1932; Froud et al., 2000; Roe, 2001) and actors with restricted access to capital (e.g. cities, local authorities, SMEs and households).

De-risking policy instruments to enable low-emission investment encompass interest rate subsidies, fee-bates, tax breaks, concessional loans from development banks, and public investment funds, including revolving funds. Given the constraints on public budgets, public guarantees can be used to secure high leverage of public financing. They imply a full direct burden on public budgets only in case of default of the project. They could back for example various forms of Green Infrastructure Funds (De Gouvello and Zelenko, 2010; Emin et al., 2014; Studart and Gallagher, 2015)[10].

The risk of defaulting can be mitigated by strong Measurement, Reporting and Verifying (MRV) systems (Bellassen et al., 2015)and by the use of notional prices recommended in public economics and currently in use in France and the UK, to calibrate public support to the provision of public goods in case of persisting distortions in pricing (Stiglitz et al., 2017). Some suggest linking these notional prices to 'social, economic and environmental value of voluntary mitigation actions' recognised by the COP21 Decision accompanying the Paris Agreement (paragraph 108) (Hourcade et al., 2015; La Rovere et al., 2017b; Shukla et al., 2017), in order to incorporate the co-benefits of mitigation.

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[10] FOOTNOTE: One prototype is the World Bank's Pilot Auction Facility on Methane and Climate Change

Such public guarantees ultimately amount to money issuance backed by low-emission projects as collateral. This explains the potentially strong link between global climate finance and the evolution of the financial and monetary system. Amongst suggested mechanisms for this evolution are the use of International Monetary Fund's (IMF's) Special Drawing Rights to fund the paid-in capital of the Green Climate Fund (Bredenkamp and Pattillo, 2010) and the creation of carbon remediation assets at a predetermined face value per avoided tonne of emissions (Aglietta et al., 2015a, b). Such a predetermined value could hedge against the fragmentation of climate finance initiatives and support the emergence of financial products backed by a new class of long-term assets.

Combining public guarantees at a predetermined value of avoided emissions, in addition to improving the consistency of non-price measures, could support the emergence of financial products backed by a new class of certified assets to attract savers in search of safe and ethical investments (Aglietta et al., 2015b). It could hedge against the fragmentation of climate finance initiatives and provide a mechanism to compensate for the 'stranded' assets caused by divestment in carbon-based activities and in lowering the systemic risk of stranded assets (Safarzyńska and van den Bergh, 2017). These new assets could also facilitate a low-carbon transition for fossil-fuel producers and help them to overcome the 'resource curse' (Ross, 2015; Venables, 2016).

Blended injection of liquidity has monetary implications. Some argue that this questions the premise that money should remain neutral (Annicchiarico and Di Dio, 2015, 2016; Nikiforos and Zezza, 2017). Central Banks or financial regulators could act as a facilitator of last resort for low-emission financing instruments, that could in turn lower the systemic risk of stranded assets (Safarzyńska and van den Bergh, 2017). This may, in time, lead to the use of carbon-based monetary instruments to diversify reserve currencies (Jaeger et al., 2013) and differentiate reserve requirements (Rozenberg et al., 2013) in the perspective of a Climate Friendly Bretton Woods (Sirkis et al., 2015; Stua, 2017).

4.4.5.5 Financial Challenge for Basic Needs and Adaptation Finance

Adaptation finance is difficult to quantify for two reasons. The first is that it is very difficult to isolate specific investment needs to enhance climate resilience from the provision of basic infrastructure that are currently underinvested (IMF, 2014; Gurara et al., 2017). The UNEP (2016) estimate of investment needs on adaptation in developing countries between 140–300 billion USD yr^{-1} in 2030, a major part being investment expenditures that are complementary with SDG-related investments focussed on universal access to infrastructure and services and meeting basic needs. Many climate adaptation-centric financial incentives are relevant to non-market services, offering fewer opportunities for market revenues while they contribute to creating resilience to climate impacts.

Hence, adaptation investments and the provision of basic needs would typically have to be supported by national and sub-national government budgets together with support from overseas development assistance and multilateral development banks (Fankhauser and Schmidt-Traub, 2011; Adenle et al., 2017; Robinson and Dornan, 2017), and a slow increase of dedicated NGO and private climate funds (Nakhooda and Watson, 2016). Even though the UNEP estimates of the costs of adaptation might be lower in a 1.5°C world (Climate Analytics, 2015) they would be higher than the UNEP 22.5 USD billion estimates of the bilateral and multilateral funding for climate change adaptation in 2014. Currently, 18–25% of climate finance flows to adaptation in developing countries (OECD, 2015, 2016a; Shine and Campillo, 2016). It remains fragmented, with small proportions flowing through UNFCCC channels (AdaptationWatch, 2015; Roberts and Weikmans, 2017).

Means of raising resources for adaptation, achieving the SDG and meeting basic needs (Durand et al., 2016; Roberts et al., 2017) include the reduction of fossil fuel subsidies (Jakob et al., 2016), increasing revenues from carbon taxes (Jakob et al., 2016), levies on international aviation and maritime transport and share of the proceeds of financial arrangements supporting mitigation activities (Keen et al., 2013). Each have different redistribution implications. Challenges, however, include the efficient use of resources, the emergence of long-term assets using infrastructure as collateral and the capacity to implement small-scale adaptation and the mainstreaming of adaptation in overall development policies. There is thus a need for greater policy coordination (Fankhauser and McDermott, 2014; Morita and Matsumoto, 2015; Sovacool et al., 2015, 2017; Lemos et al., 2016; Adenle et al., 2017; Peake and Ekins, 2017) that includes robust mechanisms for tracking, reporting, and ensuring transparency of adaptation finance (Donner et al., 2016; Pauw et al., 2016a; Roberts and Weikmans, 2017; Trabacchi and Buchner, 2017) and its consistency with the provision of basic needs (Hallegatte et al., 2016).

4.4.5.6 Towards Integrated Policy Packages and Innovative Forms of Financial Cooperation

Carbon prices, regulation and standards, improved information and appropriate financial instruments can work synergistically to meet the challenge of 'making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development', as in Article 2 in the Paris Agreement.

There is growing attention to combine the use of policy instruments that actually address three domains of action: the behavioural changes, the economic optimisation and the long-term strategies (Grubb et al., 2014). For example, de-risking low-emission investments would result in higher volumes of low-emission investments, and would in turn lead to a lower switching price for the same climate ambition (Hirth and Steckel, 2016). In the reverse direction, higher explicit carbon prices may generate more low-emission projects for a given quantum of de-risking. For example, efficiency standards for housing can increase the efficacy of carbon prices and overcome the barriers coming from the high discount rates used by households (Parry et al., 2014), while explicit and notional carbon prices can lower the risk of arbitrary standards. The calibration of innovative financial instruments to notional carbon prices could encourage large multinational companies to increase their level of internal carbon prices (UNEP, 2016). These notional prices could be higher than explicit carbon prices because they redirect new hardware investments without an immediate impact on existing capital stocks and associated interests.

Literature however shows that conflicts between poorly articulated policy instruments can undermine their efficiency (Lecuyer and Quirion, 2013; Bhattacharya et al., 2017; García-Álvarez et al., 2017). As has been illustrated in Europe, commitment uncertainty and lack of credibility of regulation have consistently led to low carbon prices in the case of the EU Emission Trading System (ETS; Koch et al., 2014; 2016). A comparative study shows how these conflicts can be avoided by policy packages that integrate many dimensions of public policies and are designed to match institutional and social context of each country and region (Bataille et al., 2015).

Even though policy packages depend upon domestic political processes, they might not reinforce the NDCs at a level consistent with the 1.5°C transition without a conducive international setting where international development finance plays a critical role. Section 4.4.1 explores the means of mainstreaming climate finance in the current evolution of the lending practices of national and multilateral bank (Badré, 2018). This could facilitate the access of developing countries to loans via bond markets at low interest rates, encouragement of the emergence of new business models for infrastructure, and encouragement of financial markets to support small-scale investments (Déau and Touati, 2017).

These financial innovations may involve non-state public actors like cities and regional public authorities that govern infrastructure investment, enable energy and food systems transitions and manage urban dynamics (Cartwright, 2015). They would help for example in raising USD 4.5–5.4 trillion yr^{-1} from 2015 to 2030 announced by the Cities Climate Finance Leadership Alliance (CCFLA, 2016) to achieve the commitments by the Covenant of Mayors of many cities to long-term climate targets (Kona et al., 2018).

The evolution of global climate financial cooperation may involve Central Banks, financial regulatory authorities, multilateral and commercial banks. There are still knowledge gaps about the form, structure and potential of these arrangements. They could be viewed as a form of a burden-sharing between high, medium and low-income countries to enhance, the deployment of ambitious Nationally

Determined Contributions (NDCs), and new forms of Common But Differentiated Responsibility and Respective Capabilities (Edenhofer et al., 2015; Hourcade et al., 2015; Ji and Sha, 2015).

4.5 Integration and Enabling Transformation

4.5.1 Assessing Feasibility of Options for Accelerated Transitions

Chapter 2 shows that 1.5°C-consistent pathways involve rapid, global climate responses to reach net-zero emissions by mid-century or earlier. Chapter 3 identifies climate change risks and impacts to which the world would need to adapt to, during these transitions and additional risks and impacts during potential 1.5°C overshoot pathways. The feasibility of these pathways is contingent upon systemic change (Section 4.3) and enabling conditions (Section 4.4), incuding policy packages. This section assesses the feasibility of options (technologies, actions and measures) that form parts of global systems under transition that make up 1.5°C-consistent pathways (Section 4.3).

Following the assessment framework developed in Chapter 1, economic and technological; institutional and socio-cultural; and environmental and geophysical feasibility are considered, and applied in to system transitions (Sections 4.3.1–4.3.4), overarching adaptation options (Section 4.3.5) and to Carbon Dioxide Removal (CDR) options (Section 4.3.7). This is done to assess the multi-dimensuional feasibility of mitigation and adaptation options that have seen considerable development and change since AR5. In the case of adaptation, the assessed AR5 options are typically clustered, for example, all options related to energy infrastructure resilience, independently of the generation source, are categorised as ‘resilience of power infrastructure’.

Table 4.10 presents sets of indicators against which the multi-dimensional feasibility of individual adaptation options relevant to limiting warming of 1.5°C, and mitigation options along 1.5°C-consistent pathways, are assessed.

Table 4.10: Sets of indicators against which the feasibility of adaptation and mitigation are assessed, for each feasibility dimension (in Sections 4.3.1-4.3.4, 4.3.5 and 4.3.7)

	Characteristics	**Adaptation indicators**	**Mitigation indicators**
	Economic	Micro-economic viability Macro-economic viability Socio-economic vulnerability reduction potential Employment & productivity enhancement potential	Cost-effectiveness Absence of distributional effects Employment & productivity enhancement potential
	Technological	Technical resource availability Risks mitigation potential	Technical scalability Maturity Simplicity Absence of risk
	Institutional	Political acceptability Legal & regulatory feasibility Institutional capacity & administrative feasibility Transparency & accountability potential	Political acceptability Legal & administrative feasibility Institutional capacity Transparency & accountability potential
	Socio-cultural	Social co-benefits (health, education) Socio-cultural acceptability Social & regional inclusiveness Intergenerational equity	Social co-benefits (health, education) Public acceptance Social & regional inclusiveness Intergenerational equity Human capabilities

	Environmental/ecological	Ecological capacity Adaptive capacity/ resilience building potential	Reduction of air pollution Reduction of toxic waste Reduction of water use Improved biodiversity
	Geophysical	Physical feasibility Land use change enhancement potential Hazard risk reduction potential	Physical feasibility (physical potentials) Limited use of land Limited use of scarce (geo)physical resources Global spread

The feasibility assessment takes the following steps. First, each of the mitigation and adaptation options is assessed along the relevant indicators grouped around six feasibility dimensions: economic, technological, institutional, socio-cultural, environmental/ecological and geophysical. Three types feasibility groupings were assessed from the underlying literature: first, if the indicator could block the feasibility of this option, second, if the indicator has neither a positive, nor a negative effect on the feasibility of the option or the evidence is mixed, and third if the indicator does not pose any barrier to the feasibility of this option. The full assessment of each option under each indicator, including the literature references on which the assessment is based, can be found in supplementary materials D.2 and D.3. When appropriate, it is indicated that there is no evidence (NE), limited evidence (LE) or that the indicator is not applicable to the option (NA).

Next, for each feasibility dimension and option, the overall feasibility for a given dimension is assessed as the mean of combined scores of the relevant underlying indicators, and classified into 'insignificant barriers' (2.5 to 3), 'mixed or moderate but still existent barriers' (1.5 to 2.5) or 'significant barriers' (below 1.5) to feasibility. Indicators assessed as NA, LE or NE are not included in this overall assessment (see supplementary material D.1 for the averaging and weighing guidance).

The results are summarised in Table 4.11 (for mitigation options) and Table 4.12 (for adaptation options) for each of the six feasibility dimensions: where dark shading indicates few feasibility barriers; moderate shading indicates that there are some barriers and light shading that multiple barriers, in this dimension, may block implementation.

A three-step process of independent validation and discussion by authors and reviewers was undertaken to make this assessment as robust as possible within the scope of this special report. It must however, be recognised that this is an indicative assessment at global scale, and both policy and implementation at regional, national and local level would need to adapt and build on this knowledge, within the particular local context and constraints.

4.5.2 Implementing Mitigation

This section builds on the insights on mitigation options in Section 4.3, applies the assessment methodology along feasibility dimensions and indicators explained in Section 4.5.1, and synthesises the assessment of the enabling conditions in Section 4.4.

4.5.2.1 Assessing of Mitigation Options for Limiting Warming to 1.5˚C Against Feasibility Dimensions

An assessment of the degree to which examples of 1.5°C-relevant mitigation options face barriers to implementation, and on which contexts this depends, is summarised in Table 4.11. An explanation of the approach is given in Section 4.5.1 and in supplementary material D.1. Selected options were mapped onto system transitions and clustered through an iterative process of literature review, expert feedback, and responses to reviewer comments. The detailed assessment and the literature underpinning the assessment can be found in supplementary material D.2.

The feasibility framework in Cross-Chapter Box 3 in Chapter 1 highlights that the feasibility of mitigation and adaptation options depends on many factors. Many of those are captured in the indicators in Table 4.10, but many depend on the specific context in which an option features. Since this Special Report did not have the mandate, space nor the literature base to undertake a regionally specific assessment. Hence the assessment is caveated as providing a broad indication of where the global barriers are likely to ignoring significant regional diversity. Regional and context-specific literature is also just emerging as recorded in knowledge gaps (Section 4.6). Nevertheless, in Table 4.11, an indicative attemot has been made to capture some relevant contextual information. The 'context' column indicates what contextual factors may affect the feasibility of an option, including regional differrences. For instance, solar irradiation in an area impacts the cost-effectiveness of solar Photovoltaic (PV), so solar irradiation is mentioned in this column.

Table 4.11: Feasibility assessment of examples of 1.5°C-relevant mitigation options with dark shading signifying the absence of barriers in the feasibility dimension, moderate shading that on average, the dimension does not have a positive, nor a negative effect on the feasibility of the option, and faint shading the presence of potentially blocking barriers. No shading means that not sufficient literature could be found to make the assessment. Evidence and agreement assessment is undertaken at the option level. The context column on the far right indicates how the assessment might change if contextual factors are different. For the methodology and literature basis, see supplementary material D.1 and D.2.

System	Mitigation option	Evidence	Agreement	Ec	Tec	Inst	Soc	Env	Geo	Context
Energy system transitions	Wind energy (on-shore & off-shore)	Robust	Medium	▨	■	▨	■	■	▨	Wind regime, economic status, space for windfarms and enhanced by legal framework for independent power producers affect uptake; cost-effectiveness affected by incentive regime.
	Solar PV	Robust	High	■	■	▨	■	■	▨	Cost-effectiveness affected by solar irradiation and incentive regime. Also enhanced by legal framework for independent power producers affect uptake.
	Bioenergy	Robust	Medium	▨	■	░	▨	░	▨	Depends on availability of biomass and land and capability to manage sustainable land use. Distributional effects depend on the agrarian (or other) system used to produce feedstock.
	Electricity storage	Robust	High	▨	▨	▨	▨	▨	▨	Batteries universal but grid flexible resources vary with area's level of development
	Power sector CCS	Robust	High	▨	▨	▨	░	▨	■	Varies with local CO2 storage capacity, presence of legal framework, level of development and quality of public engagement
	Nuclear energy	Robust	High	▨	▨	░	░	▨	■	Electricity market organisation, legal framework, standardisation & know-how, country's 'democratic fabric', institutional and technical capacity, and safety culture of public and private institutions
Land & ecosystem transitions	Reduced food wastage & efficient food production	Robust	High	▨	▨	■	▨	■	■	Will depend on the combination of individual and institutional behaviour
	Dietary shifts	Medium	High		▨		▨	■		Depends on individual behaviour, education, cultural factors and institutional support
	Sustainable intensification of agriculture	Medium	High		▨	▨	■	▨	▨	Depends on development and deployment of new technologies
	Ecosystems restoration	Medium	High	▨	■	▨	■	■	■	Depends on location and institutional factors
Urban	Land-use & urban planning	Robust	Medium	▨	▨	▨	▨	■	■	Varies with urban fabric, not geography or economy; requires capacitated local government and legitimate tenure system

	Electric cars and buses	Medium	High	🟧	🟧	🟧	🟧		🟧	Varies with degree of government intervention; requires capacity to retrofit "fuelling" stations
	Sharing schemes	Limited	Medium	🟫	🟧	🟧	🟧	🟫	🟫	Historic schemes universal new ones depend on ICT status; undermined by high crime and low levels of law enforcement
	Public transport	Robust	Medium	🟫	🟫	🟫	🟫	🟫	🟫	Depends on presence of existing 'informal' taxi systems, which may be more cost effective and affordable than capital intensive new build schemes, as well as (local) government capabilities
	Non-motorised transport	Robust	High	🟫	🟫	🟫	🟫		🟫	Viability rests on linkages with public transport, cultural factors, climate and geography
	Aviation & shipping	Medium	Medium	░	🟧	🟧		🟧	🟫	Varies with technology, governance and accountability
	Smart Grids	Medium	Medium	🟧	🟧	░	🟧	🟫	🟧	Varies with economic status and presence or quality of existing grid
	Efficient appliances	Medium	High	🟧	🟫	🟫	🟫	🟫	🟫	Adoption varies with economic status and policy framework
	Low/zero-energy buildings	Medium	High	🟫	🟧	🟧		🟫	🟫	Depends on size of existing building stock and growth of building stock
Industrial system transitions	Energy efficiency	Robust	High	🟧	🟫	🟫	🟧	🟧	🟫	Potentials and adoption depends on existing efficiency, energy prices and interest rates, as well as government incentives.
	Bio-based & circularity	Medium	Medium	🟧	🟧	░			🟧	Faces barriers in terms of pressure on natural resources and biodiversity. Product substitution depends on market organisation and government incentivisation.
	Electrification & hydrogen	Medium	High		🟧				🟧	Depends on availability of large-scale, cheap, emission-free electricity (electrification, hydrogen) or CO2 storage nearby (hydrogen). Manufacturers' appetite to embrace disruptive innovations
	Industrial CCUS	Robust	High	🟧	🟧	🟧		🟧	🟧	High concentration of CO2 in exhaust gas improve economic and technical feasibility of CCUS in industry. CO2 storage or reuse possibilities.
Carbon dioxide removal	BECCS	Robust	Medium	░	🟧	░		░	🟧	Depends on biomass availability, CO2 storage capacity, legal framework, economic status and social acceptance
	DACCS	Medium	Medium	░	░				🟫	Depends on CO2-free energy, CO2 storage capacity, legal framework, economic status and social acceptance
	Afforestation & reforestation	Robust	High	🟧	🟫		🟧	🟧	🟧	Depends on location, mode of implementation, and economic and institutional factors

	Soil carbon sequestration & biochar	Robust	High	🟫	🟧				🟧	Depends on location, soil properties, time span
	Enhanced weathering	Medium	Low		░				🟫	Depends on CO2-free energy, economic status and social acceptance

4.5.2.2 Enabling Conditions for Implementation of Mitigation Options Towards 1.5˚C

The feasibility assessment highlights six dimensions that could help inform an agenda that could be addressed by the areas discussed in Section 4.4: governance, behaviour and lifestyles, innovation, enhancing institutional capacities, policy and finance. For instance, Section 4.4.3 on behaviour offers strategies for addressing public acceptance problems, and how changes can be more effective when communication and the actions relate to people's values. This section synthesises the findings in Section 4.4 in an attempt to link them to the assessment in Table 4.11. The literature on which the discussion is based is found in Section 4.4.

From Section 4.4, including the case studies presented in the Boxes 4.1 to 4.10, several main messages can be constructed. For instance, governance would have to be multi-level and engaging different actors, while being efficient, and choosing the type of cooperation based on the specific systemic challenge or option at hand. If institutional capacity for financing and governing the various transitions is not urgently built, many countries would lack the ability to change pathways from a high-emission scenario to a low- or zero-emission scenario. In terms of innovation, governments, both national and multilateral, can contribute to the mitigation-purposed application of general purpose technologies. If this is not managed, some emission reduction could happen autonomously, but it may not lead to a 1.5ºC-consistent pathway. International cooperation on technology, including technology transfer where this does not happen autonomously, is needed and can help creating the innovation capabilities in all countries to be able to operate, maintain, adapt and regulate a portfolio of mitigation technologies. Case studies in the various sub-sections highlight the opportunities and challenges of doing this in practice. They indicate that it can be done in specific circumstances .

A combination of behaviour-oriented pricing policies and financing options can help change technologies and social behaviour as it challenges the existing, high-emission socio-technical regime on multiple levels across feasibility characteristics. For instance, for dietary change, a combination of supply-side measures with value-driven communication and economic instruments may help make a lasting transition, while only an economic instrument, such as enhanced prices or taxation, may not be as robust.

Governments could benefit from enhanced carbon prices, as a price and innovation incentive and also source of additional revenue to correct distributional effects and subsidise the development of new, cost-effective negative-emission technology and infrastructure. However, there is *high evidence* and *medium agreement* that pricing alone is insufficient. Even if prices rise significantly, they typically incentivise incremental change, but typically fail to provide the impetus for private actors to take the risk of engaging in the transformational changes that would be needed to limit warming to 1.5ºC. Apart from the incentives to change behaviour and technology, financial systems are an indispensable element of a systemic transition. If financial markets do not acknowledge climate risk and the risk of transitions, they could be organised by regulatory financial institutions, such as central banks.

Strengthening implementation revolves around more than addressing barriers to feasibility. A system transition, be it in energy, industry, land or a city, requires changing the core parameters of a system. These relate, as introduced in Section 4.2 and further elaborated in Section 4.4, to how actors cooperate, how technologies are embedded, how resources are linked, how cultures relate and what values people associate with the transition and the current regime.

4.5.3 Implementing Adaptation

Article 7 of the Paris Agreement provides an aspirational global goal for adaptation, of 'enhancing adaptive capacity, strengthening resilience, and reducing vulnerability' (UNFCCC, 2015). Adaptation implementation is gathering momentum in many regions, guided by national NDC's and National Adaptation Plans (see Cross-Chapter Box 11 in this Chapter).

Operationalising adaptation in a set of regional environments on pathways to a 1.5°C world, requires strengthened global and differentiated regional and local capacities. It also needs rapid and decisive adaptation actions to reduce the costs and magnitude of potential climate impacts (Vergara et al., 2015).

This could be facilitated by: i) enabling conditions, especially improved governance, economic measures and financing (Section 4.4); ii) enhanced clarity on adaptation options to help identify strategic priorities, sequencing and timing of implementation (Section 4.3); iii) robust monitoring and evaluation frameworks; and iv) political leadership (Magnan et al., 2015; Magnan and Ribera, 2016; Lesnikowski et al., 2017; UNEP, 2017a).

4.5.3.1 Feasible Adaptation Options

This section summarises the feasibility (defined in Cross-Chapter Box 3, Table 1 in Chapter 1 and Table 4.4) of select adaptation options using evidence presented across this chapter and in supplementary material D.3 and the expert-judgement of its authors (Table 4.12). The options assessed respond to risks and impacts identified in Chapter 3. They were selected based on options identified in AR5 (Noble et al., 2014), focusing on those relevant to 1.5°C-compatible pathways, where sufficient literature exists. Selected options were mapped onto system transitions and clustered through an iterative process of literature review, expert feedback, and responses to reviewer comments.

Besides gaps in the literature around crucial adaptation questions on the transition to a 1.5°C world (Section 4.6), there is inadequate current literature to undertake a spatially differentiated assessment (Cross-Chapter Box 3 in Chapter 1). There are also limited baselines for exposure, vulnerability and risk to help policy and implementation prioritisation. Hence, the compiled results can at best provide a broad framework to inform policymaking. Given the bottom-up nature of most adaptation implementation evidence, care needs to be taken in generalising these findings.

Options are considered as part of a systemic approach, recognising that no single solution to exits to limit warming to 1.5°C and adapting to its impacts. To respond to the local and regional context, and synergies and trade-offs between adaptation, mitigation and sustainable development, packages of options suited to local enabling conditions, can be implemented.

Table 4.12 summarises the feasibility assessment through its six dimensions with levels of evidence and agreement, and indicates how the feasibility of an adaptation option may be differentiated by certain contextual factors (last column).

Table 4.12: Feasibility assessment of examples of 1.5°C-relevant adaptation options with dark shading signifying the absence of barriers in the feasibility dimension, moderate shading that on average, the dimension does not have a positive, nor a negative effect on the feasibility of the option, and light shading the presence of potentially blocking barriers. No shading means that not sufficient literature could be found to make the assessment. NA signifies that the dimension is not applicable to that adaptation option. For methodology and literature basis, see supplementary material D.

System	Adaptation option	Evidence	Agreement	Ec	Tec	Inst	Soc	Env	Geo	Context
Energy system transitions	Power infrastructure, including water	Medium	High	▓	█	▓		▓	▓	Depends on existing power infrastructure, all generation sources and with intensive water requirements
Land & ecosystem transitions	Conservation agriculture	Medium	Medium	▓	▓	▓	▓	█	▓	Depends on irrigated/rainfed system, ecosystem characteristics, crop type, other farming practices
	Efficient irrigation	Medium	Medium	▓	▓	▓	▓	▓	▓	Depends on agricultural system, technology used, regional institutional and biophysical context
	Efficient livestock	Limited	High	▓	░		▓	█	▓	Dependent on livestock breeds, feed practices,and biophysical context (e.g. carrying capacity)
	Agroforestry	Medium	High	▓	▓	▓	▓	█	█	Depends on knowledge, financial support, and market conditions
	Community-based adaptation	Medium	High	▓		▓	▓	▓	▓	Focus on rural areas and combined with ecosystems-based adaptation, does not include urban settings
	Ecosystem restoration & avoided deforestation	Robust	Medium	▓	█	▓	▓	▓	▓	Mostly focused on existing and evaluated REDD+ projects
	Biodiversity management	Medium	Medium	▓	░	░	▓	▓		Focus on hotspots of biodiversity vulnerability and high connectivity
	Coastal defense & hardening	Robust	Medium	▓	▓	▓	▓	░	▓	Depends on locations that require it as a first adaptation option
	Sustainable aquaculture	Limited	Medium	▓	░			▓	▓	Depends on locations at risk and socio-cultural context
Urban & infrastructure system transitions	Sustainable land-use & urban planning	Medium	Medium	▓	▓	▓	▓	▓	█	Depends on nature of planning systems and enforcement mechanisms
	Sustainable water management	Robust	Medium	█	█	░	▓	▓	█	Balancing sustainable water supply and rising demand especially in low-income countries
	Green infrastructure & ecosystem services	Medium	High	▓	█	▓	█	█	▓	Depends on reconciliation of urban development with green infrastructure

	Building codes & standards	Limited	Medium	🟧	🟧	🟧	🟧	🟧	🟧	Adoption requires legal, educational, and enforcement mechanisms to regulate buildings
Industrial system transitions	Intensive industry infrastructure resilience and water management	Limited	High		🟧			🟧	🟧	Depends on intensive industry, existing infrastructure and using or requiring high demand of water
Overarching adaptation options	Disaster risk management	Medium	High	🟧	🟧	🟧	🟧	🟧	🟧	Requires institutional, technical, and financial capacity in frontline agencies and government
	Risk spreading and sharing	Medium	Medium	🟧	🟧	🟧	🟧	🟧	🟧	Requires well developed financial structures and public understanding
	Climate services	Medium	High	🟧	🟧	🟧	🟧	🟧	🟧	Depends on climate information availability and usability, local infrastructure and institutions, national priorities
	Indigenous knowledge	Medium	High	🟧	🟧	░	🟫	🟫	🟫	Dependent on recognition of Indigenous rights, laws, and governance systems
	Education and learning	Medium	High	🟧	🟧	🟧	🟧	🟫	🟫	Existing education system, funding
	Population health and health system	Medium	High	🟫	🟧	🟫	🟫	🟫	▒	Requires basic health services and infrastructure
	Social safety nets	Medium	Medium	🟧	🟧	🟧	🟧	🟫	🟫	Type and mechanism of safety net, political priorities, institutional transparency
	Human migration	Medium	Low	🟧	🟧	░	░	░	░	Hazard exposure, political and socio-cultural acceptability (in destination), migrant skills and social networks

When considered jointly, the description of adaptation options (Section 4.3), the feasibility assessment (summarised in Table 4.12), and discusson of enabling conditions (Section 4.4) show us how options can be implemented and lead towards transformational adaptation if and when needed.

The adaptation options for energy system transitions focus on existing power infrastructure resilience and water management, when required, for any type of generation source. These options are not sufficient for the far-reaching transformations required in the energy sector, which have tended to focus on technologies to shift from a fossil-based to a renewable energy system (Erlinghagen and Markard, 2012; Muench et al., 2014; Brand and von Gleich, 2015; Monstadt and Wolff, 2015; Child and Breyer, 2017; Hermwille et al., 2017). There is also need for integration of this with social-ecological systems transformations to increase the resilience of the energy sector, for which appropriate enabling conditions, such as for technological innovations, are fundamentally important. Institutional capacities can be enhanced by expanding the role of actors as transformation catalysts (Erlinghagen and Markard, 2012). The integration of ethics and justice within these transformations can help attain the SDG7 on clean energy access (Jenkins et al., 2018), while inclusion of the cultural dimension and cultural legitimacy (Amars et al., 2017) can provide a more substantial base for societal transformation. Strengthening policy instruments and regulatory frameworks and enhancing multi-level governance that focusses on resilience components can help secure these transitions (Exner et al., 2016).

For land and ecosystem transitions, conservation agriculture, efficient irrigation, agroforestry, ecosystem restoration and avoided deforestation, and coastal defence and hardening have between *medium and robust evidence* with *medium to high agreement*. The other options assessed have limited or no evidence across one or more of the feasibility dimensions. Community-based adaptation is assessed as an option many opportunities with *medium evidence* and *high agreement* though faces scaling barriers. Given the structural changes these options may require, transformational adaptation may be implied in some regions, involving enhanced multi-level governance and institutional capacities by enabling anticipatory and flexible decision-making systems that access and develop collaborative networks (Dowd et al., 2014), tackling root causes of vulnerability (Chung Tiam Fook, 2017), and developing synergies between development and climate change (Burch et al., 2017). Case studies show the use of transformational adaptation approaches for fire management (Colloff et al., 2016a), floodplain and wetland management (Colloff et al., 2016b), and forest management (Chung Tiam Fook, 2017), in which the strengthening of policy instruments and climate finance are also required.

There is growing recognition of the need for transformational adaptation within the agricultural sector but limited evidence on how to facilitate processes of deep, systemic change (Dowd et al., 2014). Case studies demonstrate that transformational adaptation in agriculture requires a sequencing and overlap between incremental and transformational adaptation actions (Hadarits et al., 2017; Termeer et al., 2017), e.g., incremental improvements to crop management while new crop varieties are being researched and field tested (Rippke et al., 2016). Broader considerations include addressing stakeholder values and attitudes (Fleming et al., 2015a), understanding and leveraging the role of social capital, collaborative networks, and information (Dowd et al., 2014), and being inclusive with rural and urban communities, and the social, political, and cultural environment (Rickards and Howden, 2012). Transformational adaptation in agriculture systems could have significant economic and institutional costs (Mushtaq, 2016), along with potential unintended negative consequences (Davidson, 2016; Rippke et al., 2016; Gajjar et al., 2018; Mushtaq, 2018), and a need to focus on the transitional space between incremental and transformational adaptation (Hadarits et al., 2017), as well as the timing of the shift from one to the other (Läderach et al., 2017).

Within urban and infrastructure transitions, green infrastructure and sustainable water management are assessed as the most feasible options, followed by sustainable land-use and urban planning. The need for transformational adaptation in urban settings arises from the root causes of poverty, failures in sustainable development, and a lack of focus on social justice (Revi et al., 2014a; Parnell, 2015; Simon and Leck, 2015; Shi et al., 2016; Ziervogel et al., 2016a; Burch et al., 2017), with the focus on governance structures and the inclusion of equity and justice (Bos et al., 2015; Shi et al., 2016; Hölscher et al., 2018).

Current implementation of Urban Ecosystems-based Adaptation (EbA) lacks a systems perspective of transformations and consideration of the normative and ethical aspects of EbA (Brink et al., 2016). Flexibility within urban planning could help deal with the multiple uncertainties of implementing adaptation (Radhakrishnan et al., 2018) (Rosenzweig and Solecki, 2014), for example, urban adaptation pathways were implemented in the aftermath of Hurricane Sandy in New York, which is considered as tipping point that led to the implementation of transformational adaptation practices.

Adaptation options for industry focus on infrastructure resilience and water management. Like with energy system transitions, technological innovation would be required, but also the enhancement of institutional capacities. Recent research illustrates transformational adaptation within industrial transitions focusing on the role of different actors and tools driving innovation, and points to the role of Nationally Appropriate Mitigation Actions in avoiding lock-ins and promoting system innovation (Boodoo and Olsen, 2017), the role of private sector in sustainability governance in the socio-political context (Burch et al., 2016), and of green entrepreneurs driving transformative change in the green economy (Gibbs and O'Neill, 2014). (Lim-Camacho et al., 2015) suggest an analysis of the complete lifecycle of supply chains as a means of identifying additional adaptation strategies, as opposed to the current focus on a part of the supply chain. Chain-wide strategies can modify the rest of the chain and present a win-win with commercial objectives.

The assessed adaptation options also have mitigation synergies and tradeoffs (assessed in Section 4.5.4) that need to be carefully considered, while planning climate action.

4.5.3.2 Monitoring and Evaluation

Monitoring and Evaluation (M&E) in adaptation implementation can promote accountability and transparency of adaptation financing, facilitate policy learning and the share good practices, pressure laggards, and guide adaptation planning. The majority of research on M&E focuses on specific policies or programmes, and has typically been driven by the needs of development organisations, donors, and governments to measure the impact and attribution of adaptation initiatives (Ford and Berrang-Ford, 2016). There is growing research examining adaptation progress across nations, sectors, and scales (Austin et al. 2016; Heidrich et al. 2016; Lesnikowski et al. 2016; Reckien et al. 2014; Robinson 2017; Araos et al. 2016a,b). Responding to need for global, regional and local adaptation, developing indicators and standardised approaches to evaluate and compare adaptation over time and across regions, countries, and sectors would enhance comparability and learning. A number of constrains continue to hamper progress on adaptation M&E, including a debate on what actually constitutes adaptation for purposes of assessing progress (Dupuis and Biesbroek 2013; Biesbroek et al. 2015), absence of comprehensive and systematically collected data on adaptation to support longitudinal assessment and comparison (Lesnikowski et al. 2016; Ford et al. 2015), lack of agreement on indicators to measure (Lesnikowski et al. 2015; Bours et al. 2015; Brooks et al. 2013), and challenges of attributing altered vulnerability to adaptation actions (UNEP 2017; Bours et al. 2015; Ford et al. 2013).

4.5.4 Synergies and Trade-Offs Between Adaptation and Mitigation

Implementing a particular mitigation or adaptation option may affect the feasibility and effectiveness of other mitigation and adaptation options. Supplementary Material E.1 provides examples of possible positive impacts (synergies) and negative impacts (trade-offs) of mitigation options for adaptation. For example, renewable energy sources such as wind energy and solar PV combined with electricity storage can increase resilience due to distributed grids, thereby enhancing both mitigation and adaptation. Yet, as another example, urban densification may reduce Greenhouse Gas (GHG) emissions, enhancing mitigation, but can also intensify heat island effects and inhibit restoration of local ecosystems if not accounted for, thereby increasing adaptation challenges.

The table in Supplementary Material E.2 provides examples of synergies and trade-offs of adaptation options for mitigation. It shows, for example, that conservation agriculture can reduce some GHG emissions and thus enhance mitigation, but at the same time increase other GHG emissions thereby reducing mitigation potential. As another example, agroforestry can reduce GHG emissions through reduced deforestation and fossil fuel consumption, but has a lower carbon sequestration potential compared with natural and secondary forest.

Maladaptive actions could increase the risk of adverse climate-related outcomes, for example, biofuel targets could lead to indirect land use change and influence local food security, through a shift in land use abroad in response to increased domestic biofuel demand, increasing global GHG emissions, rather than decreasing it.

Various options enhance both climate change mitigation and adaptation, and would hence serve two 1.5°C-related goals: reducing emissions while adapting to the associated climate change. Examples of such options are reforestation, urban and spatial planning, and land and water management.

Synergies between mitigation and adaptation may be enhanced, and trade-offs reduced, by considering enabling conditions (Section 4.4), while trade-offs can be amplified when enabling conditions are not considered (C.A. Scott et al., 2015). For example, information that is tailored to the personal situation of individuals and communities, including climate services, that are credible and targeted at the point of decision making, can enable and promote both mitigation and adaptation actions (Section 4.4.3). Similarly, multi-level governance and community participation, respectively, can enable and promote both adaptation and mitigation actions (Section 4.4.1). Governance, policies and institutions can facilitate the implementation of the Water-Energy-Food (WEF) nexus (Rasul and Sharma, 2016). The WEF can enhance food, water and energy security, particularly in cities with agricultural production areas (Biggs et al., 2015), electricity generation with intensive water requirements (Conway et al 2015), and in agriculture (El Gafy et al., 2017) and livelihoods (Biggs et al., 2015). Such a nexus approach can reduce the transport energy that is embedded in food value chains (Villarroel Walker et al., 2014), providing diverse sources of food in the face of changing climates (Tacoli et al., 2013). Urban agriculture, where integrated, can mitigate climate change and support urban flood management (Angotti, 2015; Bell et al., 2015; Biggs et al., 2015; Gwedla and Shackleton, 2015; Lwasa et al., 2015; Y.C.E. Yang et al., 2016; Sanesi et al., 2017). In the case of electricity generation, enabling conditions through a combination of carefully selected policy instruments can maximize the synergic benefits between low GHG energy production and water for energy (Shang et al., 2018). Despite the multiple benefits of maximising synergies between mitigation and adaptations options through the WEF nexus approach (Chen and Chen, 2016), there are implementation challenges given institutional complexity, political economy, and interdependencies between actors (Leck et al., 2015).

[START BOX 4.10 HERE]

Box 4.10: Bhutan: Synergies and Trade-Offs in Economic Growth, Carbon Neutrality and Happiness

Bhutan has three national goals, improving: its Gross National Happiness Index (GNHI), economic growth (Gross Domestic Product, GDP) and carbon neutrality. These goals increasingly interact and raise questions about whether they can be sustainably maintained into the future. Interventions in this enabling environment are required to comply with all three goals.

Bhutan is well known for its GNHI, which is based on a variety of indicators covering psychological well-being, health, education, cultural and community vitality, living standards, ecological issues and good governance (RGoB, 2012; Schroeder and Schroeder, 2014; Ura, 2015). The GNHI is a precursor to the Sustainable Development Goals (SDGs) (Allison, 2012; Brooks, 2013) and reflects local enabling environments. The GNHI has been measured twice, in 2010 and 2015, and this showed an increase of 1.8% (CBS, 2016). Like most emerging countries, Bhutan wants to increase its wealth and become a middle-income country (RGoB, 2013, 2016), while it remains carbon-neutral, a goal which has been in place since 2011 at COP 19 and was reiterated in its Intended Nationally Determined Contribution (NEC, 2015). Bhutan achieves its current carbon-neutral status through hydropower and forest cover (Yangka and Diesendorf, 2016) which are part of their resilience and adaptation strategy.

Nevertheless, Bhutan faces rising Greenhouse Gas (GHG) emissions. Transport and industry are the largest growth areas (NEC, 2011). Bhutan’s carbon-neutral status would be threatened by 2037 by business-as-usual approaches to economic growth (Yangka and Newman, 2018). Increases in hydropower are being planned based on climate change scenarios that suggest sufficient water supply will be available (NEC, 2011). Forest cover is expected to remain sufficient to maintain co-benefits. The biggest challenge is to electrify both freight and passenger transport (ADB, 2013). Bhutan wants to be a model for achieving economic growth consistent with limiting climate change to 1.5°C and improving its Gross National Happiness (Michaelowa et al., 2018) through synthesizing all three goals and improving its adaptive capacity.

[END BOX 4.10 HERE]

4.6 Knowledge Gaps and Key Uncertainties

The global response to limiting warming to 1.5°C is a new knowledge area, that has emerged after the Paris Agreement. This sections presents a number of knowledge gaps that have emerged from the assessment of mitigation, adaptation and Carbon Dioxide Removal (CDR) options and Solar Radiation Modification (SRM) measures, enabling conditions, and synergies and tradeoffs. Illustrative questions that emerge synthesising the more comprehensive Table 4.14 below include: how much can be realistically expected from innovation, behaviour and systemic political and economic change in improving resilience, enhancing adaptation and reducing GHG emissions? How can rates of changes be accelerated and scaled up? What is the outcome of realistic assessments of mitigation and adaptation land transitions that are compliant with sustainable development, poverty eradication and addressing inequality? What are life-cycle emissions and prospects of early-stage CDR options? How can climate and sustainable development policies converge, and how can they be organised within a global governance framework and financial system, based on principles of justice and ethics (CBDR-RC), reciprocity and partnership? To what extent limit warming to 1.5°C needs a harmonization of macro-financial and fiscal policies, that could include Central banks? How can different actors and processes in climate governance reinforce each other, and hedge against the fragmentation of initiatives?

These knowledge gaps are highlighted in Table 4.13 along with a cross-reference to the respective sections in the last column.

Table 4.13: Knowledge gaps and uncertainties

Knowledge area		***Mitigation***	***Adaptation***	***Reference***
1.5°C pathways and ensuing change		• Lack of literature specific to 1.5°C on investment costs with detailed breakdown by technology. • Lack of literature specific to 1.5°C on mitigation costs in terms of GDP and welfare. • Lack of literature on distributional implications of 1.5°C compared to 2°C or business-as-usual at sectoral and regional levels. • Limited 1.5°C-specific case studies for mitigation • Limited knowledge on the systemic and dynamic aspects of transitions to 1.5°C, including how vicious or virtuous circles might work, how self-reinforcing aspects can be actively introduced and managed.	• Lack of literature specific to 1.5°C on adaptation costs and need • Lack of literature on what overshoot means for adaptation • Lack of knowledge on avoided adaptation investments associated with limiting warming to 1.5°C, 2°C or business-as-usual • Limited 1.5°C-specific case studies for adaptation • Scant literature examining current or future adaptation options, or examining what different climate pathways mean for adaptation success • Need for transformational adaptation at 1.5°C and beyond remains largely unexplored	4.2
Options to achieve and	Energy	• The shift to variable renewables that many countries are implementing is just reaching a level where large-scale storage systems or other grid	• Relatively little literature on individual adaptation options since AR5	4.3.1

adapt to 1.5°C		flexibility options, e.g., demand response, are required to enable resilient grid systems, thus, new knowledge on the opportunities and issues associated with scaling up zero carbon grids would be needed including knowledge about how zero carbon electric grids can integrate with the full scale electrification of transport systems. • CCS suffers mostly from uncertainty about the feasibility of timely upscaling, both due to lack of regulatory capacity and concerns about storage safety and cost. • There is not much literature on the distributional implications of large-scale bioenergy deployment, the assessment of environmental feasibility is hampered by a diversity of contexts of individual studies (type of feedstock, technology, land availability), which could be improved through emerging meta-studies	• No evidence on socio-cultural acceptability of adaptation options • Lack of regional research on the implementation of adaptation options.	
	Land & ecosystems	• More knowledge would be needed on how land-based mitigation can be reconciled with land demands for adaptation and development. • While there is now more literature on the underlying mechanisms of land transitions, data is often insufficient to draw robust conclusions, and uncertainty about land availability • The lack of data counts on social and institutional information (largest knowledge gap indicated for ecosystems restoration in Table 4.11), which is therefore not widely integrated in land use modelling. • Examples of successful policy implementation and institutions related to land-based mitigation leading to co-benefits for adaptation and development are missing from the literature	• Regional information on some options does not exist, especially in the case of land use transitions. • Limited research examining socio-cultural perspectives and impacts of adaptation options, especially for efficient irrigation, coastal defense and hardening, agroforestry and biodiversity management • Lack of longitudinal, regional studies assessing the impacts of certain adaptation options such as conservation agriculture and shifting to efficient livestock systems. • More knowledge is needed on the cost-effectiveness and scalability of various adaptation options. For example, there is no evidence for the macro-economic viability of Community-based Adaptation (CbA) and biodiversity management, nor on employment and productivity enhancement	4.3.2

		• There is relatively little scientific literature on the effects of dietary shifts and reduction of food wastage on mitigation, especially regarding the institutional, technical and environmental concerns	potential for biodiversity management and coastal defense and hardening. • More knowledge is needed on risk mitigation and the potential of biodiversity management. • Lack of evidence of the political acceptability of efficient livestock • Limited evidence on legal and regulatory feasibility of conservation agriculture and no evidence on coastal defense and hardening • For transparency and accountability potential, there is limited evidence for conservation agriculture and no evidence for biodiversity management, coastal defense and hardening and sustainable aquaculture • No evidence on hazard risk reduction potential of conservation agriculture and biodiversity management.	
	Urban systems & infrastructure	• Limited evidence of effective land use planning in low income cities where tenure and land zoning is contested, and the risks of trying to implement land use planning under communal tenure. • Limited evidence on the governance of public transport from an accountability and transparency perspective • Limited evidence on relationship between toxic waste and public transport. • Limited evidence on the impacts of electric vehicles and non-motorised urban transport as most schemes are too new. • As changes in shipping and aviation have been limited to date, limited evidence of social impacts. • Knowledge about how to facilitate disruptive, demand-based innovations that may be transformative in urban systems, is needed.	• Regional and sectoral adaptation cost assessments are missing, particularly in the context of welfare losses of households, across time and space. • More knowledge is needed on the political economy of adaptation, particularly on how to impute different types of cost and benefit in a consistent manner, on adaptation performance indicators that could stimulate investment, and the impact of adaptation interventions on socio-economic, and other types, of inequality. • More evidence would be needed on hot-spots, for example the growth of peri-urban areas populated by large informal settlements. • Major uncertainties emanate from the lack of knowledge on the integration of climate adaptation and mitigation, disaster risk management, and urban poverty alleviation. • There is limited evidence on the institutional, technological and economic feasibility of green	4.3.3

		• The urban form implications of combined changes from electric, autonomous and shared/public mobility systems, is needed. • Considering distributional consequences of climate responses is an on-going need. • Knowledge gaps in the application and scale-up of combinations of new smart technologies, sustainable design, advanced construction techniques and new insulation materials, renewable energy and behaviour change in urban settlements. • The potential for leapfrog technologies to be applied to slums and new urban developments in developing countries is weak.	infrastructure and environmental services and for socio-cultural and environmental feasibility of codes and standards • In general, there is no evidence for the employment and productivity enhancement potential of most adaptation options. • There is limited evidence on the economic feasibility of sustainable water management.	
	Industry	• Lack of knowledge on potential for scaling up and global diffusion of zero- and low-emission technologies in industry • Questions remain on the socio-cultural feasibility of industry options, including human capacity and private sector acceptance of new, radically different technologies from current well-developed practices, as well as distributional effects of potential new business models • As the industrial transition unfolds, lack of knowledge on its dynamic interactions with other sectors, in particular with the power sector (and infrastructure) for electrification of industry, with food production and other users of biomass in case of bio-based industry developments, and with CDR technologies in the case of CC(U)S. • Life-cycle assessment-based comparative analysis of CCUS options are missing, as well as life-cycle information on electrification and hydrogen. • Impacts of industrial system transitions are not well understood, especially on employment, identity and well-being, in particular in the case of substitution	• Very limited evidence on how industry would adapt to the consequences of 1.5 or 2°C temperature increases, in particular large and immobile industrial clusters in low-lying areas and availability of transportation and (cooling) water resources and infrastructure. • There is limited evidence on the economic, institutional and socio-cultural feasibility of adaptation options available to industry.	4.3.4

		of conventional , high-carbon industrial products with lower-carbon alternatives, as well as electrification and use of hydrogen.		
	Short-lived climate forcers	• Limited evidence of co-benefits and trade-offs of SLCF reduction (e.g., better health outcomes, agricultural productivity improvements). • Integration of SLCFs into emissions accounting and international reporting mechanisms enabling a better understanding of the links between black carbon, air pollution, climate change and agricultural productivity.		4.3.6
	CDR	• A bottom-up analysis of CDR options, indicates that there are still key uncertainties around the individual technologies. This – includes Ocean-based options will be assessed in depth in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). Assessments of environmental aspects are missing, especially for ‘newer’ options like Enhanced Weathering or Direct Air Carbon Capture. • In order to obtain more information on realistically available and sustainable removal potentials, more bottom-up, regional studies, also taking into account also social issues, would be needed. These can better inform the modeling of 1.5°C pathways. • Knowledge gaps on issues of governance and public acceptance, the impacts of large-scale removals on the carbon cycle, the potential to accelerate deployment and upscaling, and means of incentivisation. • Knowledge gaps on integrated systems of renewable energy and CDR technologies such as enhanced weathering and DACCS		4.3.7

		• Knowledge gaps on the use of captured CO_2 is generating negative emissions and as mitigation option.		
	Overarching Adaptation Options	• There is no evidence on technical and institutional feasibility of educational options • There is limited evidence on employment and productivity enforcement potential of climate services • There is limited evidence on socio-cultural acceptability of social safety nets • There is a small but growing literature on human migration as an adaptation strategy. Scant literature on the cost effectiveness of migration.		4.3.5
Enabling conditions	Governance	• As technological changes have begun to accelerate, there is lack of knowledge on new mechanisms that can enable private enterprise to mainstream this activity and reasons for success and failure need to be researched. • Research is thin on effective multi-level governance in particular in developing countries, including participation by civil society, women and minoritiesGaps in knowledge remain pertaining to partnerships within local governance arrangements that may act as mediators and drivers for achieving global ambition and local action. • Methods for assessing contribution and aggregation of non-state actors in limiting warming to 1.5°C • Knowledge gap on an enhanced framework for assessment of the ambition of NDCs	• The ability to identify explanatory factors affecting the progress of climate policy is constrained by a lack of data on adaptation actions across nations, regions, and sectors, compounded by an absence of frameworks for assessing progress. Most hypotheses on what drives adaptation remain untested. • Limited empirical assessment of how governance affects adaptation across cases • Focus on ‘success’ stories and leading adaptors overlooks lessons from situations where no or unsuccessful adaptation is taking place	4.4.1
	Institutions	• Lack of 1.5°C-specific literature • Role of regulatory financial institutions and their capacity to guarantee financial stability of economies when investments potentially face risks both because of climate impacts and because of the systems transitions if lower temperature scenarios are pursued. • Knowledge gaps on how to build capabilities across all countries and regions globally to implement, maintain, manage, govern and further develop mitigation options for 1.5°C. • While importance of Indigenous and local knowledge is recognized, the ability to scale up beyond the local remains challenging and little examined • There is a lack of monitoring and evaluation (M&E) of adaptation measures, with most studies enumerating M&E challenges and emphasising the importance of context and social learning. Very few studies evaluate		4.4.2

		whether and why an adaptation initiative has been effective. One of the challenges of M&E for both mitigation and adaptation is a lack of high quality information for modellings. Adaptation M&E is additionally challenged by limited understanding on what indicators to measure and how to attribute altered vulnerability to adaptation actions.		
	Lifestyle and behavioural change	• Whereas mitigation pathways studies address (implicitly or explicitly) the reduction or elimination of market failures (e.g., external costs, information asymmetries) *via* climate or energy policies, no study addresses behavioural change strategies in the relationship with mitigation and adaptation actions in the 1.5°C context. • Limited knowledge on GHG emission reduction potential of diverse mitigation behaviour across the world. • Most studies on factors enabling lifestyle changes have been conducted in high income countries, more knowledge needed from low- and middle-income countries, and the focus in typically on enabling individual behavior change, far less on enabling change in organisations and political systems • Limited understanding and treatment of behavioural change and the potential effects of related policies in ambitious mitigation pathways, e.g., in Integrated Assessment Models.	• Knowledge gaps on factors enabling adaptation behaviour, except for behaviour in agriculture. • Little is known about cognitive and motivational factors promoting adaptive behavior. • Little is known about how potential adaptation actions might affect behavior to influence vulnerability outcomes	4.4.3
		Lack of insight on what can enable changes in adaptation and mitigation behaviour in organisations and political systems.		
	Technological innovation	• Quantitative estimates for mitigation and adaptation potentials at economy or sector scale as a result of the combination of general purpose technologies and mitigation technologies have been scarce, except for some evidence in the transport sector. • Evidence on the role of international organisations, including the UNFCCC, in building capabilities and enhancing technological innovation for 1.5°C, except for some parts of the transport sector. • Technology transfer trials to enable leapfrog applications in developing countries have limited evidence		4.4.4
	Policy	• More empirical research would be needed to derive robust conclusions on effectiveness of policies for	• Understanding of what polices work (and do not work) is limited for adaptation in general and for	4.4.5

		enabling transition to 1.5°C and on which factors aid decision-makers seeking to ratchet up their NDCs	1.5°C in particular, beyond specific case studies.	
	Finance	Knowledge gaps persist with respect to the instruments to match finance to its most effective use in mitigation and adaptation.		4.4.5
Synergies and tradeoffs between adaptation and mitigation		• Strong claims are made with respect to synergies and trade-offs, but there is little knowledge to underpin these, especially of co-benefits by region. • Water-energy conservation relationships of individual conservation measures in industries other than the water and energy sectors have not been investigated in detail. • There is no evidence on synergies with adaptation of CCS in the power sector and of enhanced weathering under carbon dioxide removal. • There is no evidence on trade-offs with adaptation of low and zero-energy buildings, and circularity and substitution and bio-based industrial system transitions. • There is no evidence of synergies or trade-offs with mitigation of CbA • There is no evidence of trade-offs with mitigation of the built environment, on adaptation options for industrial energy, and climate services		4.5.4
SRM		• In spite of increasing attention to the different SRM measures and their potential to keep global temperature below 1.5°C, knowledge gaps remain not only with respect to the physical understanding of SRM options, but also concerning ethical issues. • We do not know how to govern SRM in order to avoid unilateral action and how to prevent possible reductions in mitigation (‘moral hazard’).		4.3.8

Frequently Asked Questions

FAQ 4.1: What transitions could enable limiting global warming to 1.5°C?

Summary: *In order to limit warming to 1.5°C above preindustrial levels, the world would need to transform in a number of complex and connected ways. While transitions towards lower greenhouse gas emissions are underway in some cities, regions, countries, businesses and communities, there are few that are currently consistent with limiting warming to 1.5°C. Meeting this challenge would require a rapid escalation in the current scale and pace of change, particularly in the coming decades. There are many factors that affect the feasibility of different adaptation and mitigation options that could help limit warming to 1.5°C and adapting to the consequences.*

There are actions across all sectors can substantially reduce greenhouse gas emissions. This Special Report assesses energy, land and ecosystems, urban and infrastructure, and industry in developed and developing nations to see how they would need to be transformed to limit warming to 1.5°C. Examples of actions include shifting to low- or zero-emission power generation, such as renewables; changing food systems, such as diet changes away from land-intensive animal products; electrifying transport and developing 'green infrastructure', such as building green roofs, or improving energy efficiency by smart urban planning, which will change the layout of many cities.

Because these different actions are connected, a 'whole systems' approach would be needed for the type of transformations that could limit warming to 1.5°C. This means that all relevant companies, industries and stakeholders would need to be involved to increase the support and chance of successful implementation. As an illustration, the deployment of low-emission technology (e.g., renewable energy projects or a bio-based chemical plants) would depend upon economic conditions (e.g., employment generation or capacity to mobilise investment), but also on social/cultural conditions (e.g., awareness and acceptability) and institutional conditions (e.g., political support and understanding).

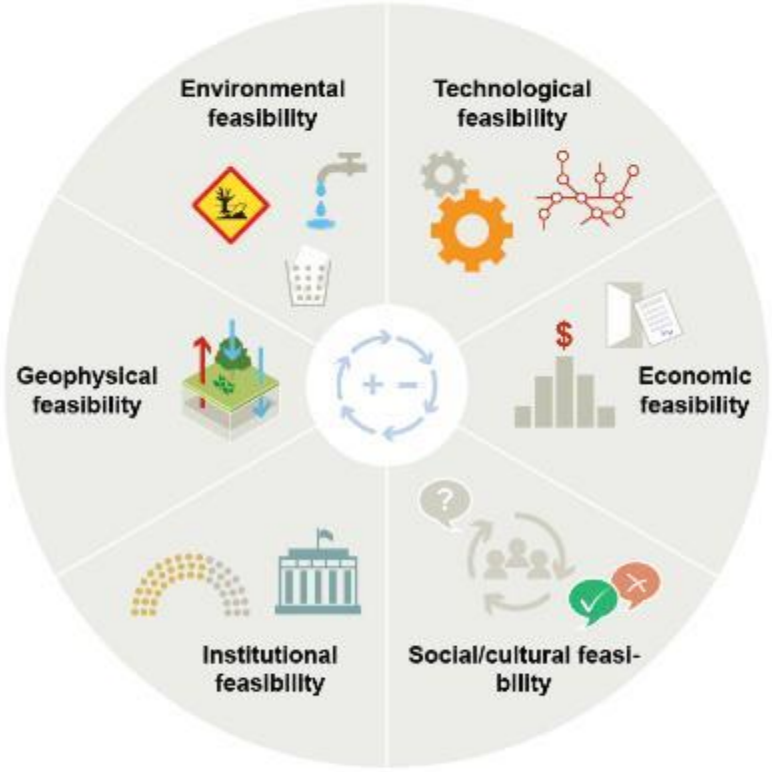
To limit warming to1.5°C, mitigation would have to be large-scale and rapid. Transitions can be transformative or incremental, and they often, but not always, go hand in hand. Transformative change can arise from growth in demand for a new product or market, such that it displaces an existing one. This is sometimes called 'disruptive innovation'. For example, high demand for LED lighting is now making more energy-intensive, incandescent lighting near-obsolete, with the support of policy action that spurred rapid industry innovation. Similarly, smart phones have become global in use within ten years. But electric cars, which were released around the same time, have not been adopted so quickly because the bigger, more connected transport and energy systems are harder to change. Renewable energy, especially solar and wind, is considered to be disruptive by some as it is rapidly being adopted and is transitioning faster than predicted. But its demand is not yet uniform. Urban systems that are moving towards transformation are coupling solar and wind with battery storage and electric vehicles in a more incremental transition, though this would still require changes in regulations, tax incentives, new standards, demonstration projects and education programmes to enable markets for this system to work.

Transitional changes are already underway in many systems but limiting warming to 1.5°C would require a rapid escalation in the scale and pace of transition, particularly in the next 10-20 years. While limiting warming to 1.5°C would involve many of the same types of transitions as limiting warming to 2°C, the pace of change would need to be much faster. While the *pace* of change that would be required to limit warming to 1.5°C can be found in the past, there is no historical precedent for the *scale* of the necessary transitions, in particular in a socially and economically sustainable way. Resolving such speed and scale issues would require people's support, public-sector interventions and private-sector cooperation.

Different types of transitions carry with them different associated costs and requirements for institutional or governmental support. Some are also easier to scale up than others, and some need more government support than others. Transitions between, and within, these systems are connected and none would be sufficient on its own to limit warming to 1.5°C.

The ‘feasibility’ of adaptation and mitigation options or actions within each system that together can limit warming to 1.5°C within the context of sustainable development and efforts to eradicate poverty requires careful consideration of multiple different factors. These factors include: (i) whether sufficient natural systems and resources are available to support the various options for transitioning (known as *environmental feasibility*); (ii) the degree to which the required technologies are developed and available (known as *technological feasibility*); (iii) the economic conditions and implications (known as *economic feasibility*); (iv) what are the implications for human behaviour and health (known as *social/cultural feasibility*); and (v) what type of institutional support would be needed, such as governance, institutional capacity and political support (known as *institutional feasibility*). An additional factor (vi - known as the *geophysical feasibility*) addresses the capacity of physical systems to carry the option, for example whether it is geophysically possible to implement large-scale afforestation consistent with 1.5°C.

Promoting enabling conditions, such as finance, innovation and behaviour change, would reduce barriers to the options, make the required speed and scale of the system transitions more likely, and therefore would increase the overall feasibility limiting warming to 1.5°C.



FAQ4.1: **The different feasibility dimensions towards limiting warming to 1.5°C**

Assessing the feasibility of different adaptation and mitigation options/actions requires consideration across six dimensions.

FAQ4.1, Figure 1: The different dimensions to consider when assessing the ‘feasibility’ of adaptation and mitigation options or actions within each system that can help to limit warming to 1.5°C. These are: (i) the environmental feasibility; (ii) the technological feasibility; (iii) the economic feasibility; (iv) the social/cultural feasibility; (v) the institutional feasibility; and (vi) the geophysical feasibility.

FAQ 4.2: What are Carbon Dioxide Removal and negative emissions?

Summary: *Carbon Dioxide Removal (CDR) refers to the process of removing CO_2 from the atmosphere. Since this is the opposite of emissions, practices or technologies that remove CO_2 are often described as achieving 'negative emissions'. The process is sometimes referred to more broadly as Greenhouse Gas Removal if it involves removing gases other than CO_2. There are two main types of CDR: either enhancing existing natural processes that remove carbon from the atmosphere (e.g., by increasing its uptake by trees, soil, or other 'carbon sinks') or using chemical processes to, for example, capture CO_2 directly from the ambient air and storing it elsewhere (i.e., underground). All CDR methods are at different stages of development and some are more conceptual than others, as they have not been tested at scale.*

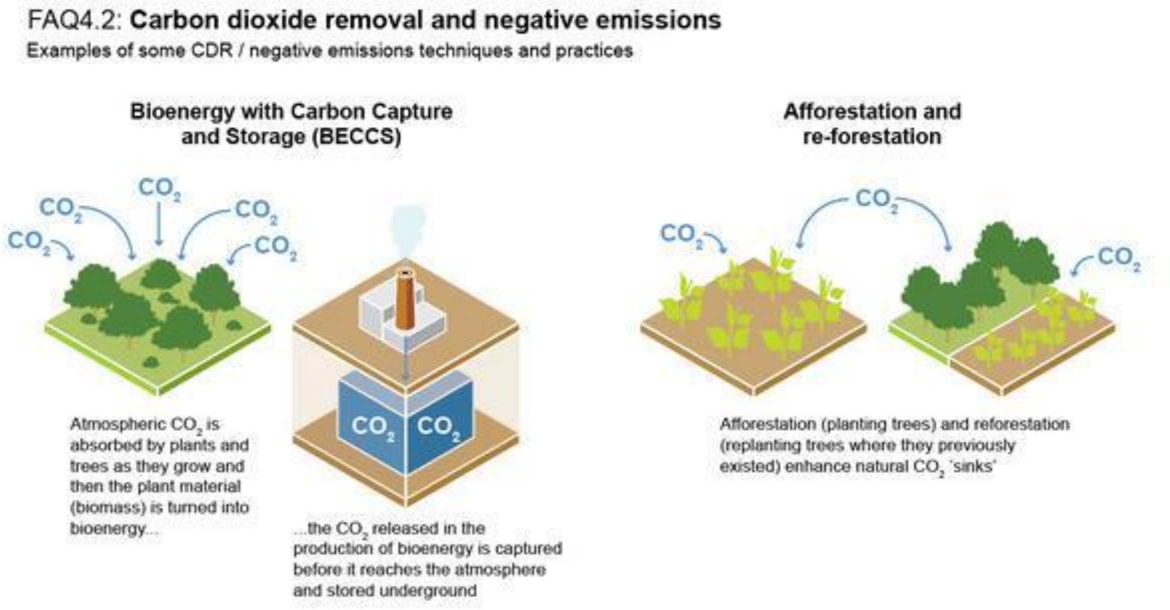
Limiting warming to 1.5°C above preindustrial levels would require unprecedented rates of transformation in many areas, including in the energy and industrial sectors, for example. Conceptually, it is possible that techniques to draw CO_2 out of the atmosphere (known as Carbon Dioxide Removal, or CDR) could contribute to limiting warming to 1.5°C. One use of CDR could be to compensate for greenhouse gas emissions from sectors that cannot completely decarbonise, or which may take a long time to do so.

If global temperature temporarily overshoots 1.5°C, CDR would be required to reduce the atmospheric concentration of CO_2 to bring global temperature back down. To achieve this temperature reduction, the amount of CO_2 drawn out of the atmosphere would need to be greater than the amount entering the atmosphere, resulting in 'net negative emissions'. This would involve a greater amount of CDR than stabilising atmospheric CO_2 concentration – and, therefore, global temperature – at a certain level. The larger and longer an overshoot, the greater the reliance on practices that remove CO_2 from the atmosphere.

There are a number of CDR methods, each with different potentials for achieving negative emissions, as well as different associated costs and side effects. They are also at differing levels of development, with some more conceptual than others. One example of a CDR method in the demonstration phase is a process known as Bioenergy with Carbon Capture and Storage (BECCS), in which atmospheric CO_2 is absorbed by plants and trees as they grow and then the plant material (biomass) is burned to produce bioenergy. The CO_2 released in the production of bioenergy is captured before it reaches the atmosphere and stored in geological formations deep underground on very long timescales. Since the plants absorb CO_2 as they grow and the process does not emit CO_2, the overall effect can be to reduce atmospheric CO_2.

Afforestation (planting new trees) and reforestation (replanting trees where they previously existed) are also considered forms of CDR because they enhance natural CO_2 'sinks'. Another category of CDR techniques uses chemical processes to capture CO_2 from the air and store it away on very long timescales. In a process known as Direct Air Carbon Capture and Storage (DACCS), CO_2 is extracted directly from the air and stored in geological formations deep underground. Converting waste plant material into a charcoal-like substance called biochar and burying it in soil can also be used to store carbon away from the atmosphere for decades to centuries.

There can be beneficial side effects of some types of CDR, other than removing CO_2 from the atmosphere. For example, restoring forests or mangroves can enhance biodiversity and protect against flooding and storms. But there could also be risks involved with some CDR methods. For example, deploying BECCS at large scale would require a large amount of land to cultivate the biomass required for bioenergy. This could have consequences for sustainable development if the use of land competes with producing food to support a growing population, biodiversity conservation, or land rights. There are also other considerations. For example, there are uncertainties about how much it would cost to deploy DACCS as a CDR technique, given that removing CO_2 from the air requires considerable energy.



FAQ4.2, Figure 1: Carbon Dioxide Removal (CDR) refers to the process of removing CO_2 from the atmosphere. Thereare a number of CDR techniques, each with different potential for achieving ‘negative emissions’, as well as different associated costs and side effects.

FAQ 4.3: Why is adaptation important in a 1.5°C warmer world?

***Summary**: Adaptation is the adjustment process to current or expected changes in climate and its effects. Even though climate change is a global problem, its impacts are experienced differently across the world. This means that responses are often specific to the local context, and so people in different regions are adapting in different ways. A rise in global temperature from 1°C to 1.5°C, and beyond, increases the need for adaptation. Therefore, stabilising global temperatures at 1.5°C above pre-industrial levels would require a smaller adaptation effort than for 2°C. Despite many successful examples around the world, progress in adaptation is, in many regions, in its infancy and unevenly distributed globally.*

Adaptation refers to the process of adjustment to actual or expected changes in climate and its effects. Since different parts of the world are experiencing the impacts of climate change differently, there is similar diversity in how people in a given region are adapting to those impacts.

The world is already experiencing the impacts from 1°C of global warming above preindustrial levels and there are many examples of adaptation to impacts associated with this warming. Examples of adaptation efforts taking place around the world include investing in flood defences such as building sea walls or restoring mangroves, efforts to guide development away from high risk areas, modifying crops to avoid yield reductions, and using social learning (social interactions that changes understanding on the community level) to modify agricultural practices, amongst many others. Adaptation also involves building capacity to respond better to climate change impacts, including making governance more flexible and strengthening financing mechanisms such as providing different types of insurance.

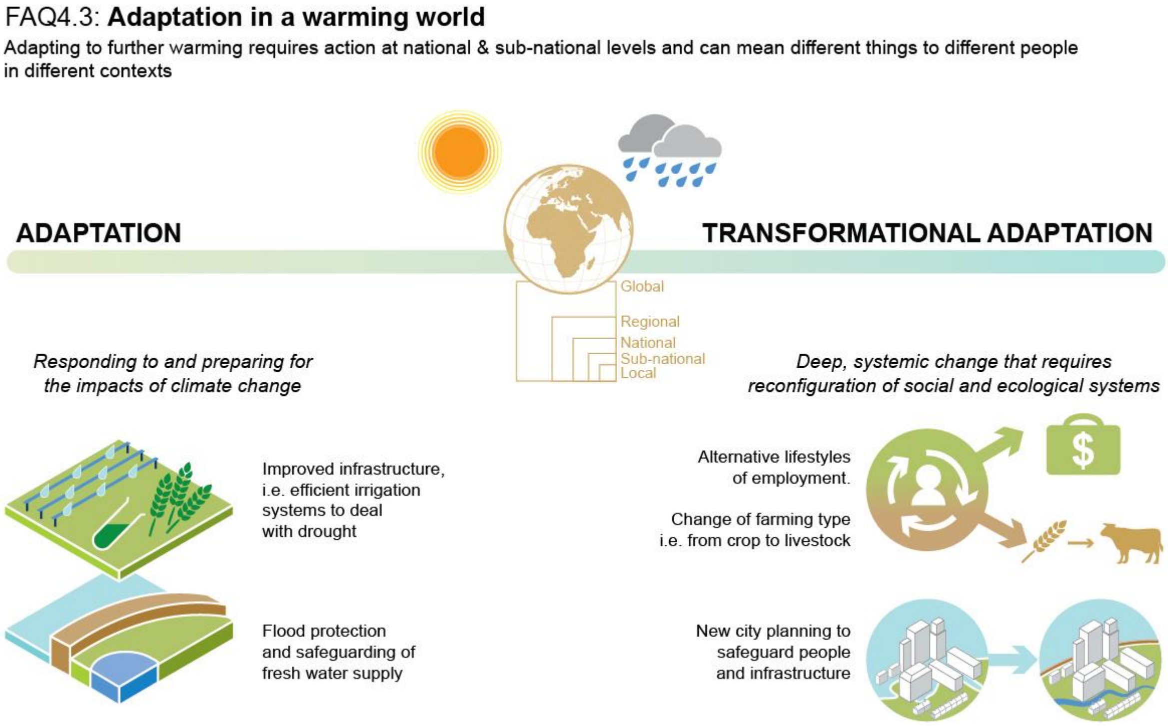
In general, an increase in global temperature from present day to 1.5°C or 2°C (or higher) above preindustrial temperatures would increase the need for adaptation. Therefore, stabilising global temperature increase at 1.5°C would require a smaller adaptation effort than for 2°C.

Since adaptation is still in early stages in many regions, this raises questions about the capacity of vulnerable communities to cope with any amount of further warming. Successful adaptation can be supported at the national and sub-national levels, with national governments playing an important role in coordination, planning, determining policy priorities, and distributing resources and support. Given that the need for adaptation can be very different from one community to the next, the kinds of measures that can successfully reduce climate risks will also depend heavily on the local context.

When done successfully, adaptation can allow individuals to adjust to the impacts of climate change in ways that minimise negative consequences and maintain their livelihoods. This could involve, for example, a farmer switching drought-tolerant crops to deal with increasing occurrences of heat waves. In some cases, however, the impacts of climate change could result in entire systems changing significantly, such as moving to an entirely new agricultural system in areas where the climate is no longer suitable for current practices. Constructing sea walls to stop flooding due to sea level rising from climate change is another example of adaptation, but developing city planning to change how flood water is managed throughout the city would be an example of transformational adaptation. These actions require significantly more institutional, structural, and financial support. While this kind of transformational adaptation wouldn’t be needed everywhere in a 1.5°C world, the scale of change needed would be challenging to implement, as it requires additional support such as through financial assistance and behavioural change. Few empirical examples exist to date.

Examples from around the world show that adaptation is an iterative process. Adaptation pathways describe how communities can make decisions about adaptation in an ongoing and flexible way. Such pathways allow for pausing, evaluating the outcomes of specific adaptation actions, and modifying the strategy as appropriate. Due to their flexible nature, adaptation pathways can help to identify the most effective ways to minimise the impacts of present and future climate change for a given local context. This is important since adaptation can sometimes exacerbate vulnerabilities and existing inequalities if poorly designed. The unintended negative consequences of adaptation that can sometimes occur is known as ‘maladaptation’. Maladaptation can be seen if a particular adaptation option has negative consequences for some (e.g., rainwater harvesting upstream might reduce water availability downstream) or if an adaptation intervention in the present has trade-offs in the future (e.g., desalination plants may improve water availability in the present but have large energy demands over time).

While adaptation is important to reduce the negative impacts from climate change, adaptation measures on their own are not enough to prevent climate change impacts entirely. The more global temperature rises, the more frequent, severe, and erratic the impacts will be, and adaptation may not protect against all risks. Examples of where limits may be reached include substantial loss of coral reefs, massive range losses for terrestrial species, more human deaths from extreme heat, and losses of coastal-dependent livelihoods in low lying islands and coasts.



FAQ4.3, Figure 1: Examples of adaptation and transformational adaptation. Adapting to further warming requires action at national & sub-national levels and can mean different things to different people in different contexts. While transformational adaptation wouldn't be needed everywhere in a world limited to 1.5°C warming, the scale of change needed would be challenging to implement.

References

Aakre, S., S. Kallbekken, R. Van Dingenen, and D.G. Victor, 2018: Incentives for small clubs of Arctic countries to limit black carbon and methane emissions. *Nature Climate Change*, **8(1)**, 85-90, doi:10.1038/s41558-017-0030-8.

Aall, C., K. Groven, and G. Lindseth, 2007: The Scope of Action for Local Climate Policy: The Case of Norway. *Global Environmental Politics*, **7(2)**, 83-101, doi:10.1162/glep.2007.7.2.83.

Aarts, H. and A.P. Dijksterhuis, 2000: The Automatic Activation of Goal-directed Behaviour: The case of travel habit. *Journal of Environmental Psychology*, **20(1)**, 75-82, doi:10.1006/jevp.1999.0156.

Aarts, H., B. Verplanken, and A. Knippenberg, 1998: Predicting Behavior From Actions in the Past: Repeated Decision Making or a Matter of Habit? *Journal of Applied Social Psychology*, **28(15)**, 1355-1374, doi:10.1111/j.1559-1816.1998.tb01681.x.

Abanades, J.C., E.S. Rubin, M. Mazzotti, and H.J. Herzog, 2017: On the climate change mitigation potential of CO2 conversion to fuels. *Energy Environ. Sci.*, **10(12)**, 2491-2499, doi:10.1039/C7EE02819A.

Abanades, J.C. et al., 2015: Emerging CO2 capture systems. *International Journal of Greenhouse Gas Control*, **40**, 126-166, doi:10.1016/j.ijggc.2015.04.018.

Abbott, K.W., 2012: The transnational regime complex for climate change. *Environment and Planning C: Government and Policy*, **30(4)**, 571-590, doi:10.1068/c11127.

Abbott, K.W. and D. Snidal, 2009: Strengthening International Regulation Through Transnational New Governance: Overcoming the Orchestration Deficit.. *Vanderbilt Journal of Transnational Law*, **42**, 501-578.

Abbott, K.W., S. Day, O.C. College, and S.M. Ave, 2012: The transnational regime complex for climate change. **,** **30(1)**, 571-590, doi:10.1068/c11127.

Abdulai, I. et al., 2018: Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. *Global Change Biology*, **24(1)**, 273-286, doi:10.1111/gcb.13885.

Abrahamse, W. and L. Steg, 2013: Social influence approaches to encourage resource conservation: A meta-analysis. *Global Environmental Change*, **23**, 1773-1785, doi:10.1016/j.gloenvcha.2013.07.029.

Abrahamse, W., L. Steg, C. Vlek, and T. Rothengatter, 2005: A review of intervention studies aimed at household energy conservation. *Journal of Environmental Psychology*, **25(3)**, 273-291, doi:10.1016/j.jenvp.2005.08.002.

Abrahamse, W., L. Steg, C. Vlek, and T. Rothengatter, 2007: The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioral antecedents. *Journal of Environmental Psychology*, **27**, 265-276, doi:10.1016/j.jenvp.2007.08.002.

ACOLA, 2017: *The Role of Energy Storage in Australia's Future Energy Supply Mix*. Australian Council of Learned Academics, Melbourne, VIC, 158 pp.

AdaptationWatch, 2015: *Toward Mutual Accountability: The 2015 Adaptation Finance Transparency Gap Report*. AdaptationWatch.

ADB, 2013: *Bhutan transport 2040: integrated strategic vision*. Asian Development Bank (ADB), Mandaluyong City, Philippines, 24 pp.

Aden, N., 2017: Necessary but not sufficient: the role of energy efficiency in industrial sector low-carbon transformation. *Energy Efficiency*, doi:https://doi.org/10.1007/s12053-017-9570-z.

Adenle, A.A. et al., 2017: Managing Climate Change Risks in Africa - A Global Perspective. *Ecological Economics*, **141**, 190-201, doi:10.1016/j.ecolecon.2017.06.004.

Adger et al., 2003: Adaptation to climate change in the developing world. *Progress in Development Studies*, **3**, 179-195.

Adger, W.N., N.W. Arnell, and E.L. Tompkins, 2005: Successful adaptation to climate change across scales. *Global environmental change*, **15(2)**, 77-86.

Adger, W.N. et al., 2003: Adaptation to climate change in the developing world. *Progress in Development Studies*, **3**, 179-195.

Adger, W.N. et al., 2015: Focus on environmental risks and migration: causes and consequences. *Environmental Research Letters*, **10(6)**, 60201, doi:10.1088/1748-9326/10/6/060201.

Aebischer, B. and L.M. Hilty, 2015: The Energy Demand of ICT: A Historical Perspective and Current Methodological Challenges. *ICT Innovations for Sustainability*, 71-103.

Afionis, S., L.C. Stringer, N. Favretto, J. Tomei, and M.S. Buckeridge, 2014: Unpacking Brazil's Leadership in the Global Biofuels Arena: Brazilian Ethanol Diplomacy in Africa. *Global Environmental Politics*, **14(2)**, 82-101, doi:10.1162/GLEP.

Agee, E.M., A. Orton, E.M. Agee, and A. Orton, 2016: An Initial Laboratory Prototype Experiment for Sequestration of Atmospheric CO 2. *Journal of Applied Meteorology and Climatology*, **55(8)**, 1763-1770, doi:10.1175/JAMC-D-16-0135.1.

Aglietta, M., E. Espagne, and B. Perrissin Fabert, 2015a: *A proposal to finance low carbon investment in Europe*. France Stratégie, Paris, France, 1-12 pp.

Aglietta, M., J.–C. Hourcade, C. Jaeger, and B.P. Fabert, 2015b: Financing transition in an adverse context: climate finance beyond carbon finance. *International Environmental Agreements: Politics, Law and Economics*, **15(4)**, 403-420, doi:10.1007/s10784-015-9298-1.

Agrawal, A., C. E.R., and E.R. Gerber, 2015: Motivational Crowding in Sustainable Development Interventions. *American Political Science Review*, **109(3)**, 470-487.

Agrawala, S., M. Carraro, N. Kingsmill, E. Lanzi, and G. Prudent-richard, 2011: Private Sector Engagement in Adaptation to Climate Change: Approaches to Managing Climate Risks. OECD Environment Working Paper No 39, 56 pp.

Aguilera, E., L. Lassaletta, A. Gattinger, and B.S. Gimeno, 2013: Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, Ecosystems & Environment*, **168**, 25-36, doi:10.1016/j.agee.2013.02.003.

Ahern, J., S. Cilliers, and J. Niemelä, 2014: The concept of ecosystem services in adaptive urban planning and design: A framework for supporting innovation. *Landscape and Urban Planning*, **125(Supplement C)**, 254-259, doi:https://doi.org/10.1016/j.landurbplan.2014.01.020.

Ahlfeldt, G. and E. Pietrostefani, 2017: *Demystifying Compact Urban Growth: Evidence From 300 Studies From Across the World*. Coalition for Urban Transitions, OECD, 1-84 pp.

Ahlm, L. et al., 2017: Marine cloud brightening &amp;ndash; as effective without clouds. *Atmospheric Chemistry and Physics Discussions*, **17**, 13071-13087, doi:10.5194/acp-2017-484.

Åhman, M., L.J. Nilsson, and B. Johansson, 2016: Global climate policy and deep decarbonization of energy-intensive industries. *Climate Policy*, **17(5)**, 634-649, doi:10.1080/14693062.2016.1167009.

Aitken, M., 2010: Wind power and community benefits: Challenges and opportunities. *Energy Policy*, **38(10)**, 6066-6075, doi:10.1016/j.enpol.2010.05.062.

Ajanovic, A. and R. Haas, 2017: The impact of energy policies in scenarios on GHG emission reduction in passenger car mobility in the EU-15. *Renewable and Sustainable Energy Reviews*, **68**, 1088-1096, doi:10.1016/j.rser.2016.02.013.

Akbari, H., H.D. Matthews, and D. Seto, 2012: The long-term effect of increasing the albedo of urban areas. *Environmental Research Letters*, **7(2)**, 024004, doi:10.1088/1748-9326/7/2/024004.

Åkerman, J., 2011: The role of high-speed rail in mitigating climate change - The Swedish case Europabanan from a life cycle perspective. *Transportation Research Part D: Transport and Environment*, **16(3)**, 208-217, doi:https://doi.org/10.1016/j.trd.2010.12.004.

Akter, S., T.J. Krupnik, and F. Khanam, 2017: Climate change skepticism and index versus standard crop insurance demand in coastal Bangladesh. *Regional Environmental Change*, **17(8)**, 2455-2466, doi:10.1007/s10113-017-1174-9.

Akter, S., T.J. Krupnik, F. Rossi, and F. Khanam, 2016: The influence of gender and product design on farmers' preferences for weather-indexed crop insurance. *Global Environmental Change*, **38**, 217-229, doi:10.1016/j.gloenvcha.2016.03.010.

Albers, R.A.W. et al., 2015: Overview of challenges and achievements in the climate adaptation of cities and in the Climate Proof Cities program. *Building and Environment*, **83**, 1-10, doi:10.1016/j.buildenv.2014.09.006.

Albright, R. et al., 2016: Reversal of ocean acidification enhances net coral reef calcification. *Nature*, **531(7594)**, 362-365, doi:10.1038/nature17155.

Aldrich, D.P., C. Page, and C.J. Paul, 2016: Social Capital and Climate Change Adaptation. *Oxford Research Encyclopedia of Climate Science*, **1**, doi:10.1093/acrefore/9780190228620.013.342.

Aldy, J. et al., 2016: Economic tools to promote transparency and comparability in the Paris Agreement. *Nature Climate Change*, **6**, 1000, doi:10.1038/nclimate3106.

Alexander, C. et al., 2011: Linking indigenous and scientific knowledge of climate change. *BioScience*, **61(6)**, 477-484, doi:10.1525/bio.2011.61.6.10.

Alexander, P. et al., 2017: Losses, inefficiencies and waste in the global food system. *Agricultural Systems*, **153**, 190-200, doi:10.1016/j.agsy.2017.01.014.

Alexandratos, N. and J. Bruinsma, 2012: World Agriculture Towards 2030/2050. The 2012 Revision. .

Alfieri, L. et al., 2017: Global projections of river flood risk in a warmer world. *Earth's Future*, **5(2)**, 171-182, doi:10.1002/2016EF000485.

Ali, S.H. et al., 2017: Mineral supply for sustainable development requires resource governance. *Nature*, **543**, 367, doi:10.1038/nature21359.

Alkama, R. and A. Cescatti, 2016: Biophysical climate impacts of recent changes in global forest cover. *Science*, **351(6273)**, 600-604, doi:10.1126/science.aac8083.

Allan, J.I. and J. Hadden, 2017: Exploring the framing power of NGOs in global climate politics. *Environmental Politics*, **26(4)**, 600-620, doi:10.1080/09644016.2017.1319017.

Allcott, H., 2011: Social norms and energy conservation. *Journal of Public Economics*, **95(9-10)**, 1082-1095, doi:10.1016/j.jpubeco.2011.03.003.

Allison, E., 2012: Gross National Happiness. In: *The Berkshire Encyclopedia of Sustainability: Measurements, Indicators, and Research Methods for Susrainability* [Spellerberg, I., D.S. Fogel, L.M. Butler Harrington, and

S.E. Fredericks (eds.)]. Berkshire Publishing Group, Great Barrington, MA, USA, pp. 180-184.

Alló, M. and M.L. Loureiro, 2014: The role of social norms on preferences towards climate change policies: A meta-analysis. *Energy Policy*, **73**, 563-574, doi:10.1016/j.enpol.2014.04.042.

Almeida Prado, F. et al., 2016: How much is enough? An integrated examination of energy security, economic growth and climate change related to hydropower expansion in Brazil. *Renewable and Sustainable Energy Reviews*, **53**, 1132-1136, doi:10.1016/j.rser.2015.09.050.

Alterskjær, K., J.E. Kristjánsson, and O. Seland, 2012: Sensitivity to deliberate sea salt seeding of marine clouds - Observations and model simulations. *Atmospheric Chemistry and Physics*, **12(5)**, 2795-2807, doi:10.5194/acp-12-2795-2012.

Altieri, K.E. et al., 2016: Achieving development and mitigation objectives through a decarbonization development pathway in South Africa. *Climate Policy*, **16(Sup 1)**, s78-s91, doi:10.1080/14693062.2016.1150250.

AMAP, 2017a: *Adaptation Actions for a Changing Arctic: Barents Area Overview Report*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 24 pp.

AMAP, 2017b: *Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xiv + 255 pp.

AMAP, 2018: *Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region*. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, xvi + 354 pp.

Amars, L., M. Fridahl, M. Hagemann, F. Röser, and B.–O. Linnér, 2017: The transformational potential of Nationally Appropriate Mitigation Actions in Tanzania: assessing the concept's cultural legitimacy among stakeholders in the solar energy sector. *Local Environment*, **22(1)**, 86-105, doi:10.1080/13549839.2016.1161607.

Amin, A. and L.R. Cirolia, 2018: Politics/matter: Governing Cape Town's informal settlements. *Urban Studies*, **55(2)**, 274-295, doi:10.1177/0042098017694133.

Amorim, H., M.L. Lopes, J.V. De Castro Oliveira, M.S. Buckeridge, and G.H. Goldman, 2011: Scientific challenges of bioethanol production in Brazil. *Applied Microbiology and Biotechnology*, **91(5)**, 1267-1275, doi:10.1007/s00253-011-3437-6.

Amundsen, H., G.K. Hovelsrud, C. Aall, M. Karlsson, and H. Westskog, 2018: Local governments as drivers for societal transformation: towards the 1.5 °C ambition. *Current Opinion in Environmental Sustainability*, **31**, 23-29, doi:10.1016/j.cosust.2017.12.004.

Anacona, P.I., A. Mackintosh, and K. Norton, 2015: Reconstruction of a glacial lake outburst flood (GLOF) in the Engaño Valley, Chilean Patagonia: Lessons for GLOF risk management. *Science of The Total Environment*, **527-528(Supplement C)**, 1-11, doi:https://doi.org/10.1016/j.scitotenv.2015.04.096.

Anderson, S.T. and R.G. Newell, 2004: Information programs for technology adoption: the case of energy-efficiency audits. *Resource and Energy Economics*, **26(1)**, 27-50.

Andersson, M., P. Bolton, and F. Samama, 2016: Hedging Climate Risk. *Financial Analysts Journal*, **72(3)**.

Andonova, L., T.N. Hale, and C. Roger, 2017: National Policies and Transnational Governance of Climate Change: Substitutes or Complements? *International Studies Quarterly*, 1-16, doi:10.1093/isq/sqx014.

Andow, D.A. and C. Zwahlen, 2006: Assessing environmental risks of transgenic plants. *Ecology Letters*, **9(2)**, 196-214, doi:10.1111/j.1461-0248.2005.00846.x.

André, C., D. Boulet, H. Rey-Valette, and B. Rulleau, 2016: Protection by hard defence structures or relocation of assets exposed to coastal risks: Contributions and drawbacks of cost-benefit analysis for long-term adaptation choices to climate change. *Ocean and Coastal Management*, **134**, 173-182, doi:10.1016/j.ocecoaman.2016.10.003.

Andrews-Speed, P. and G. Ma, 2016: Household Energy Saving in China: The Challenge of Changing Behaviour. In: *China's Energy Efficiency and Conservation: Household Behaviour, Leglisation, Regional Analysis and Impacts* [Su, B. and E. Thomson (eds.)]. SpringerBriefs in Environment, Security, Development and Peace, pp. 23-39.

Anenberg, S.C. et al., 2012: Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environmental Health Perspectives*, **120(6)**, 831-839, doi:10.1289/ehp.1104301.

Angotti, T., 2015: Urban agriculture: long-term strategy or impossible dream? *Public Health*, **129(4)**, 336-341, doi:10.1016/j.puhe.2014.12.008.

Anguelovski, I., E. Chu, and J.A. Carmin, 2014: Variations in approaches to urban climate adaptation: Experiences and experimentation from the global South. *Global Environmental Change*, **27(1)**, 156-167, doi:10.1016/j.gloenvcha.2014.05.010.

Annicchiarico, B. and F. Di Dio, 2015: Environmental policy and macroeconomic dynamics in a new Keynesian model. *Journal of Environmental Economics and Management*, **69(1)**, 1-21, doi:10.1016/j.jeem.2014.10.002.

Annicchiarico, B. and F. Di Dio, 2016: GHG Emissions Control and Monetary Policy. *Environmental and Resource Economics*, 1-29, doi:10.1007/s10640-016-0007-5.

Anshelm, J. and A. Hansson, 2014: Battling Promethean dreams and Trojan horses: Revealing the critical discourses of geoengineering. *Energy Research and Social Science*, **2**, 135-144, doi:10.1016/j.erss.2014.04.001.

Arab, A., A. Khodaei, Z. Han, and S.K. Khator, 2015: Proactive Recovery of Electric Power Assets for Resiliency Enhancement. *IEEE Access***, 3**, 99-109, doi:10.1109/ACCESS.2015.2404215.

Araos, M., J. Ford, L. Berrang-Ford, R. Biesbroek, and S. Moser, 2016a: Climate change adaptation planning for Global South megacities: the case of Dhaka. *Journal of Environmental Policy and Planning***, 19(6)**, 682-696, doi:10.1080/1523908X.2016.1264873.

Araos, M. et al., 2016b: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science and Policy***, 66**, 375-382, doi:10.1016/j.envsci.2016.06.009.

Archer, D., 2016: Building urban climate resilience through community-driven approaches to development. *International Journal of Climate Change Strategies and Management***, 8(5)**, 654-669, doi:10.1108/IJCCSM-03-2014-0035.

Archer, D. et al., 2014: Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale. *Climate and Development***, 6(4)**, 345-356, doi:10.1080/17565529.2014.918868.

Arezki, R., P. Bolton, S. Peters, F. Samama, and J. Stiglitz, 2016: From Global Savings Glut to Financing Infrastructure: The Advent of Investment Platforms. WP/16/18.

Arino, Y. et al., 2016: Estimating option values of solar radiation management assuming that climate sensitivity is uncertain. *Proceedings of the National Academy of Sciences of the United States of America***, 113(21)**, 5886-91, doi:10.1073/pnas.1520795113.

Armah, F.A., I. Luginaah, H. Hambati, R. Chuenpagdee, and G. Campbell, 2015: Assessing barriers to adaptation to climate change in coastal Tanzania: Does where you live matter? *Population and Environment***, 37(2)**, 231-263, doi:10.1007/s11111-015-0232-9.

Arnold, U., A. De Palmenaer, T.B. Brück, and K. Kuse, 2018: Energy Efficient Carbon Fiber Production with Concentrated Solar Power: Process-Design and Techno-Economic Analysis. *Industrial & Engineering Chemistry Research* (in press), doi:10.1021/acs.iecr.7b04841.

Arthur, W.B., 2009: The nature of technology: What it is and how it evolves. .

Arunrat, N., C. Wang, N. Pumijumnong, S. Sereenonchai, and W. Cai, 2017: Farmers' intention and decision to adapt to climate change: A case study in the Yom and Nan basins, Phichit province of Thailand. *Journal of Cleaner Production***, 143**, 672-685, doi:10.1016/j.jclepro.2016.12.058.

Arze del Granado, F.J., D. Coady, and R. Gillingham, 2012: The Unequal Benefits of Fuel Subsidies: A Review of Evidence for Developing Countries. *World Development***, 40(11)**, 2234-2248, doi:10.1016/j.worlddev.2012.05.005.

Asayama, S., M. Sugiyama, and A. Ishii, 2017: Ambivalent climate of opinions: Tensions and dilemmas in understanding geoengineering experimentation. *Geoforum***, 80**, 82-92, doi:10.1016/j.geoforum.2017.01.012.

Asensio, O.I. and M.A. Delmas, 2015: Nonprice incentives and energy conservation. *Proceedings of the National Academy of Sciences***, 112(6)**, 1-6, doi:10.1073/pnas.1401880112.

Asfaw, S. and B. Davis, 2018: Can Cash Transfer Programmes Promote Household Resilience? Cross-Country Evidence from Sub-Saharan Africa. *Climate Smart Agriculture : Building Resilience to Climate Change*, 227-250, doi:10.1007/978-3-319-61194-5_11.

Asfaw, S., A. Carraro, B. Davis, S. Handa, and D. Seidenfeld, 2017: Cash transfer programmes, weather shocks and household welfare: evidence from a randomised experiment in Zambia. *Journal of Development Effectiveness***, 9(4)**, 419-442, doi:10.1080/19439342.2017.1377751.

Ashworth, P., S. Wade, D. Reiner, and X. Liang, 2015: Developments in public communications on CCS. *International Journal of Greenhouse Gas Control***, 40**, 449-458, doi:10.1016/j.ijggc.2015.06.002.

Atela, J.O., C.H. Quinn, and P.A. Minang, 2014: Are REDD projects pro-poor in their spatial targeting? Evidence from Kenya. *Applied Geography***, 52**, 14-24, doi:10.1016/J.APGEOG.2014.04.009.

Aumont, O. and L. Bopp, 2006: Globalizing results from ocean in situ iron fertilization studies. *Global Biogeochemical Cycles***, 20(2)**, doi:10.1029/2005GB002591.

Austin, S.E. et al., 2015: Public health adaptation to climate change in canadian jurisdictions. *International Journal of Environmental Research and Public Health***, 12(1)**, doi:10.3390/ijerph120100623.

Averchenkova, A., F. Crick, A. Kocornik-Mina, H. Leck, and S. Surminski, 2016: Multinational and large national corporations and climate adaptation: are we asking the right questions? A review of current knowledge and a new research perspective. *Wiley Interdisciplinary Reviews: Climate Change***, 7(4)**, 517-536, doi:10.1002/wcc.402.

Axelrod, R. and W.D. Hamilton, 1981: The Evolution of Cooperation. *Science***, 211(4489)**, 1390-1396.

Aykut, S.C., 2016: Taking a wider view on climate governance: moving beyond the 'iceberg,' the 'elephant,' and the 'forest'. *Wiley Interdisciplinary Reviews: Climate Change***, 7(3)**, doi:10.1002/wcc.391.

Ayling, J. and N. Gunningham, 2017: Non-state governance and climate policy: the fossil fuel divestment movement. *Climate Policy***, 17(2)**, 131-149, doi:10.1080/14693062.2015.1094729.

Azeiteiro, U.M., W. Leal Filho, and L. Aires, 2017: Climate Literacy and Innovations in Climate Change Education. *International Journal of Global Warming***, 12(3)**.

Azevedo, I. and V.M.S. Leal, 2017: Methodologies for the evaluation of local climate change mitigation actions: A review. *Renewable and Sustainable Energy Reviews*, **79**, 681-690, doi:10.1016/j.rser.2017.05.100.

Bäckstrand, K. and J.W. Kuyper, 2017: The democratic legitimacy of orchestration: the UNFCCC, non-state actors, and transnational climate governance. *Environmental Politics*, **26(4)**, 764-788, doi:10.1080/09644016.2017.1323579.

Badré, B., 2018: *Can Finance Save the World?: Regaining Power over Money to Serve the Common Good*. 288 pp.

Bager, S. and L. Mundaca, 2017: Energy Research & Social Science Making 'Smart Meters' smarter ? Insights from a behavioural economics pilot fi eld experiment in Copenhagen , Denmark. *Energy Research & Social Science*, **28(April)**, 68-76, doi:10.1016/j.erss.2017.04.008.

Bahadur, A. and T. Tanner, 2014: Transformational resilience thinking: putting people, power and politics at the heart of urban climate resilience. *Environment and Urbanization*, **26(1)**, 200-214, doi:10.1177/0956247814522154.

Bahn, O., M. Chesney, J. Gheyssens, R. Knutti, and A.C. Pana, 2015: Is there room for geoengineering in the optimal climate policy mix? *Environmental Science and Policy*, **48(i)**, 67-76, doi:10.1016/j.envsci.2014.12.014.

Bai, X. et al., 2018: Six research priorities for cities and climate change. *Nature*, **555(7694)**, 23-25, doi:10.1038/d41586-018-02409-z.

Baik, E. et al., 2018: Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States. *Proceedings of the National Academy of Sciences of the United States of America*, **115(13)**, 3290-3295, doi:10.1073/pnas.1720338115.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924-929, doi:10.1038/nclimate2353.

Baker, L.H. et al., 2015: Climate responses to anthropogenic emissions of short-lived climate pollutants. *Atmospheric Chemistry and Physics*, **15(14)**, 8201-8216, doi:10.5194/acp-15-8201-2015.

Bakker, D.C.E., A.J. Watson, and C.S. Law, 2001: Southern Ocean iron enrichment promotes inorganic carbon drawdown. *Deep Sea Research Part II: Topical Studies in Oceanography*, **48(11)**, 2483-2507, doi:10.1016/S0967-0645(01)00005-4.

Bakker, S. et al., 2017: Low-Carbon Transport Policy in Four ASEAN Countries: Developments in Indonesia, the Philippines, Thailand and Vietnam. *Sustainability*, **9(7)**, 1217, doi:10.3390/su9071217.

Bala, G. et al., 2007: Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences*, **104(16)**, 6550-6555, doi:10.1073/pnas.0608998104.

Balcombe, P., D. Rigby, and A. Azapagic, 2013: Motivations and barriers associated with adopting microgeneration energy technologies in the UK. *Renewable and Sustainable Energy Reviews*, **22**, 655-666, doi:10.1016/j.rser.2013.02.012.

Baltz, E.A. et al., 2017: Achievement of Sustained Net Plasma Heating in a Fusion Experiment with the Optometrist Algorithm. *Scientific Reports*, **7(1)**, 6425, doi:10.1038/s41598-017-06645-7.

Bamberg, S., 2000: The Promotion of New Behavior by Forming an Implementation Intention: Results of a Field Experiment in the Domain of Travel Mode Choice. *Journal of Applied Social Psychology*, **30**, 1903-1922.

Bamberg, S., 2002: Implementation intention versus monetary incentive comparing the effects of interventions to promote the purchase of organically produced food. *Journal of Economic Psychology*, **23**, 573-587.

Banerjee, A. and B.D. Solomon, 2003: Eco-labeling for energy efficiency and sustainability: a meta-evaluation of US programs. *Energy Policy*, **31**, 109-123.

Barbarossa, C., P. De Pelsmacker, and I. Moons, 2017: Personal Values, Green Self-identity and Electric Car Adoption. *Ecological Economics*, **140**, 190-200, doi:10.1016/j.ecolecon.2017.05.015.

Barkakaty, B. et al., 2017: Emerging materials for lowering atmospheric carbon. *Environmental Technology & Innovation*, **7**, 30-43.

Barker, T. and J. Kohler, 1998: Equity and Ecotax Reform in the EU: Achieving a 10 per cent Reduction in CO2 Emissions Using Excise Duties. *Fiscal Studies*, **19(4)**, 375-402, doi:10.1111/j.1475-5890.1998.tb00292.x.

Barrett, S., 2015: Subnational Adaptation Finance Allocation: Comparing Decentralized and Devolved Political Institutions in Kenya. *Global Environmental Politics*, **15(3)**, 118-139, doi:10.1162/GLEP_a_00314.

Bartos, M.D. and M. Chester, 2015: Impacts of climate change on electric power supply in the Western United States. *Nature Climate Change*, **5(8)**, 748-752, doi:10.1038/nclimate2648.

Bataille, C., D. Sawyer, and N. Melton, 2015: *Pathways to deep decarbonization in Canada*. SDSN-IDDRI, 54 pp.

Bataille, C. et al., 2018: Technology and policy options for making heavy industry products consistent with 1.5-2°C compatible deep decarbonization pathways. *Journal of Cleaner Production*, **187**, 960-973.

Bates, B.R., B.L. Quick, and A.A. Kloss, 2009: Antecedents of intention to help mitigate wildfire: Implications for campaigns promoting wildfire mitigation to the general public in the wildland-urban interface. *Safety Science*, **47(3)**, 374-381, doi:10.1016/j.ssci.2008.06.002.

Bathiany, S., V. Dakos, M. Scheffer, and T.M. Lenton, 2018: Climate models predict increasing temperature variability in poor countries. *Science Advances*, **4(5)**, eaar5809, doi:10.1126/sciadv.aar5809.

Battiston, S. et al., 2017: A climate stress-test of the financial system. *Nature Climate Change*, **7(4)**, 283-288, doi:10.1038/nclimate3255.

Baudron, F., C. Thierfelder, I. Nyagumbo, and B. Gérard, 2015: Where to target conservation agriculture for African smallholders? How to overcome challenges associated with its implementation? Experience from Eastern and Southern Africa. *Environments*, **2(3)**, 338-357.

Bauer, N., S.K. Rose, S. Fujimori, D.P. Vuuren, and J. Weyant, 2018: Global energy sector emission reductions and bioenergy use : overview of the bioenergy demand phase of the EMF-33 model comparison. *Climate Change*.

Baul, T.K., A. Alam, H. Strandman, and A. Kilpelï¿½inen, 2017: Net climate impacts and economic profitability of forest biomass production and utilization in fossil fuel and fossil-based material substitution under alternative forest management. *Biomass and Bioenergy*, **98**, 291-305, doi:10.1016/j.biombioe.2017.02.007.

Baumgärtner, S., M.A. Drupp, J.N. Meya, J.M. Munz, and M.F. Quaas, 2017: Income inequality and willingness to pay for environmental public goods. *Journal of Environmental Economics and Management*, **85**, 35-61.

Bayraktarov, E. et al., 2016: The cost and feasibility of marine coastal restoration. *Ecological Applications*, **26(4)**, 1055-1074, doi:10.1890/15-1077.

Beatley, T., 2011: *Biophilic Cities: Integrating Nature into Urban Design and Planning*. Island Press, Washington DC, USA, 208 pp.

Beaudoin, M. and P. Gosselin, 2016: An effective public health program to reduce urban heat islands in Québec, Canada. *Revista Panamericana de Salud Publica*, **40(3)**, 160-166.

Beccali, M., M. Bonomolo, G. Ciulla, A. Galatioto, and V. Brano, 2015: Improvement of energy efficiency and quality of street lighting in South Italy as an action of Sustainable Energy Action Plans. The case study of Comiso (RG). *Energy, Volume*, **92(3)**, 394-408.

Bekera, B. and R.A. Francis, 2015: A Bayesian method for thermo-electric power generation drought risk assessment. In: *Safety and Reliability of Complex Engineered Systems - Proceedings of the 25th European Safety and Reliability Conference, ESREL 2015*.

Bell, L.W., A.D. Moore, and J.A. Kirkegaard, 2014: Evolution in crop-livestock integration systems that improve farm productivity and environmental performance in Australia. *European Journal of Agronomy*, **57**, 10-20.

Bell, T., R. Briggs, R. Bachmayer, and S. Li, 2015: Augmenting Inuit knowledge for safe sea-ice travel - The SmartICE information system. In: *2014 Oceans - St. John's, OCEANS 2014*.

Bellamy, R. and P. Healey, 2018: Slippery slope' or 'uphill struggle'? Broadening out expert scenarios of climate engineering research and development. *Environmental Science and Policy*, **83(January)**, 1-10, doi:10.1016/j.envsci.2018.01.021.

Bellamy, R., J. Lezaun, and J. Palmer, 2017: Public perceptions of geoengineering research governance: An experimental deliberative approach. *Global Environmental Change*, **45(June)**, 194-202, doi:10.1016/j.gloenvcha.2017.06.004.

Belmonte, N. et al., 2016: A comparison of energy storage from renewable sources through batteries and fuel cells: A case study in Turin, Italy. *International Journal of Hydrogen Energy*, **41(46)**, 21427-21438, doi:10.1016/j.ijhydene.2016.07.260.

Bendito, A. and E. Barrios, 2016: Convergent Agency: Encouraging Transdisciplinary Approaches for Effective Climate Change Adaptation and Disaster Risk Reduction. *International Journal of Disaster Risk Science*, **7(4)**, 430-435, doi:10.1007/s13753-016-0102-9.

Benmarhnia, T. et al., 2016: A Difference-in-Differences Approach to Assess the Effect of a Heat Action Plan on Heat-Related Mortality, and Differences in Effectiveness According. *Environmental health perspectives*, **124(11)**, 1694-1699.

Berdahl, M. et al., 2014: Arctic cryosphere response in the Geoengineering Model Intercomparison Project G3 and G4 scenarios. *Journal of Geophysical Research: Atmospheres*, **119**, 1308-1321, doi:10.1002/2013JD021264.Received.

Bergek, A., S. Jacobsson, B. Carlsson, S. Lindmark, and A. Rickne, 2008: Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, **37(3)**, 407-429, doi:10.1016/j.respol.2007.12.003.

Berle, A.A. and G.C. Means, 1932: *The Modern Corporation and Private Property*. Harcourt, Brace and World, New York, NY, USA.

Bernauer, T. and R. Gampfer, 2013: Effects of civil society involvement on popular legitimacy of global environmental governance. *Global Environmental Change*, **23(2)**, 439-449, doi:10.1016/j.gloenvcha.2013.01.001.

Bernauer, T. and R. Gampfer, 2015: How robust is public support for unilateral climate policy? *Environmental Science & Policy*, **54**, 316-330, doi:10.1016/j.envsci.2015.07.010.

Bernauer, T., R. Gampfer, T. Meng, and Y.– Su, 2016a: Could more civil society involvement increase public support for climate policy-making ? Evidence from a survey experiment in China. *Global Environmental Change*, **40**, 1-12, doi:10.1016/j.gloenvcha.2016.06.001.

Bernauer, T., L. Dong, L.F. McGrath, I. Shaymerdenova, and H. Zhang, 2016b: Unilateral or Reciprocal Climate Policy? Experimental Evidence from China. *Politics and Governance*, **4(3)**, 152-171, doi:10.17645/pag.v4i3.650.

Berrang-Ford, L., J.D. Ford, and J. Paterson, 2011: Are we adapting to climate change? *Global Environmental Change*,

21(1), 25-33, doi:10.1016/j.gloenvcha.2010.09.012.

Berrang-Ford, L. et al., 2014: What drives national adaptation? A global assessment. *Climatic Change***, 124(1-2)**, 441-450, doi:10.1007/s10584-014-1078-3.

Bertoldi, P., 2017: Are current policies promoting a change in behaviour, conservation and sufficiency? An analysis of existing policies and recommendations for new and effective policies. In: *Proceedings of the ECEEE 2017 Summer Study on Consumption, Efficiency & Limits*. ECEEE, Stockholm, Sweden, pp. 201-211.

Bertoldi, P., S. Rezessy, and V. Oikonomou, 2013: Rewarding energy savings rather than energy efficiency: Exploring the concept of a feed-in tariff for energy savings. *Energy Policy***, 56**, 526-535, doi:10.1016/j.enpol.2013.01.019.

Bertoldi, P., T. Ribeiro Serrenho, and P. Zangheri, 2016: Consumer Feedback Systems: How Much Energy Saving Will They Deliver and for How Long? In: *Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings*. ACEEE, Washington DC, USA.

Bertoldi, P., A. Kona, S. Rivas, and J.F. Dallemand, 2018: Towards a global comprehensive and transparent framework for cities and local governments enabling an effective contribution to the Paris climate agreement. *Current Opinion in Environmental Sustainability***, 30**, 67-74, doi:10.1016/j.cosust.2018.03.009.

Betsill, M.M. and H. Bulkeley, 2006: Cities and the Multilevel Governance of Global Climate Change. *Global Governance***, 12(2)**, 141-159, doi:10.2307/27800607.

Bettini, Y., R.R. Brown, and F.J. de Haan, 2015: Exploring institutional adaptive capacity in practice: examining water governance adaptation in Australia. *Ecology and Society***, 20(1)**, art47, doi:10.5751/ES-07291-200147.

Betts, R.A. et al., 2018: Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5°C and 2°C global warming with a higher-resolution global climate model. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences***, 376(2119)**, 20160452, doi:10.1098/rsta.2016.0452.

Betzold, C., 2015: Adapting to climate change in small island developing states. *Climatic Change***, 133(3)**, 481-489, doi:10.1007/s10584-015-1408-0.

Beyer, C., 2014: Strategic Implications of Current Trends in Additive Manufacturing. *Journal of Manufacturing Science and Engineering***, 136(6)**, 064701, doi:10.1115/1.4028599.

Bhagat, R., 2017: Migration, Gender and Right to the City. *Economic & Political Weekly***, LII(32)**, 35-40.

Bhattacharya, S., K. Giannakas, and K. Schoengold, 2017: Market and welfare effects of renewable portfolio standards in United States electricity markets. *Energy Economics***, 64**, 384-401, doi:10.1016/j.eneco.2017.03.011.

Bhave, A. et al., 2017: Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO2 targets. *Applied Energy***, 190**, 481-489, doi:10.1016/J.APENERGY.2016.12.120.

Biddau, F., A. Armenti, and P. Cottone, 2012: Special Thematic Section on " Rethinking Prefigurative Politics " Socio-Psychological Aspects of Grassroots Participation in the Transition Movement : An Italian Case Study. *Journal of Social and Political Psychology***, 4(1)**, 142-165, doi:10.5964/jspp.v4i1.518.

Bidwell, D., 2016: Thinking through participation in renewable energy decisions. *Nature Energy***, 1(5)**, doi:10.1038/nenergy.2016.51.

Biermann, F., 2010: Beyond the intergovernmental regime: Recent trends in global carbon governance. *Current Opinion in Environmental Sustainability***, 2(4)**, 284-288, doi:10.1016/j.cosust.2010.05.002.

Biggs, E.M. et al., 2015: Sustainable development and the water-energy-food nexus: A perspective on livelihoods. *Environmental Science & Policy***, 54**, 389-397, doi:10.1016/j.envsci.2015.08.002.

Bikhchandani, S. and S. Sharma, 2000: Herd Behavior in Financial Markets. **, 47(3)**, 279-310.

Birk, T. and K. Rasmussen, 2014: Migration from atolls as climate change adaptation: Current practices, barriers and options in Solomon Islands. *Natural Resources Forum***, 38(1)**, 1-13, doi:10.1111/1477-8947.12038.

Bishop, M.L. and A. Payne, 2012: Climate change and the future of Caribbean development. *The Journal of Development Studies***, 48(10)**, 1536-1553.

Blaabjerg, F., Z. Chen, and S.B. Kjaer, 2004: Power Electronics as Efficient Interface in Dispersed Power Generation Systems. *IEEE Transactions on Power Electronics***, 19(5)**, 1184-1194, doi:10.1109/TPEL.2004.833453.

Black, A. and P. Fraser, 2002: Stock market short-termism-an international perspective. *Journal of Multinational Financial Management***, 12(2)**, 135-158, doi:10.1016/S1042-444X(01)00044-5.

Blanchet, T., 2015: Struggle over energy transition in Berlin: How do grassroots initiatives affect local energy policy-making? *Energy Policy***, 78**, 246-254, doi:10.1016/j.enpol.2014.11.001.

Blanco, G. et al., 2014: Drivers, Trends and Mitigation. In: *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 351-411.

Blennow, K., J. Persson, M. Tomé, and M. Hanewinkel, 2012: Climate Change: Believing and Seeing Implies

Adapting. *Plos ONE*, **7(11)**, 1435-1439.

BNEF, 2017: *Bloomberg New Energy Outlook*. Bloomberg New Energy Finance, New York, NY, USA.

Bodansky, D., 2013: The who, what, and wherefore of geoengineering governance. *Climatic Change*, **121(3)**, 539-551, doi:10.1007/s10584-013-0759-7.

Bodansky, D. and E. Diringer, 2014: Alternative Models for the 2015 Climate Change Agreement. *FNI Climate Policy Perspectives*, **13**.

Bodle, R., G. Homan, S. Schiele, and T. E., 2012: *The Regulatory Framework for Climate-Related Geoengineering Relevant to the Convention on Biological Diversity. Part II of: Geoengineering in Relation to the Convention on Biological Diversity: Technical and Regulatory Matters.*. 152 pp.

Bodnar, P, et al., 2018: Underwriting 1.5°C: competitive approaches to financing accelerated climate change mitigation. *Climate Policy*, **18(3)**, 368-382, doi:10.1080/14693062.2017.1389687.

Böhringer, C., A., Löschel, U. Moslener, and, T.F. Rutherford et al. 2009: EU climate policy up to 2020: An economic impact assessment. *Energy Economics*.

Bolderdijk, J.W., J. Knockaert, E.M. Steg, and E.T. Verhoef, 2011: Author ' s personal copy Effects of Pay-As-You-Drive vehicle insurance on young drivers' speed choice: Results of a Dutch field experiment. *Accident Analysis & Prevention*, **43**, 1181-1186, doi:10.1016/j.aap.2010.12.032.

Bolderdijk, J.W., M. Gorsira, K. Keizer, and L. Steg, 2013a: Values determine the (in)effectiveness of informational interventions in promoting pro-environmental behavior. *PLoS ONE*, **8(12)**, e83911, doi:10.1371/journal.pone.0083911.

Bolderdijk, J.W., L. Steg, E.S. Geller, P.K. Lehman, and T. Postmes, 2013b: Comparing the effectiveness of monetary versus moral motives in environmental campaigning. *Nature Climate Change*, **3(1)**, 1-4, doi:10.1038/nclimate1767.

Bond, T.C. et al., 2013: Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, **118(11)**, 5380-5552, doi:10.1002/jgrd.50171.

Bonsch, M. et al., 2016: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11-24, doi:10.1111/gcbb.12226.

Boodoo, Z. and K.H. Olsen, 2017: Assessing transformational change potential: the case of the Tunisian cement Nationally Appropriate Mitigation Action (NAMA). *Climate Policy*, 1-19, doi:10.1080/14693062.2017.1386081.

Booth, M.S., 2018: Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy. *Environmental Research Letters*, **13(3)**, 035001, doi:10.1088/1748-9326/aaac88.

Bord, R.J., R.E. O'Connor, and A. Fisher, 2000: In what sense does the public need to understand global climate change? *Public Understanding of Science*, **9(3)**, 205-218.

Bos, J.J., R.R. Brown, and M.A. Farrelly, 2015: Building networks and coalitions to promote transformational change: Insights from an Australian urban water planning case study. *Environmental Innovation and Societal Transitions*, **15**, 11-25, doi:10.1016/J.EIST.2014.10.002.

Bosomworth, K., A. Harwood, P. Leith, and P. Wallis, 2015: *Adaptation Pathways: a playbook for developing options for climate change adaptation in NRM*. Southern Slopes Climate Adaptation Research Partnership (SCARP): RMIT University, University of Tasmania, and Monash University, 26 pp.

Boucher, O. and G.A. Folberth, 2010: New Directions: Atmospheric methane removal as a way to mitigate climate change? *Atmospheric Environment*, **44(27)**, 3343-3345, doi:10.1016/j.atmosenv.2010.04.032.

Boulamanti, A. and J.A. Moya, 2017: *Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry*. 237 pp.

Bouman, E.A., E. Lindstad, A.I. Rialland, and A.H. Strømman, 2017: State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping - A review. *Transportation Research Part D: Transport and Environment*, **52(Part A)**, 408-421, doi:https://doi.org/10.1016/j.trd.2017.03.022.

Bowen, K.J. et al., 2017: Implementing the "Sustainable Development Goals": towards addressing three key governance challenges - collective action, trade-offs, and accountability. *Current Opinion in Environmental Sustainability*, **26-27(May)**, 90-96, doi:10.1016/j.cosust.2017.05.002.

Bows, A. and T. Smith, 2012: The (low-carbon) shipping forecast: opportunities on the high seas. *Carbon Management*, **3(6)**, 525-528, doi:10.4155/cmt.12.68.

Bows-Larkin, A., 2015: All adrift: aviation, shipping, and climate change policy. *Climate Policy*, **15(6)**, 681-702, doi:10.1080/14693062.2014.965125.

Boyd, P.W., 2016: Development of geopolitically relevant ranking criteria for geoengineering methods. *Earth's Future*, **4(11)**, 523-531, doi:10.1002/2016EF000447.

Boykoff, M.T., A. Ghoshi, and K. Venkateswaran, 2013: Media discourse on adapation: competing vision of "success" in the Indian context. In: *Successful Adaptation to Climate Change: Linking Science and Policy in a Rapidly Changing World* [Moser, S.C. and M.T. Boykoff (eds.)]. Routledge, Abingdon, Oxon, UK and New York, NY, USA, pp. 237-252.

Boysen, L.R. et al., 2017: The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, **5(5)**, 463-474, doi:10.1002/2016EF000469.

Bradley, P., A. Coke, and M. Leach, 2016: Financial incentive approaches for reducing peak electricity demand, experience from pilot trials with a UK energy provider. *Energy Policy*, **98**, 108-120, doi:10.1016/j.enpol.2016.07.022.

Brambilla, A., G. Salvalai, M. Imperadori, and M.M. Sesana, 2018: Nearly zero energy building renovation: From energy efficiency to environmental efficiency, a pilot case study. *Energy and Buildings*, **166**, 271-283, doi:10.1016/j.enbuild.2018.02.002.

Brand, U. and A. von Gleich, 2015: Transformation toward a Secure and Precaution - Oriented Energy System with the Guiding Concept of Resilience - Implementation of Low-Exergy Solutions in Northwestern Germany. *Energies*, **8(7)**, 6995-7019, doi:10.3390/en8076995.

Branger, F. and P. Quirion, 2014: Climate policy and the 'carbon haven' effect. *Wiley Interdisciplinary Reviews: Climate Change*, **5(1)**, 53-71, doi:10.1002/wcc.245.

Branger, F., P. Quirion, and J. Chevallier, 2016: Carbon leakage and competitiveness of cement and steel industries under the EU ETS: Much ado about nothing. *Energy Journal*, **37(3)**, 109-135, doi:10.5547/01956574.37.3.fbra.

Braun, C., C. Merk, G. Pönitzsch, K. Rehdanz, and U. Schmidt, 2017: Public perception of climate engineering and carbon capture and storage in Germany: survey evidence. *Climate Policy*, **3062(August)**, 1-14, doi:10.1080/14693062.2017.1304888.

Bredenkamp, H. and C. Pattillo, 2010: Financing the Response to Climate Change. IMF Station Position Note SPN10/06, 14 pp.

Bremer, J. and M.K. Linnenluecke, 2016: Determinants of the perceived importance of organisational adaptation to climate change in the Australian energy industry. *Australian Journal of Management*, **42(3)**, 502-521, doi:10.1177/0312896216672273.

Breyer, C. et al., 2017: On the role of solar photovoltaics in global energy transition scenarios. *Progress in Photovoltaics: Research and Applications*, **25(8)**, 727-745, doi:10.1002/pip.2885.

Bridgeman, B., 2017: Population growth underlies most other environmental problems: Comment on Clayton et al. (2016). *American Psychologist*, **72(4)**, 386-387, doi:10.1037/amp0000137.

Bright, R.M., K. Zhao, R.B. Jackson, and F. Cherubini, 2015: Quantifying surface albedo and other direct biogeophysical climate forcings of forestry activities. *Global Change Biology*, **21(9)**, 3246-3266, doi:10.1111/gcb.12951.

Briley, L., D. Brown, and S.E. Kalafatis, 2015: Overcoming barriers during the co-production of climate information for decision-making. *Climate Risk Management*, **9**, 41-49, doi:10.1016/j.crm.2015.04.004.

Bring, A. et al., 2016: Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *Journal of Geophysical Research: Biogeosciences*, **121(3)**, 621-649, doi:10.1002/2015JG003131.

Brink, E. et al., 2016: Cascades of green: A review of ecosystem-based adaptation in urban areas. *Global Environmental Change*, **36**, 111-123, doi:10.1016/j.gloenvcha.2015.11.003.

Brockington, J.D., I.M. Harris, and R.M. Brook, 2016: Beyond the project cycle: a medium-term evaluation of agroforestry adoption and diffusion in a south Indian village. *Agroforestry Systems*, **90(3)**, 489-508, doi:10.1007/s10457-015-9872-0.

Broehm, M., J. Strefler, and N. Bauer, 2015: *Techno-Economic Review of Direct Air Capture Systems for Large Scale Mitigation of Atmospheric CO2*. 28 pp.

Broekhoff, D., G. Piggot, and P. Erickson, 2018: Building Thriving, Low-Carbon Cities: An Overview of Policy Options for National Governments. 124 pp.

Brondízio, E.S., A.C.B. de Lima, S. Schramski, and C. Adams, 2016: Social and health dimensions of climate change in the Amazon. *Annals of Human Biology*, **43(4)**, 405-414, doi:10.1080/03014460.2016.1193222.

Brooks, S.J., 2013: Avoiding the Limits to Growth: Gross National Happiness in Bhutan as a Model for Sustainable Development. *Sustainability*, **5(9)**, doi:10.3390/su5093640.

Brosch, T., M.K. Patel, and D. Sander, 2014: Affective influences on energy-related decisions and behaviors. *Frontiers in Energy Research*, **2(March)**, 1-12, doi:10.3389/fenrg.2014.00011.

Broto, V.C., 2017: Energy landscapes and urban trajectories towards sustainability. *Energy Policy*, **108(December 2016)**, 755-764, doi:10.1016/j.enpol.2017.01.009.

Brown, D. and G. McGranahan, 2016: The urban informal economy, local inclusion and achieving a global green transformation. *Habitat International*, **53**, 97-105, doi:10.1016/j.habitatint.2015.11.002.

Brown, M.A., G. Kim, A.M. Smith, and K. Southworth, 2017: Exploring the impact of energy efficiency as a carbon mitigation strategy in the U.S.. *Energy Policy*, **109**, 249-259, doi:10.1016/j.enpol.2017.06.044.

Brown, R.M., C.R. Dillon, J. Schieffer, and J.M. Shockley, 2016: The carbon footprint and economic impact of precision agriculture technology on a corn and soybean farm. *Journal of Environmental Economics and Policy*, **5(3)**, 335-348, doi:10.1080/21606544.2015.1090932.

BRT Data, 2018: Key Indicators Per Region. https://brtdata.org (Accessed: 15 May 2018).

Bruce, P., R. Catlow, and P. Edwards, 2010: Energy materials to combat climate change. *Philosophical Transactions of* *the Royal Society A: Mathematical, Physical and Engineering Sciences*, **368(1923)**, 3225 LP - 3225.

Bruckner, T. et al., 2014: Energy Systems. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, United Kingdom and New York, NY, USA.

Brüggemann, M., F. De Silva-Schmidt, I. Hoppe, D. Arlt, and J.B. Schmitt, 2017: The appeasement effect of a United Nations climate summit on the German public. *Nature Climate Change*, 1-7, doi:10.1038/nclimate3409.

Brügger, A., T.A. Morton, and S. Dessai, 2015: Hand in hand: Public endorsement of climate change mitigation and adaptation. *PLoS ONE*, **10(4)**, 1-18, doi:10.1371/journal.pone.0124843.

Brugnach, M., M. Craps, and A. Dewulf, 2017: Including indigenous peoples in climate change mitigation: addressing issues of scale, knowledge and power. *Climatic Change*, **140(1)**, 19-32, doi:10.1007/s10584-014-1280-3.

Brulle, R.J., J. Carmichael, and J.C. Jenkins, 2012: Shifting public opinion on climate change: an empirical assessment of factors influencing concern over climate change in the U.S., 2002-2010. *Climatic Change*, **114(2)**, 169-188, doi:10.1007/s10584-012-0403-y.

Brunes, E. and D. Ohlhorst, 2011: Wind power generation in Germany: a transdisciplinary view on the innovation biography. *J. Transdiscipl. Environ. Stud.*, **10**, 45-67.

Bryan, E., T.T. Deressa, G.A. Gbetibouo, and C. Ringler, 2009: Adaptation to climate change in Ethiopia and South Africa: options and constraints. *Environmental Science and Policy*, **12(4)**, 413-426, doi:10.1016/j.envsci.2008.11.002.

Bryan, E., Q. Bernier, M. Espinal, and C. Ringler, 2017: Making climate change adaptation programmes in sub-Saharan Africa more gender responsive: insights from implementing organizations on the barriers and opportunities. *Climate and Development*, 1-15, doi:10.1080/17565529.2017.1301870.

Brzoska, M. and C. Fröhlich, 2016: Climate change, migration and violent conflict: vulnerabilities, pathways and adaptation strategies. *Migration and Development*, **5(2)**, 190-210, doi:10.1080/21632324.2015.1022973.

Buchholz, T., M.D. Hurteau, J. Gunn, and D. Saah, 2016: A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies. *GCB Bioenergy*, **8(2)**, 281-289, doi:10.1111/gcbb.12245.

Buck, H.J., 2012: Geoengineering: Re-making Climate for Profit or Humanitarian Intervention? *Development and Change*, **43(1)**, 253-270, doi:10.1111/j.1467-7660.2011.01744.x.

Buck, H.J., 2016: Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change*, **139(2)**, 155-167, doi:10.1007/s10584-016-1770-6.

Buck, H.J., A.R. Gammon, and C.J. Preston, 2014: Gender and geoengineering. *Hypatia*, **29(3)**, 651-669, doi:10.1111/hypa.12083.

Buckeridge, M., 2015: Árvores urbanas em São Paulo: planejamento, economia e água. *Estudos Avançados*, **29(84)**, 85-101, doi:10.1590/S0103-40142015000200006.

Budnitz, R.J., 2016: Nuclear power: Status report and future prospects. *Energy Policy*, **96(Supplement C)**, 735-739, doi:https://doi.org/10.1016/j.enpol.2016.03.011.

Bui, M. et al., 2018: Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science* (in press), doi:10.1039/C7EE02342A.

Bulkeley, H., 2005: Reconfiguring environmental governance: Towards a politics of scales and networks. *Political Geography*, **24(8)**, 875-902, doi:10.1016/j.polgeo.2005.07.002.

Bulkeley, H. et al., 2011: The Role of Institutions, Governance, and Urban Planning for Mitigation and Adaptation. In: *Cities and Climate Change*. The World Bank, pp. 125-159.

Bulkeley, H. et al., 2012: Governing climate change transnationally: Assessing the evidence from a database of sixty initiatives. *Environment and Planning C: Government and Policy*, **30(4)**, 591-612, doi:10.1068/c11126.

Bunce, A. and J. Ford, 2015: How is adaptation, resilience, and vulnerability research engaging with gender? *Environ. Res. Lett. Environ. Res. Lett*, **10(10)**, 123003, doi:10.1088/1748-9326/10/12/123003.

Burch, S., C. Mitchell, M. Berbes-Blazquez, and J. Wandel, 2017: Tipping Toward Transformation: Progress, Patterns and Potential for Climate Change Adaptation in the Global South. *Journal of Extreme Events*, **04(01)**, 1750003, doi:10.1142/S2345737617500038.

Burch, S. et al., 2016: Governing and accelerating transformative entrepreneurship: exploring the potential for small business innovation on urban sustainability transitions. *Current Opinion in Environmental Sustainability*, **22**, 26-32, doi:10.1016/J.COSUST.2017.04.002.

Burney, J.A. and R.L. Naylor, 2012: Smallholder Irrigation as a Poverty Alleviation Tool in Sub-Saharan Africa. *World Development*, **40(1)**, 110-123, doi:10.1016/j.worlddev.2011.05.007.

Burnham, M. and Z. Ma, 2017: Climate change adaptation: factors influencing Chinese smallholder farmers' perceived self-efficacy and adaptation intent. *Regional Environmental Change*, **17(1)**, 171-186, doi:10.1007/s10113-016-0975-6.

Burns, W. and S. Nicholson, 2017: Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *Journal of Environmental Studies and Sciences*, **15(2)**, doi:10.1007/s13412-017-0445-6.

Burns, W.C.G., 2011: Climate geoengineering: solar radiation management and its implications for intergenerational equity. *Stanford Journal of Law, Science & Policy*, **4**, 39-55.

Burt, A., B. Hughes, and G. Milante, 2014: Eradicating Poverty in Fragile States: Prospects of Reaching The 'High-Hanging' Fruit by 2030. WPS7002, 35 pp.

Bushee, B.J., 2001: Do Institutional Investors Prefer Near-Term Earnings over Long-Run Value? *Contemporary Accounting Research*, **18(2)**, 207-246, doi:10.1506/J4GU-BHWH-8HME-LE0X.

Bustamante, J.G., A.S. Rattner, and S. Garimella, 2016: Achieving near-water-cooled power plant performance with air-cooled condensers. *Applied Thermal Engineering*, **105**, 362-371, doi:10.1016/j.applthermaleng.2015.05.065.

Butler, C. and J. Adamowski, 2015: Empowering marginalized communities in water resources management: Addressing inequitable practices in Participatory Model Building. *Journal of Environmental Management*, **153**, 153-162, doi:10.1016/j.jenvman.2015.02.010.

Butler, J.R.A. et al., 2015: Integrating Top-Down and Bottom-Up Adaptation Planning to Build Adaptive Capacity: A Structured Learning Approach. *Coastal Management*, **43(4)**, 346-364, doi:10.1080/08920753.2015.1046802.

Butler, J.R.A. et al., 2016: Scenario planning to leap-frog the Sustainable Development Goals: An adaptation pathways approach. *Climate Risk Management*, **12**, 83-99, doi:10.1016/j.crm.2015.11.003.

Butler, L. and K. Neuhoff, 2008: Comparison of feed-in tariff, quota and auction mechanisms to support wind power development. *Renewable Energy*, **33(8)**, 1854-1867, doi:10.1016/j.renene.2007.10.008.

Cabeza, L.F. et al., 2013: Affordable construction towards sustainable buildings: review on embodied energy in building materials. *Current Opinion in Environmental Sustainability*, **5(2)**, 229-236, doi:10.1016/j.cosust.2013.05.005.

Caldecott, B., 2017: Introduction to special issue: stranded assets and the environment. *Journal of Sustainable Finance & Investment*, **7(1)**, 1-13, doi:10.1080/20430795.2016.1266748.

Caldeira, K. and G. Bala, 2017: Reflecting on 50 years of geoengineering research. *Earth's Future*, **5(1)**, 10-17, doi:10.1002/2016EF000454.

Calel, R. and A. Dechezleprêtre, 2016: Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. *Review of Economics and Statistics*, **98(1)**, 173-191, doi:10.1162/REST_a_00470.

Calvin, K. et al., 2014: Trade-offs of different land and bioenergy policies on the path to achieving climate targets. *Climatic Change*, **123(3-4)**, 691-704, doi:10.1007/s10584-013-0897-y.

Campbell, T.H. and A.C. Kay, 2014: Solution aversion: On the relation between ideology and motivated disbelief. *Journal of Personality and Social Psychology*, **107(5)**, 809-824, doi:10.1037/a0037963.

Campiglio, E., 2016: Beyond Carbon Pricing: The Role of Banking and Monetary Policy in Financing the Transition to a Low- Carbon Economy. *Ecological Economics*, **121(C)**, 220-230.

Campos, I.S. et al., 2016: Climate adaptation, transitions, and socially innovative action-research approaches. *Ecology and Society*, **21(1)**, art13, doi:10.5751/ES-08059-210113.

Camps-Calvet, M., J. Langemeyer, L. Calvet-Mir, and E. Gómez-Baggethun, 2016: Ecosystem services provided by urban gardens in Barcelona, Spain: Insights for policy and planning. *Environmental Science & Policy*, **62**, 14-23, doi:10.1016/j.envsci.2016.01.007.

Canadell, J.G. and E.D. Schulze, 2014: Global potential of biospheric carbon management for climate mitigation. *Nature Communications*, **5**, 1-12, doi:10.1038/ncomms6282.

Canales, F.A., A. Beluco, and C.A.B. Mendes, 2015: A comparative study of a wind hydro hybrid system with water storage capacity: Conventional reservoir or pumped storage plant? *Journal of Energy Storage*, **4**, 96-105, doi:10.1016/j.est.2015.09.007.

Caney, S., 2012: Just Emissions. *Philosophy & Public Affairs*, **40(4)**, 255-300, doi:10.1111/papa.12005.

Caney, S., 2014: Two Kinds of Climate Justice: Avoiding Harm and Sharing Burdens. *Journal of Political Philosophy*, **22(2)**, 125-149, doi:10.1111/jopp.12030.

Cannon, T., 2015: Disasters, vulnerability and the significance of culture. In: *Cultures and Disasters: Understanding Cultural Framings in Disaster Risk Reduction*. Routledge.

Capon, S.J. et al., 2013: Riparian Ecosystems in the 21st Century: Hotspots for Climate Change Adaptation? *Ecosystems*, **16(3)**, 359-381, doi:10.1007/s10021-013-9656-1.

Carlsson-Kanyama, A. and A.D. González, 2009: Potential contributions of food consumption patterns to climate change. *The American Journal of Clinical Nutrition*, **89(5)**, 1704S-1709S, doi:10.3945/ajcn.2009.26736AA.

Carney, M., 2016: Breaking the tragedy of the horizon climate change and financial stability. http://www.bankofengland.co.uk/publications/Pages/speeches/2015/844.aspx (Accessed: 25 July 2017).

Carr, W.A. et al., 2013: Public engagement on solar radiation management and why it needs to happen now. *Climatic Change*, **121(3)**, 567-577, doi:10.1007/s10584-013-0763-y.

Carreño, M.L. et al., 2017: Holistic disaster risk evaluation for the urban risk management plan of Manizales, Colombia. *International Journal of Disaster Risk Science*, **8(3)**, 258-269.

Carrico, A.R., H.B. Truelove, M.P. Vandenbergh, and D. Dana, 2015: Does learning about climate change adaptation change support for mitigation? *Journal of Environmental Psychology*, **41**, 19-29, doi:10.1016/j.jenvp.2014.10.009.

Carter, J.G. et al., 2015: Climate change and the city: Building capacity for urban adaptation. *Progress in Planning*, **95**, 1-66, doi:10.1016/j.progress.2013.08.001.

Cartwright, A., 2015: Better Growth, Better Cities: Rethinking and Redirecting Urbanisation in Africa. 44 pp.

Cartwright, A. et al., 2013: Economics of climate change adaptation at the local scale under conditions of uncertainty and resource constraints: the case of Durban, South Africa. *Environment and Urbanization*, **25(1)**, 139-156, doi:10.1177/0956247813477814.

Cass, N., G. Walker, and P. Devine-Wright, 2010: Good neighbours, public relations and bribes: The politics and perceptions of community benefit provision in renewable energy development in the UK. *Journal of Environmental Policy and Planning*, **12(3)**, 255-275, doi:10.1080/1523908x.2010.509558.

Castán Broto, V., 2017: Urban Governance and the Politics of Climate change. *World Development*, **93**, 1-15, doi:10.1016/j.worlddev.2016.12.031.

Castán Broto, V. and H. Bulkeley, 2013: A survey of urban climate change experiments in 100 cities. *Global Environmental Change*, **23(1)**, 92-102, doi:10.1016/j.gloenvcha.2012.07.005.

Cayuela, M.L. et al., 2014: Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems & Environment*, **191**, 5-16, doi:https://doi.org/10.1016/j.agee.2013.10.009.

CBD, 2008: Decision IX/16: Biodiversity and Climate Change. In: *Ninth meeting of the Conference of the Parties to the Convention on Biological Diversity, COP 9*. Convention on Biological Diversity (CBD), Nagoya, Japan.

CBD, 2010: Decision X/33: Biodiversity and climate change. In: *Tenth meeting of the Conference of the Parties to the Convention on Biological Diversity, COP 10*. Convention on Biological Diversity (CBD), Bonn, Germany.

CBS, 2016: *A Compass Towards a Just and Harmonious Society: 2015 GNH Survey Report*. Centre for Bhutan Studies & GNH Research, Thimphu, Bhutan, 342 pp.

CCFLA, 2016: *Localizing Climate Finance: Mapping Gaps and Opportunities, Designing solutions*. 29 pp.

CCRIF, 2017: *Annual Report 2016-2017*. 107 pp.

Chadburn, S.E. et al., 2017: An observation-based constraint on permafrost loss as a function of global warming. *Nature Climate Change*, **7(0316)**, doi:10.1038/nclimate3262.

Chaffin, B.C. and L.H. Gunderson, 2016: Emergence, institutionalization and renewal: Rhythms of adaptive governance in complex social-ecological systems. *Journal of Environmental Management*, **165**, 81-87, doi:10.1016/j.jenvman.2015.09.003.

Chaffin, B.C., H. Gosnell, and B.A. Cosens, 2014: A Decade of Adaptive Governance Scholarship: Synthesis and Future Directions. *Ecology and Society*, **19(3)**, 56.

Challinor, A.J. et al., 2014: A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, **4(4)**, 287-291, doi:10.1038/nclimate2153.

Chambers, L.E. et al., 2017: A database for traditional knowledge of weather and climate in the Pacific. *Meteorological Applications*, **24(3)**, 491-502, doi:10.1002/met.1648.

Chandel, M.K., L.F. Pratson, and R.B. Jackson, 2011: The potential impacts of climate-change policy on freshwater use in thermoelectric power generation. *Energy Policy*, **39(10)**, 6234-6242, doi:10.1016/j.enpol.2011.07.022.

Chandel, S.S., A. Sharma, and B.M. Marwaha, 2016: Review of energy efficiency initiatives and regulations for residential buildings in India. *Renewable and Sustainable Energy Reviews*, **54**, 1443-1458, doi:10.1016/j.rser.2015.10.060.

Chang, N., M.V. Vasquez, C.F. Chen, S. Imen, and L. Mullon, 2015: Global nonlinear and nonstationary climate change effects on regional precipitation and forest phenology in Panama, Central America. *Hydrological Processes*, **29(3)**, 339-355, doi:10.1002/hyp.10151.

Chang'a, L.B., P.Z. Yanda, and J. Ngana, 2010: Indigenous knowledge in seasonal rainfall prediction in Tanzania : A case of the South-western Highland of Tanzania. *Journal of Geography and Regional Planning*, **3(April)**, 66-72.

Chant, S., M. Klett-davies, and J. Ramalho, 2017: *Challenges and potential solutions for adolescent girls in urban settings: a rapid evidence review*.

Chapin, F.S., C.N. Knapp, T.J. Brinkman, R. Bronen, and P. Cochran, 2016: Community-empowered adaptation for self-reliance. *Current Opinion in Environmental Sustainability*, **19**, 67-75, doi:10.1016/j.cosust.2015.12.008.

Chatrchyan, A.M. et al., 2017: United States agricultural stakeholder views and decisions on climate change. *Wiley Interdisciplinary Reviews: Climate Change*, e469, doi:10.1002/wcc.469.

Chelleri, L., J.J. Waters, M. Olazabal, and G. Minucci, 2015: Resilience trade-offs: addressing multiple scales and temporal aspects of urban resilience. *Environment and Urbanization*, **27(1)**, 181-198, doi:10.1177/0956247814550780.

Chen, C. and M. Tavoni, 2013: Direct air capture of CO2 and climate stabilization: A model based assessment. *Climatic Change*, **118(1)**, 59-72, doi:10.1007/s10584-013-0714-7.

Chen, M.–, 2015: An examination of the value-belief-norm theory model in predicting pro-environmental behaviour in

Taiwan. *Asian Journal of Social Psychology*, **18**, 145-151, doi:10.1111/ajsp.12096.

Chen, S. and B. Chen, 2016: Urban energy-water nexus: A network perspective. *Applied Energy*, **184**, 905-914, doi:10.1016/j.apenergy.2016.03.042.

Chen, Y. and Y. Xin, 2017: Implications of geoengineering under the 1.5°c target: Analysis and policy suggestions. *Advances in Climate Change Research*, **7**, 1-7, doi:10.1016/j.accre.2017.05.003.

Cheng, V.K.M. and G.P. Hammond, 2017: Life-cycle energy densities and land-take requirements of various power generators: A UK perspective. *Journal of the Energy Institute*, **90(2)**, 201-213, doi:10.1016/J.JOEI.2016.02.003.

Cheshmehzangi, A., 2016: China's New-type Urbanisation Plan (NUP) and the Foreseeing Challenges for Decarbonization of Cities: A Review. *Energy Procedia*, **104(5)**, 146-152, doi:10.1016/j.egypro.2016.12.026.

Chichilnisky, G. and G. Heal (eds.), 2000: *Equity and Efficiency in Environmental Markets: Global Trade in Carbon Dioxide Emissions*. Columbia University Press, 280 pp.

Child, M. and C. Breyer, 2017: Transition and transformation: A review of the concept of change in the progress towards future sustainable energy systems. *Energy Policy*, **107**, 11-26, doi:10.1016/J.ENPOL.2017.04.022.

Chiroleu-Assouline, M. and M. Fodha, 2011: Environmental Tax and the Distribution of Income among Heterogeneous Workers. *Annals of Economics and Statistics*, **103/104(103)**, 71-92, doi:10.2307/41615494.

Chitnis, M. and S. Sorrell, 2015: Living up to expectations: Estimating direct and indirect rebound effects for UK households. *Energy Economics*, **52**, S100-S116, doi:10.1016/j.eneco.2015.08.026.

Christensen, C., M. Raynor, and R. McDonald, 2015: What is Disruptive Innovation? *Harvard Business Review*.

Christoforidis, G.C., K.C. Chatzisavvas, S. Lazarou, and C. Parisses, 2013: Covenant of Mayors initiative - Public perception issues and barriers in Greece. *Energy Policy*, **60**, 643-655, doi:10.1016/j.enpol.2013.05.079.

Christophers, B., 2017: Climate Change and Financial Instability: Risk Disclosure and the Problematics of Neoliberal Governance. *Annals of the American Association of Geographers*, **107(5)**, 1108-1127, doi:10.1080/24694452.2017.1293502.

Chu, E., I. Anguelovski, and J.A. Carmin, 2016: Inclusive approaches to urban climate adaptation planning and implementation in the Global South. *Climate Policy*, **16(3)**, 372-392, doi:10.1080/14693062.2015.1019822.

Chu, E., I. Anguelovski, and D. Roberts, 2017: Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities*, **60**, 378-387, doi:10.1016/j.cities.2016.10.016.

Chu, S., 2015: Car restraint policies and mileage in Singapore. *Transportation Research Part A: Policy and Practice*, **77(C)**, 404-412.

Chum, H. et al., 2011: Bioenergy. In: *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, and C. von Stechow (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Chung Tiam Fook, T., 2017: Transformational processes for community-focused adaptation and social change: a synthesis. *Climate and Development*, **9(1)**, 5-21, doi:10.1080/17565529.2015.1086294.

Ciplet, D., J.T. Roberts, and M.R. Khan, 2015: *Power in a warming world: The new global politics of climate change and the remaking of environmental inequality*. MIT Press.

CISL, 2015: *Unhedgeable Risk: How climate change sentiment impacts investment*. 64 pp.

Clack, C.T.M. et al., 2017: Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *Proceedings of the National Academy of Sciences of the United States of America*, **114(26)**, 6722-6727, doi:10.1073/pnas.1610381114.

Clark, M. and D. Tilman, 2017: Comparative analysis of environmental impacts of agricultural production systems , agricultural input efficiency, and food choice Comparative analysis of environmental impacts of agricultural production systems , agricultural input efficiency , and food. *Environ. Res. Lett*, **12**, doi:https://doi.org/10.1088/1748-9326/aa6cd5.

Clarke, L. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413-510.

Clayton, S. et al., 2015: Psychological research and global climate change. *Nature Climate Change*, **5(7)**, 640-646, doi:10.1038/nclimate2622.

Clayton, S. et al., 2017: Psychologists and the Problem of Population Growth : Reply to Bridgeman (2017). *American Psychologist*, **72(4)**, 388-389, doi:10.1037/amp0000152.

Clémençon, R., 2016: The two sides of the Paris climate agreement: Dismal failure or historic breakthrough? *Journal of Environment & Development*, **25(1)**, 3-24.

Clemens, M., J. Rijke, A. Pathirana, J. Evers, and N. Hong Quan, 2015: Social learning for adaptation to climate change in developing countries: insights from Vietnam. *Journal of Water and Climate Change*, **8(4)**, doi:10.2166/wcc.2015.004.

Clements, J., A. Ray, and G. Anderson, 2013: *The Value of Climate Services Across Economic and Public Sectors: A Review of Relevant Literature*. United States Agency for International Development (USAID).

Climate Analytics, 2015: *Africa's Adaptation Gap 2: Bridging the gap - mobilising sources*.

Cloutier, G. et al., 2015: Planning adaptation based on local actors' knowledge and participation: a climate governance experiment. *Climate Policy*, **15(4)**, 458-474, doi:10.1080/14693062.2014.937388.

Coady, D., I. Parry, L. Sears, and B. Shang, 2017: How Large Are Global Fossil Fuel Subsidies? *World Development*, **91**, 11-27, doi:10.1016/j.worlddev.2016.10.004.

Cochran, P. et al., 2013: Indigenous frameworks for observing and responding to climate change in Alaska. *Climatic Change*, **120(3)**, 557-567, doi:10.1007/s10584-013-0735-2.

Cochrani, I., R. Hubert, V. Marchal, and R. Youngman, 2014: *Public Financial Institutions and the Low-carbon Transition: Five Case Studies on Low-Carbon Infrastructure and Project Investment*. OECD Environment Working Papers, No. 72, OECD Publishing, Paris.

Coe, R., F. Sinclair, and E. Barrios, 2014: Scaling up agroforestry requires research 'in' rather than 'for' development. *Current Opinion in Environmental Sustainability*, **6(1)**, 73-77, doi:10.1016/j.cosust.2013.10.013.

Cole, D.H., 2015: Advantages of a polycentric approach to climate change policy. *Nature Climate Change*, **5(2)**, 114-118, doi:10.1038/nclimate2490.

Colenbrander, S. et al., 2017: Can low-carbon urban development be pro-poor? The case of Kolkata, India. *Environment and Urbanization*, **29(1)**, 139-158, doi:10.1177/0956247816677775.

Collas, L., R.E. Green, A. Ross, J.H. Wastell, and A. Balmford, 2017: Urban development, land sharing and land sparing: the importance of considering restoration. *Journal of Applied Ecology*, **54(6)**, 1865-1873, doi:10.1111/1365-2664.12908.

Colloff, M.J. et al., 2016a: Adaptation services and pathways for the management of temperate montane forests under transformational climate change. *Climatic Change*, **138(1-2)**, 267-282, doi:10.1007/s10584-016-1724-z.

Colloff, M.J. et al., 2016b: Adaptation services of floodplains and wetlands under transformational climate change. *Ecological Applications*, **26(4)**, 1003-1017, doi:10.1890/15-0848.

Colloff, M.J. et al., 2017: An integrative research framework for enabling transformative adaptation. *Environmental Science & Policy*, **68**, 87-96, doi:10.1016/j.envsci.2016.11.007.

Combet, E., 2013: Fiscalité carbone et progrès social. Application au cas français., École des Hautes Études en Sciences Sociales (EHESS), 412 pp.

Combet, E., F. Ghersi, J.C. Hourcade, and D. Théry, 2010: Carbon Tax and Equity: The Importance of Policy Design. In: *Critical Issues In Environmental Taxation* [Dias Soares, C., J. Milne, H. Ashiabor, K. Deketelaere, and L. Kreiser (eds.)]. Oxford University Press, pp. 277-295.

Cooney, G., J. Littlefield, J. Marriott, and T.J. Skone, 2015: Evaluating the Climate Benefits of CO2-Enhanced Oil Recovery Using Life Cycle Analysis. *Environmental Science & Technology*, **49(12)**, 7491-7500, doi:10.1021/acs.est.5b00700.

Cooper, J.A.G., M.C. O'Connor, and S. McIvor, 2016: Coastal defences versus coastal ecosystems: A regional appraisal. *Marine Policy* (in press), doi:10.1016/j.marpol.2016.02.021.

Cooper-Searle, S., F. Livesey, and J.M. Allwood, 2018: Why are Material Efficiency Solutions a Limited Part of the Climate Policy Agenda? An application of the Multiple Streams Framework to UK policy on CO2 emissions from cars. *Environmental Policy and Governance*, **28(1)**, 51-64, doi:10.1002/eet.1782.

Coq-Huelva, D., A. Higuchi, R. Alfalla-Luque, R. Burgos-Morán, and R. Arias-Gutiérrez, 2017: Co-Evolution and Bio-Social Construction: The Kichwa Agroforestry Systems (Chakras) in the Ecuadorian Amazonia. *Sustainability*, **9(11)**, 1920, doi:10.3390/su9101920.

Corfee-Morlot, J., I. Cochran, S. Hallegatte, and P.J. Teasdale, 2011: Multilevel risk governance and urban adaptation policy. *Climatic Change*, **104(1)**, 169-197.

Corner, A. and A. Randall, 2011: Selling climate change? The limitations of social marketing as a strategy for climate change public engagement. *Global environmental change*, **21(3)**, 1005-1014.

Corner, A. and N. Pidgeon, 2014: Geoengineering, climate change scepticism and the 'moral hazard' argument: an experimental study of UK public perceptions. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **372(2031)**, 20140063-20140063, doi:10.1098/rsta.2014.0063.

Cortekar, J. and M. Groth, 2015: Adapting energy infrastructure to climate change - Is there a need for government interventions and legal obligations within the German "energiewende"? *Energy Procedia*, **73**, 12-17, doi:10.1016/j.egypro.2015.07.552.

Costa, D., P. Burlando, and C. Priadi, 2016: The importance of integrated solutions to flooding and water quality problems in the tropical megacity of Jakarta. *Sustainable Cities and Society*, **20(Supplement C)**, 199-209, doi:10.1016/j.scs.2015.09.009.

Coulibaly, J.Y., B. Chiputwa, T. Nakelse, and G. Kundhlande, 2017: Adoption of agroforestry and the impact on household food security among farmers in Malawi. *Agricultural Systems*, **155**, 52-69, doi:10.1016/j.agsy.2017.03.017.

Cowen, L. and B. Gatersleben, 2017: Testing for the size heuristic in householders' perceptions of energy consumption. *Journal of Environmental Psychology*, **54**, 103-115, doi:10.1016/j.jenvp.2017.10.002.

Cox, K., M. Renouf, A. Dargan, C. Turner, and D. Klein-Marcuschamer, 2014: Environmental life cycle assessment (LCA) of aviation biofuel from microalgae, Pongamia pinnata, and sugarcane molasses. *Biofuels, Bioproducts and Biorefining*, **8(4)**, 579-593, doi:10.1002/bbb.1488.

Craig, R.K. et al., 2017: Balancing stability and flexibility in adaptive governance: an analysis of tools available in U.S. environmental law. *Ecology and Society*, **22(2)**, art3, doi:10.5751/ES-08983-220203.

Crassous, R., J.C. Hourcade, and O. Sassi, 2006: Endogenous Structural Change and Climate Targets. *The Energy Journal*, **27**, 259-276.

Creutzig, F., E. Corbera, S. Bolwig, and C. Hunsberger, 2013: Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment. *Environmental Research Letters*, **8(3)**, 035047, doi:10.1088/1748-9326/8/3/035047.

Creutzig, F., G. Baiocchi, R. Bierkandt, P.–P. Pichler, and K.C. Seto, 2015a: Global typology of urban energy use and potentials for an urbanization mitigation wedge. *Proceedings of the National Academy of Sciences*, **112(20)**, 6283-6288, doi:10.1073/pnas.1315545112.

Creutzig, F. et al., 2015b: Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy*, **7(5)**, 916-944, doi:10.1111/gcbb.12205.

Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy*, **2**, 17140, doi:10.1038/nenergy.2017.140.

Creutzig, F. et al., 2018: Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, **8(4)**, 268-271, doi:10.1038/s41558-018-0121-1.

Croci, E., B. Lucchitta, G. Janssens-Maenhout, S. Martelli, and T. Molteni, 2017: Urban CO2 mitigation strategies under the Covenant of Mayors: An assessment of 124 European cities. *Journal of Cleaner Production*, **169**, 161-177, doi:10.1016/j.jclepro.2017.05.165.

Crook, J.A., L.S. Jackson, and P.M. Forster, 2016: Can increasing albedo of existing ship wakes reduce climate change? *Journal of Geophysical Research: Atmospheres*, **121(4)**, 1549-1558, doi:10.1002/2015JD024201.

Crook, J.A., L.S. Jackson, S.M. Osprey, and P.M. Forster, 2015: A comparison of temperature and precipitation responses to different Earth radiation management geoengineering schemes. *Journal of Geophysical Research: Atmospheres*, **120(18)**, doi:10.1002/2015JD023269.

Cui, Z. et al., 2018: Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, doi:10.1038/nature25785.

Culwick, C. and K. Bobbins, 2016: A Framework for a Green Infrastructure Planning Approach in the Gauteng City-Region. , 132.

Cunningham, S.C. et al., 2015: Balancing the environmental benefits of reforestation in agricultural regions. *Perspectives in Plant Ecology, Evolution and Systematics*, **17(4)**, 301-317, doi:10.1016/j.ppees.2015.06.001.

Cunsolo, A. and N.R. Ellis, 2018: Ecological grief as a mental health response to climate change-related loss. *Nature Climate Change*, **8(4)**, 275-281, doi:10.1038/s41558-018-0092-2.

Cunsolo Willox, A., S.L. Harper, and V.L. Edge, 2013: Storytelling in a digital age: digital storytelling as an emerging narrative method for preserving and promoting indigenous oral wisdom. *Qualitative Research*, **13(2)**, 127-147, doi:10.1177/1468794112446105.

Cunsolo Willox, A. et al., 2012: "From this place and of this place:" Climate change, sense of place, and health in Nunatsiavut, Canada. *Social Science and Medicine*, **75(3)**, 538-547, doi:10.1016/j.socscimed.2012.03.043.

Dʼ Agostino, D., 2015: Assessment of the progress towards the establishment of definitions of Nearly Zero Energy Buildings (nZEBs) in European Member States. *Journal of Building Engineering*, **1**, 20-32, doi:10.1016/j.jobe.2015.01.002.

Daamen, D.D.L., H. Staats, H.A.M. Wilke, and M. Engelen, 2001: Improving Environmental Behavior in Companies. *Environment and Behavior*, **33(2)**, 229-248, doi:10.1177/00139160121972963.

Dagnet, Y. et al., 2016: Staying on Track from Paris: Advancing the Key Elements of the Paris Agreement. World Resources Institute, Washington DC, USA.

D'Agostino, D. and D. Parker, 2018: A framework for the cost-optimal design of nearly zero energy buildings (NZEBs) in representative climates across Europe. *Energy*, **149**, 814-829, doi:10.1016/j.energy.2018.02.020.

Dahlmann, K. et al., 2016: Climate-Compatible Air Transport System-Climate Impact Mitigation Potential for Actual and Future Aircraft. *Aerospace*, **3(4)**, 38, doi:10.3390/aerospace3040038.

Daioglou, V. et al., 2017: Greenhouse gas emission curves for advanced biofuel supply chains. *Nature Climate Change*, **7(12)**, 920-924, doi:10.1038/s41558-017-0006-8.

DaMatta, F.M., A. Grandis, B.C. Arenque, and M.S. Buckeridge, 2010: Impacts of climate changes on crop physiology and food quality. *Food Research International*, **43(7)**, 1814-1823, doi:10.1016/j.foodres.2009.11.001.

Dang, H., E. Li, I. Nuberg, and J. Bruwer, 2014: Understanding farmers' adaptation intention to climate change: A structural equation modelling study in the Mekong Delta, Vietnam. *Environmental Science and Policy*, **41**, 11-22, doi:10.1016/j.envsci.2014.04.002.

Dang Phan, T.–H., R. Brouwer, and M. Davidson, 2014: The economic costs of avoided deforestation in the developing world: A meta-analysis. *Journal of Forest Economics*, **20(1)**, 1-16, doi:10.1016/j.jfe.2013.06.004.

Darela, J.P., D.M. Lapola, R.R. Torres, and M.C. Lemos, 2016: Socio-climatic hotspots in Brazil: how do changes driven by the new set of IPCC climatic projections affect their relevance for policy? *Climatic Change*, **136(3-4)**, 413-425, doi:10.1007/s10584-016-1635-z.

Daron, J.D., K. Sutherland, C. Jack, and B.C. Hewitson, 2015: The role of regional climate projections in managing complex socio-ecological systems. *Regional Environmental Change*, **15(1)**, 1-12, doi:10.1007/s10113-014-0631-y.

David, Z., 2017: Indirect land use change: much ado about (almost) nothing. *GCB Bioenergy*, **9(3)**, 485-488, doi:10.1111/gcbb.12368.

Davidson, D., 2016: Gaps in agricultural climate adaptation research. *Nature Climate Change*, **6(5)**, 433-435, doi:10.1038/nclimate3007.

Davidson, P., C. Burgoyne, H. Hunt, and M. Causier, 2012: Lifting options for stratospheric aerosol geoengineering: advantages of tethered balloon systems. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 4263-4300, doi:10.1098/rsta.2011.0639.

Davin, E.L., S.I. Seneviratne, P. Ciais, A. Olioso, and T. Wang, 2014: Preferential cooling of hot extremes from cropland albedo management. *Proceedings of the National Academy of Sciences of the United States of America*, **111(27)**, 9757-9761, doi:10.1073/pnas.1317323111.

Dawson, J., E.J. Stewart, M.E. Johnston, and C.J. Lemieux, 2016: Identifying and evaluating adaptation strategies for cruise tourism in Arctic Canada. *Journal of Sustainable Tourism*, **24(10)**, 1425-1441, doi:10.1080/09669582.2015.1125358.

de Boer, J., W.J.W. Botzen, and T. Terpstra, 2016a: Flood risk and climate change in the Rotterdam area, The Netherlands: enhancing citizen's climate risk perceptions and prevention responses despite skepticism. *Regional environmental change*, **16(6)**, 1613-1622.

de Boer, J., A. de Witt, and H. Aiking, 2016b: Help the climate, change your diet: A cross-sectional study on how to involve consumers in a transition to a low-carbon society. *Appetite*, **98**, 19-27, doi:10.1016/j.appet.2015.12.001.

de Coninck, H.C. and S.M. Benson, 2014: Carbon Dioxide Capture and Storage: Issues and Prospects. *Annual Review of Environment and Resources*, **39**, 243-70, doi:10.1146/annurev-environ-032112-095222.

de Coninck, H.C. and D. Puig, 2015: Assessing climate change mitigation technology interventions by international institutions. *Climatic Change*, **131(3)**, 417-433, doi:10.1007/s10584-015-1344-z.

de Coninck, H.C. and A. Sagar, 2017: Technology Development and Transfer (Article 10). In: *The Paris Agreement on Climate Change* [Klein, D., M.P. Carazo, M. Doelle, J. Bulmer, and A. Higham (eds.)]. Oxford University Press, Oxford, U.K. pp. 258-276.

de Freitas, L.C. and S. Kaneko, 2011: Ethanol demand under the flex-fuel technology regime in Brazil. *Energy Economics*, **33(6)**, 1146-1154, doi:https://doi.org/10.1016/j.eneco.2011.03.011.

De Gouvello, C. and I. Zelenko, 2010: *Scaling up the Financing of Emissions Reduction Projects for Low Carbon Development in Developing Countries. Proposal for a Low-carbon Development Facility*. World Bank Paper No. 203, World Bank, Washington DC, USA.

de Haan, P., M.G. Mueller, and R.W. Scholz, 2009: How much do incentives affect car purchase? Agent-based microsimulation of consumer choice of new cars - Part II: Forecasting effects of feebates based on energy-efficiency. *Energy Policy*, **37(3)**, 1083-1094, doi:10.1016/j.enpol.2008.11.003.

de Jong, S. et al., 2017: Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnology for Biofuels*, **10(1)**, 64, doi:10.1186/s13068-017-0739-7.

de Souza, A.P., A. Grandis, D.C.C. Leite, and M.S. Buckeridge, 2014: Sugarcane as a Bioenergy Source: History, Performance, and Perspectives for Second-Generation Bioethanol. *Bioenergy Research*, **7(1)**, 24-35, doi:10.1007/s12155-013-9366-8.

De Souza, A.P., B.C. Arenque, E.Q.P. Tavares, and M.S. Buckeridge, 2016: Transcriptomics and Genetics Associated with Plant Responses to Elevated CO2 Atmospheric Concentrations. In: *Plant Genomics and Climate Change* [Edwards, D. and J. Batley (eds.)]. Springer New York, New York, NY, USA, pp. 67-83.

De Souza, A.P., J.–C. Cocuron, A.C. Garcia, A.P. Alonso, and M.S. Buckeridge, 2015: Changes in Whole-Plant Metabolism during the Grain-Filling Stage in Sorghum Grown under Elevated CO2 and Drought.. *Plant physiology*, **169(3)**, 1755-65, doi:10.1104/pp.15.01054.

De Stefano, A. and M.G. Jacobson, 2018: Soil carbon sequestration in agroforestry systems: a meta-analysis. *Agroforestry Systems*, **92(2)**, 285-299, doi:10.1007/s10457-017-0147-9.

de Wit, M. and A. Faaij, 2010: European biomass resource potential and costs. *Biomass and Bioenergy*, **34(2)**, 188-202, doi:10.1016/J.BIOMBIOE.2009.07.011.

Deaton, A., 2013: *The Great Escape Health, Wealth, and the Origins of Inequality*. Princeton University Press, Princeton, NJ, USA.

Déau, T. and J. Touati, 2017: Financing Sustainable Infrastructure. In: *Coping with the Climate Crisis Mitigation Policies and Global Coordination* []. pp. 167-178.

DeBeer, C.M., H.S. Wheater, S.K. Carey, and K.P. Chun, 2016: Recent climatic, cryospheric, and hydrological changes over the interior of western Canada: A review and synthesis. *Hydrology and Earth System Sciences*, **20(4)**, 1573-1598, doi:10.5194/hess-20-1573-2016.

Decanio, S.J., 1993: Barriers within firms to energy- efficient investments. *Energy Policy*, **21(9)**, 906-914.

DeCicco, J.M. et al., 2016: Carbon balance effects of U.S. biofuel production and use. *Climatic Change*, **138(3-4)**, 667-680, doi:10.1007/s10584-016-1764-4.

del Ninno, C., S. Coll-Black, and P. Fallavier, 2016: Social Protection: Building Resilience Among the Poor and Protecting the Most Vulnerable. *Confronting Drought in Africa's Drylands: Opportunities for Enhancing Resilience*, 165-184, doi:doi:10.1596/978-1-4648-0817-3_ch10.

Delmas, M.A., M. Fischlein, and O.I. Asensio, 2013: Information strategies and energy conservation behavior: A meta-analysis of experimental studies from 1975 to 2012. *Energy Policy*, **61**, 729-739, doi:10.1016/j.enpol.2013.05.109.

Demailly, D. and P. Quirion, 2008: European Emission Trading Scheme and competitiveness: A case study on the iron and steel industry. *Energy Economics*, **30(4)**, 2009-2027, doi:10.1016/j.eneco.2007.01.020.

Demski, C., C. Butler, K.A. Parkhill, A. Spence, and N.F. Pidgeon, 2015: Public values for energy system change. *Global Environmental Change*, **34**, 59-69, doi:10.1016/j.gloenvcha.2015.06.014.

Demski, C., S. Capstick, N. Pidgeon, N. Frank, and A. Spence, 2017: Experience of extreme weather affects climate change mitigation and adaptation responses. *Climatic Change*, **140(2)**, 149-1164, doi:10.1007/s10584-016-1837-4.

Demuzere, M. et al., 2014: Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, **146**, 107-115, doi:10.1016/j.jenvman.2014.07.025.

den Elzen, M. et al., 2016: Contribution of the G20 economies to the global impact of the Paris agreement climate proposals. *Climatic Change*, **137(3-4)**, 655-665, doi:10.1007/s10584-016-1700-7.

Deng, X. and C. Zhao, 2015: Identification of Water Scarcity and Providing Solutions for Adapting to Climate Changes in the Heihe River Basin of China. *Advances in Meteorology*, **2015**, 1-13, doi:10.1155/2015/279173.

Deo, R.C., 2011: On meteorological droughts in tropical Pacific Islands: Time-series analysis of observed rainfall using Fiji as a case study. *Meteorological Applications*, **18(2)**, 171-180, doi:10.1002/met.216.

Devereux, S., 2016: Social protection for enhanced food security in sub-Saharan Africa. *Food Policy*, **60**, 52-62, doi:10.1016/j.foodpol.2015.03.009.

Devine-Wright, P., 2009: Rethinking NIMBYism: The role of place attachment and place identity in explaining place-protective action. *Journal of Community & Applied Social Psychology*, **19(6)**, 426-441, doi:10.1002/casp.1004.

Devine-Wright, P., 2013: Think global, act local? The relevance of place attachments and place identities in a climate changed world. *Global Environmental Change*, **23(1)**, 61-69, doi:10.1016/j.gloenvcha.2012.08.003.

Devine-wright, P. and Y. Howes, 2010: Disruption to place attachment and the protection of restorative environments: A wind energy case study. *Journal of Environmental Psychology*, **30(3)**, 271-280, doi:10.1016/j.jenvp.2010.01.008.

Dhar, S., M. Pathak, and P.R. Shukla, 2017: Electric vehicles and India's low carbon passenger transport: a long-term co-benefits assessment. *Journal of Cleaner Production*, **146(Supplement C)**, 139-148, doi:10.1016/j.jclepro.2016.05.111.

Dhar, T.K. and L. Khirfan, 2017: Climate change adaptation in the urban planning and design research: missing links and research agenda. *Journal of Environmental Planning and Management*, **60(4)**, 602-627, doi:10.1080/09640568.2016.1178107.

Diekmann, A. and P. Preisendörfer, 2003: Rationality and Society. *Rational*, **15**, 441-472, doi:10.1177/1043463103154002.

Dietz, T., 2013: Bringing values and deliberation to science communication. *Proceeding of the National Academy of Sciences of the United States of America (PNAS)*, **110**, 14081-14087, doi:10.1073/pnas.1212740110.

Dietz, T., A. Dan, and R. Shwom, 2007: Support for Climate Change Policy: Social Psychological and Social Structural Influences. *Rural Sociology*, **72(2)**, 185-214.

Dietz, T., P.C. Stern, and E.U. Weber, 2013: Reducing Carbon-Based Energy Consumption through Changes in Household Behavior. *Daedalus*, **142(1)**, 78-89, doi:10.1162/DAED_a_00186.

Dietz, T., G.T. Gardner, J. Gilligan, P.C. Stern, and M.P. Vandenbergh, 2009: Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. *Proceedings of the National Academy of Sciences*, **106(44)**, 18452-18456, doi:10.1073/pnas.0908738106.

Dietz, T., K.A. Frank, C.T. Whitley, J. Kelly, and R. Kelly, 2015: Political influences on greenhouse gas emissions from US states. *Proceeding of the National Academy of Sciences of the United States of America (PNAS)*,

112(27), 8254-8259, doi:10.1073/pnas.1417806112.

Dilling, L. and R. Hauser, 2013: Governing geoengineering research: Why, when and how? *Climatic Change*, **121(3)**, 553-565, doi:10.1007/s10584-013-0835-z.

Ding, D., E.W. Maibach, X. Zhao, C. Roser-Renouf, and A. Leiserowitz, 2011: Support for climate policy and societal action are linked to perceptions about scientific agreement. *Nature Climate Change*, **1(9)**, 462-466, doi:10.1038/nclimate1295.

Dinner, I., E.J. Johnson, D.G. Goldstein, and K. Liu, 2011: Partitioning default effects: Why people choose not to choose. *Journal of Experimental Psychology: Applied*, **17(4)**, 432-432, doi:10.1037/a0026470.

Dircke, P. and A. Molenaar, 2015: Climate change adaptation; innovative tools and strategies in Delta City Rotterdam. *Water Practice and Technology*, **10(4)**, 674-680.

Dobson, S., 2017: Community-driven pathways for implementation of global urban resilience goals in Africa. *International Journal of Disaster Risk Reduction*, **26**, 78-84, doi:10.1016/j.ijdrr.2017.09.028.

Dóci, G. and E. Vasileiadou, 2015: "Let's do it ourselves" Individual motivations for investing in renewables at community level. *Renewable and Sustainable Energy Reviews*, **49**, 41-50, doi:10.1016/j.rser.2015.04.051.

Dodman, D., 2009: Blaming cities for climate change? An analysis of urban greenhouse gas emissions inventories. *Environment and Urbanization*, **21(1)**, 185-201, doi:10.1177/0956247809103016.

Dodman, D., S. Colenbrander, and D. Archer, 2017a: Conclusion. In: *Responding to climate change in Asian cities: Governance for a more resilient urban future* [Archer, D., S. Colenbrander, and D. Dodman (eds.)]. Routledge Earthscan, Abingdon, UK.

Dodman, D., H. Leck, M. Rusca, and S. Colenbrander, 2017b: African Urbanisation and Urbanism: Implications for risk accumulation and reduction. *International Journal of Disaster Risk Reduction*, **26(June)**, 7-15, doi:10.1016/j.ijdrr.2017.06.029.

Dogan, E., J.W. Bolderdijk, and L. Steg, 2014: Making Small Numbers Count: Environmental and Financial Feedback in Promoting Eco-driving Behaviours. *Journal of Consumer Policy*, **37(3)**, 413-422, doi:10.1007/s10603-014-9259-z.

Donner, S.D., M. Kandlikar, and S. Webber, 2016: Measuring and tracking the flow of climate change adaptation aid to the developing world. *Environmental Research Letters*, **11(5)**, 054006, doi:10.1088/1748-9326/11/5/054006.

Dooley, K., 2017: Routines, Rigidity and Real Estate: Organisational Innovations in the Workplace. *Sustainability*, **9(6)**, 998, doi:10.3390/su9060998.

Dorsch, M.J. and C. Flachsland, 2017: A Polycentric Approach to Global Climate Governance. *Global Environmental Politics*, **17(2)**, 45-64, doi:10.1162/GLEP_a_00400.

Dorward, P., G. Clarkson, and R. Stern, 2015: *Participatory integrated climate services for agriculture (PICSA): Field manual*. 65 pp.

Dougill, A.J. et al., 2017: Mainstreaming conservation agriculture in Malawi: Knowledge gaps and institutional barriers. *Journal of Environmental Management*, **195**, 25-34, doi:10.1016/j.jenvman.2016.09.076.

Douglas, I., 2017: Flooding in African cities, scales of causes, teleconnections, risks, vulnerability and impacts. *International Journal of Disaster Risk Reduction*, **26**, 34-42, doi:10.1016/j.ijdrr.2017.09.024.

Dowd, A.–M. et al., 2014: The role of networks in transforming Australian agriculture. *Nature Climate Change*, **4(7)**, 558-563, doi:10.1038/nclimate2275.

Doyle, J., 2011: Acclimatizing nuclear? Climate change, nuclear power and the reframing of risk in the UK news media. *International Communication Gazette*, **73(1-2)**, 107-125.

Drews, S. and J.C.J.M. Van den Bergh, 2016: What explains public support for climate policies ? A review of empirical and experimental studies review of empirical and experimental studies. *Climate Policy*, **16(7)**, 855-876, doi:10.1080/14693062.2015.1058240.

Dréze, J. and N. Stern, 1990: Policy Reform, Shadow Prices, and Market Prices. *Journal of Public Economics*, **42**, 1-45.

Droste, N. et al., 2016: Steering innovations towards a green economy: Understanding government intervention. *Journal of Cleaner Production*, **135**, 426-434, doi:10.1016/j.jclepro.2016.06.123.

Dubois, U., 2012: From targeting to implementation: The role of identification of fuel poor households. *Energy Policy*, **49**, 107-115, doi:https://doi.org/10.1016/j.enpol.2011.11.087.

Dunlap, R.E. and A.M. McCright, 2011: Organized climate change denial. In: *The Oxford handbook of climate change and society* []. pp. 144-160.

Durand, A. et al., 2016: *Financing Options for Loss and Damage: a Review and Roadmap*. Deutsches Institut für Entwicklungspolitik gGmbH.

Eakin, H. et al., 2015: Information and communication technologies and climate change adaptation in Latin America and the Caribbean: a framework for action. *Climate and Development*, **7(3)**, 208-222, doi:10.1080/17565529.2014.951021.

Eakin, H. et al., 2016: Cognitive and institutional influences on farmers' adaptive capacity: insights into barriers and opportunities for transformative change in central Arizona. *Regional Environmental Change*, **16(3)**, 801-814, doi:10.1007/s10113-015-0789-y.

Eakin, H.C.C., M.C.C. Lemos, and D.R.R. Nelson, 2014: Differentiating capacities as a means to sustainable climate change adaptation. *Global Environmental Change*, **27(1)**, 1-8, doi:10.1016/j.gloenvcha.2014.04.013.

Eastham, S.D., D.W. Keith, and S.R.H. Barrett, 2018: Mortality tradeoff between air quality and skin cancer from changes in stratospheric ozone. *Environmental Research Letters*, **13(3)**, 34035, doi:10.1088/1748-9326/aaad2e.

Ebeling, F. and S. Lotz, 2015: Domestic uptake of green energy promoted by opt-out tariffs. *Nature Cliimate Change*, **5(June)**, 868-871, doi:10.1038/NCLIMATE2681.

Eberhard, A., O. Rosnes, M. Shkaratan, and H. Vennemo, 2011: *Africa's Power Infrastructure: Investment, Integration, Efficiency*. 352 pp.

Eberhard, A., K. Gratwick, E. Morella, and P. Antmann, 2016: *Independent Power Projects in Sub-Saharan Africa: Lessons from Five Key Countries*. The World Bank, Washington, DC, 382 pp.

Eberhard, A., K. Gratwick, E. Morella, and P. Antmann, 2017: Accelerating investments in power in sub-Saharan Africa. *Nature Energy*, **2(2)**, 17005, doi:10.1038/nenergy.2017.5.

Ecker, F., 2017: Promoting Decentralized Sustainable Energy Systems in Different Supply Scenarios: The Role of Autarky Aspiration Promoting Decentralized sustainable energy systems in Different supply scenarios : The role of autarky aspiration. *Frontiers in Energy Research*, **5**, 14, doi:10.3389/fenrg.2017.00014.

Edenhofer, O. et al., 2015: Closing the emission price gap. *Global Environmental Change*, **31**, 132-143, doi:10.1016/j.gloenvcha.2015.01.003.

Edler, J. and J. Fagerberg, 2017: Innovation policy: what, why, and how. *Oxford Review of Economic Policy*, **33(1)**, 2-23, doi:10.1093/oxrep/grx001.

EEA, 2017: *Aviation and shipping - impacts on Europe's environment: TERM 2017: Transport and Environment Reporting Mechanism (TERM) report*. European Environment Agency (EEA), Copenhagen, 70 pp.

Eisenack, K. and R. Stecker, 2012: A framework for analyzing climate change adaptations as actions. *Mitigation and Adaptation Strategies for Global Change*, **17(3)**, 243-260, doi:10.1007/s11027-011-9323-9.

Eisenberg, D.A., 2016: Transforming building regulatory systems to address climate change. *Building Research & Information*, **44(5-6)**, 468-473, doi:10.1080/09613218.2016.1126943.

Ek, K. and P. Söderholm, 2008: Households' switching behavior between electricity suppliers in Sweden. *Utilities Policy*, **16(4)**, 254-261, doi:10.1016/j.jup.2008.04.005.

Ek, K. and P. Söderholm, 2010: The devil is in the details: Household electricity saving behavior and the role of information. *Energy Policy*, **38(3)**, 1578-1587, doi:10.1016/j.enpol.2009.11.041.

Ekblom, A., L. Gillson, and M. Notelid, 2017: Water flow, ecological dynamics, and management in the lower Limpopo Valley: a long-term view. *Wiley Interdisciplinary Reviews: Water*, **4(5)**, e1228, doi:10.1002/wat2.1228.

El Gafy, I., N. Grigg, and W. Reagan, 2017: Dynamic Behaviour of the Water-Food-Energy Nexus: Focus on Crop Production and Consumption. *Irrigation and Drainage*, **66(1)**, 19-33, doi:10.1002/ird.2060.

Elia, E.F., S. Mutula, and C. Stilwell, 2014: Indigenous Knowledge use in seasonal weather forecasting in Tanzania : the case of semi-arid central Tanzania. *South African Journal of Libraries and Information Science*, **80(1)**, 18-27, doi:10.7553/80-1-180.

Eliasson, J., 2014: The role of attitude structures, direct experience and reframing for the success of congestion pricing. *Transportation Research Part A: Policy and Practice*, **67**, 81-95, doi:10.1016/j.tra.2014.06.007.

Eliseev, A., 2012: Climate change mitigation via sulfate injection to the stratosphere: impact on the global carbon cycle and terrestrial biosphere. *Atmospheric and Oceanic Optics*, **25(6)**, 405-413, doi:10.1134/S1024856012060024.

Elliott, J. et al., 2014: Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences*, **111(9)**, 3239-3244, doi:10.1073/pnas.1222474110.

Ellison, D. et al., 2017: Trees, forests and water: Cool insights for a hot world. *Global Environmental Change*, **43**, 51-61, doi:10.1016/j.gloenvcha.2017.01.002.

Elmqvist, T. et al., 2013: *The world's first global assessment of the effects of urbanization on biodiversity and ecosystem services*.

Elmqvist, T. et al., 2015: Benefits of restoring ecosystem services in urban areas. *Current Opinion in Environmental Sustainability*, **14(Supplement C)**, 101-108, doi:10.1016/j.cosust.2015.05.001.

Elshout, P.M.F., R. van Zelm, R. Karuppiah, I.J. Laurenzi, and M.A.J. Huijbregts, 2014: A spatially explicit data-driven approach to assess the effect of agricultural land occupation on species groups. *The International Journal of Life Cycle Assessment*, **19(4)**, 758-769, doi:10.1007/s11367-014-0701-x.

Emin, G., M. Lepetit, A. Grandjean, and O. Ortega, 2014: *Massive financing of the energy transition (SFTE feasibility study: synthesis report Energy renovation of public buildings)*.

Emmer, A., J. Klimeš, M. Mergili, V. Vilímek, and A. Cochachin, 2016: 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods. *CATENA*, **147(Supplement C)**, 269-279, doi:https://doi.org/10.1016/j.catena.2016.07.032.

Ensor, J. and B. Harvey, 2015: Social learning and climate change adaptation: evidence for international development practice. *Wiley Interdisciplinary Reviews: Climate Change*, **6(5)**, 509-522, doi:10.1002/wcc.348.

Erb, K.–H. et al., 2009: Eating the Planet: Feeding and fuelling the world sustainably, fairly and humanely - a scoping study. , 1-132.

Erb, K.–H. et al., 2016a: Exploring the biophysical option space for feeding the world without deforestation. *Nature Communications*, **7**, 11382, doi:10.1038/NCOMMS11382.

Erb, K.–H. et al., 2016b: Land management: data availability and process understanding for global change studies. *Global Change Biology*, **23(2)**, 512-533, doi:10.1111/gcb.13443.

Erb, K.–H. et al., 2017: Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature*, **553(7686)**, 73-76, doi:10.1038/nature25138.

Eric Bickel, J., 2013: Climate engineering and climate tipping-point scenarios. *Environment Systems & Decisions*, **33(1)**, 152-167, doi:10.1007/s10669-013-9435-8.

Ericsson, K. and S. Werner, 2016: The introduction and expansion of biomass use in Swedish district heating systems. *Biomass and Bioenergy*, **94**, 57-65, doi:10.1016/J.BIOMBIOE.2016.08.011.

Eriksson, L., J. Garvill, and A.M. Nordlund, 2006: Acceptability of travel demand management measures : The importance of problem awareness, personal norm, freedom, and fairness. *Journal of Environmental Psychology*, **26**, 15-26, doi:10.1016/j.jenvp.2006.05.003.

Eriksson, L., J. Garvill, and A.M. Nordlund, 2008: Acceptability of single and combined transport policy measures: The importance of environmental and policy specific beliefs. *Transportation Research Part A: Policy and Practice*, **42(8)**, 1117-1128, doi:10.1016/j.tra.2008.03.006.

Erker, S., R. Stangl, and G. Stoeglehner, 2017: Resilience in the light of energy crises - Part II: Application of the regional energy resilience assessment. *Journal of Cleaner Production*, **164**, doi:10.1016/j.jclepro.2017.06.162.

Erlinghagen, S. and J. Markard, 2012: Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change. *Energy Policy*, **51**, 895-906, doi:10.1016/J.ENPOL.2012.09.045.

Esham, M. and C. Garforth, 2013: Agricultural adaptation to climate change: insights from a farming community in Sri Lanka. *Mitigation and Adaptation Strategies for Global Change*, **18(5)**, 535-549, doi:10.1007/s11027-012-9374-6.

ESRB ASC, 2016: *Too late, too sudden: Transition to a low-carbon economy and systemic risk*. ESRB ASC Report No 6, 22 pp.

Evans, J., J. O'Brien, and B. Ch Ng, 2018: Towards a geography of informal transport: Mobility, infrastructure and urban sustainability from the back of a motorbike. *Transactions of the Institute of British Geographers*, doi:10.1111/tran.12239.

Evans, L. et al., 2012: Self-interest and pro-environmental behaviour. *Nature Climate Change*, **3(2)**, 122-125, doi:10.1038/nclimate1662.

Evans, M., V. Roshchanka, and P. Graham, 2017: An international survey of building energy codes and their implementation. *Journal of Cleaner Production*, **158**, 382-389, doi:10.1016/j.jclepro.2017.01.007.

Ewing, R., S. Hamidi, and J.B. Grace, 2016: Compact development and VMT-Environmental determinism, self-selection, or some of both? *Environment and Planning B: Planning and Design*, **43(4)**, 737-755, doi:10.1177/0265813515594811.

Exner, A. et al., 2016: Measuring regional resilience towards fossil fuel supply constraints. Adaptability and vulnerability in socio-ecological Transformations-the case of Austria. *Energy Policy*, **91**, 128-137, doi:10.1016/j.enpol.2015.12.031.

Eyre, N., S.J. Darby, P. Grünewald, E. McKenna, and R. Ford, 2018: Reaching a 1.5°C target: socio-technical challenges for a rapid transition to low-carbon electricity systems. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160462, doi:10.1098/rsta.2016.0462.

Ezeji, T., 2017: Production of Bio-Derived Fuels and Chemicals. *Fermentation*, **3(3)**, 42, doi:10.3390/fermentation3030042.

Fader, M., S. Shi, W. von Bloh, A. Bondeau, and W. Cramer, 2016: Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. *Hydrology and Earth System Sciences*, **20(2)**, 953-973, doi:10.5194/hess-20-953-2016.

Faehn, T. and E.T. Isaksen, 2016: Diffusion of Climate Technologies in the Presence of Commitment Problems. *The Energy Journal*, **37(2)**, 155-180, doi:10.5547/01956574.37.2.tfae.

Fainstein, S.S., 2018: Resilience and justice: planning for New York City. *Urban Geography*, 1-8, doi:10.1080/02723638.2018.1448571.

Fajardy, M. and N. Mac Dowell, 2017: Can BECCS deliver sustainable and resource efficient negative emissions? *Energy & Environmental Science*, **10(6)**, 1389-1426, doi:10.1039/C7EE00465F.

Falkner, R., 2016: The Paris Agreement and the new logic of international climate politics. *International Affairs*, **92(5)**, 1107-1125.

Faludi, J., C. Bayley, S. Bhogal, and M. Iribarne, 2015: Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. *Rapid Prototyping Journal*, **21(1)**, 14-33, doi:10.1108/RPJ-07-2013-0067.

Fang, Y., B. Singh, B.P. Singh, and E. Krull, 2014: Biochar carbon stability in four contrasting soils. *European Journal of Soil Science***, 65(1)**, 60-71, doi:10.1111/ejss.12094.

Fankhauser, S. and G. Schmidt-Traub, 2011: From adaptation to climate-resilient development: The costs of climate-proofing the Millennium Development Goals in Africa. *Climate and Development***, 3(2)**, 94-113, doi:10.1080/17565529.2011.582267.

Fankhauser, S. and T.K.J. McDermott, 2014: Understanding the adaptation deficit: Why are poor countries more vulnerable to climate events than rich countries? *Global Environmental Change***, 27(1)**, 9-18, doi:10.1016/j.gloenvcha.2014.04.014.

FAO, 2013: Food wastage footprint. Impacts on natural resources. Summary Report. *Food wastage footprint Impacts on natural resources*, 63.

FAO & NZAGRC, 2017a: *Low emissions development of the beef cattle sector in Uruguay - reducing enteric methane for food security and livelihoods*. 34 pp.

FAO & NZAGRC, 2017b: *Options for low emission development in the Kenya dairy sector - reducing enteric methane for food security and livelihoods*. 43 pp.

FAO & NZAGRC, 2017c: *Supporting low emissions development in the Ethiopian dairy cattle sector - reducing enteric methane for food security and livelihoods*. 34 pp.

Farfan, J. and C. Breyer, 2017: Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator. *Journal of Cleaner Production***, 141**, 370-384, doi:10.1016/j.jclepro.2016.09.068.

Farrow, K., G. Grolleau, and L. Ibanez, 2017: Social Norms and Pro-environmental Behavior: A Review of the Evidence. *Ecological Economics***, 140**, 1-13, doi:10.1016/j.ecolecon.2017.04.017.

Fasihi, M., D. Bogdanov, and C. Breyer, 2017: Long-Term Hydrocarbon Trade Options for the Maghreb Region and Europe-Renewable Energy Based Synthetic Fuels for a Net Zero Emissions World. *Sustainability***, 9(2)**, doi:10.3390/su9020306.

Favretto, N., L.C. Stringer, M.S. Buckeridge, and S. Afionis, 2017: Policy and Diplomacy in the Production of Second Generation Ethanol in Brazil: International Relations with the EU, the USA and Africa BT - Advances of Basic Science for Second Generation Bioethanol from Sugarcane. *Advances of Basic Science for Second Generation from Sugarcane*, 197-212, doi:10.1007/978-3-319-49826-3_11.

Fawcett, T., F. Hvelplund, and N.I. Meyer, 2010: Making It Personal: Per Capita Carbon Allowances. In: *Generating Electricity in a Carbon-Constrained World* [Sioshansi, F.P. (ed.)]. Academic Press, Boston, MA, USA, pp. 87-107.

Fazey, I. et al., 2017: Transformation in a changing climate: a research agenda. *Climate and Development*, 1-21, doi:10.1080/17565529.2017.1301864.

Fazey, I. et al., 2018: Energy Research & Social Science Ten essentials for action-oriented and second order energy transitions, transformations and climate change research. *Energy Research & Social Science***, 40(April 2017)**, 54-70, doi:10.1016/j.erss.2017.11.026.

Fell, H., D. Burtraw, R.D. Morgenstern, and K.L. Palmer, 2012: Soft and hard price collars in a cap-and-trade system: A comparative analysis. *Journal of Environmental Economics and Management***, 64(2)**, 183-198, doi:10.1016/j.jeem.2011.11.004.

Feng, E.Y., D.P. Keller, W. Koeve, and A. Oschlies, 2016: Could artificial ocean alkalinization protect tropical coral ecosystems from ocean acidification? *Environmental Research Letters***, 11(7)**, 074008, doi:10.1088/1748-9326/11/7/074008.

Feola, G., A.M. Lerner, M. Jain, M.J.F. Montefrio, and K. Nicholas, 2015: Researching farmer behaviour in climate change adaptation and sustainable agriculture: Lessons learned from five case studies. *Journal of Rural Studies***, 39**, 74-84, doi:10.1016/j.jrurstud.2015.03.009.

Fernández-Giménez, M.E., B. Batkhishig, B. Batbuyan, and T. Ulambayar, 2015: Lessons from the Dzud: Community-Based Rangeland Management Increases the Adaptive Capacity of Mongolian Herders to Winter Disasters. *World Development***, 68**, 48-65, doi:10.1016/j.worlddev.2014.11.015.

Ferrario, F. et al., 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications***, 5(May)**, 1-9, doi:10.1038/ncomms4794.

Few, R., D. Morchain, D. Spear, A. Mensah, and R. Bendapudi, 2017: Transformation, adaptation and development: relating concepts to practice. *Palgrave Communications***, 3**, 17092, doi:10.1057/palcomms.2017.92.

Fielding, K.S. and M.J. Hornsey, 2016: A Social Identity Analysis of Climate Change and Environmental Attitudes and Behaviors: Insights and Opportunities. *Frontiers in Psychology***, 7(FEB)**, 1-12, doi:10.3389/fpsyg.2016.00121.

Fielding, K.S., R. Mcdonald, and W.R. Louis, 2008: Theory of planned behaviour, identity and intentions to engage in environmental activism. *Journal of Environmental Psychology***, 28**, 318-326, doi:10.1016/j.jenvp.2008.03.003.

Figueres, C. et al., 2017: Three years to safeguard our climate. *Nature***, 546(7660)**, 593-595.

Fink, J.H., 2013: Geoengineering cities to stabilise climate. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability***, 166(5)**, 242-248, doi:10.1680/ensu.13.00002.

Finlayson, C., 2012: Forty years of wetland conservation and wise use. *Aquatic Conservation: Marine and Freshwater*

*Ecosystems***, 22(2)**, 139-143, doi:10.1002/aqc.2233.

Finlayson, C.M. et al., 2017: Policy considerations for managing wetlands under a changing climate. *Marine and Freshwater Research***, 68(10)**, 1803-1815, doi:10.1071/MF16244.

Finley, R.J., 2014: An overview of the Illinois Basin - Decatur Project. *Greenhouse Gases: Science and Technology***, 4(5)**, 571-579, doi:10.1002/ghg.1433.

Finon, D., 2013: Towards a global governance of nuclear safety: an impossible quest ? *Revue de l'Energie***, 616**, 440-450.

Finon, D. and F.A. Roques, 2013: European Electricity Market Reforms: The "Visible Hand" of Public Coordination. *Economics of Energy & Environmental Policy*.

Fischer, C., M. Greaker, and K.E. Rosendahl, 2017: Robust technology policy against emission leakage: The case of upstream subsidies. *Journal of Environmental Economics and Management***, 84**, 44-61, doi:10.1016/j.jeem.2017.02.001.

Fishman, E., S. Washington, and N. Haworth, 2015: Bikeshare's impact on active travel: Evidence from the United States, Great Britain, and Australia. *Journal of Transport & Health***, 2(2)**, 135-142, doi:10.1016/j.jth.2015.03.004.

Fishman, R., N. Devineni, and S. Raman, 2015: Can improved agricultural water use efficiency save India's groundwater? *Environmental Research Letters***, 10(8)**, 84022.

Fleming, A., S.E. Park, and N.A. Marshall, 2015a: Enhancing adaptation outcomes for transformation: climate change in the Australian wine industry. *Journal of Wine Research***, 26(2)**, 99-114, doi:10.1080/09571264.2015.1031883.

Fleming, A., A.M. Dowd, E. Gaillard, S. Park, and M. Howden, 2015b: "Climate change is the least of my worries": Stress limitations on adaptive capacity. *Rural Society***, 24(1)**, 24-41, doi:10.1080/10371656.2014.1001481.

Fleurbaey, M. and P.J. Hammond, 2004: Interpersonally Comparable Utility. In: *Handbook of Utility Theory: Volume 2 Extensions* [Barbera, S., P.J. Hammond, and C. Seidl (eds.)]. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 1179-1285.

Fleurbaey, M. et al., 2014: Sustainable Development and Equity. In: *Climate Change 2014: Mitigation of Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 283-350.

Flynn, M., J. Ford, T. Pearce, S. Harper, and IHACC Research Team, 2018: Participatory scenario planning and climate change impacts, adaptation, and vulnerability research in the Arctic. *Environmental Science & Policy***, 79**, 45-53.

Foley, J.A. et al., 2011: Solutions for a cultivated planet. *Nature*, doi:10.1038/nature10452.

Forbes, B.C. et al., 2009: High resilience in the Yamal-Nenets social-ecological system, West Siberian Arctic, Russia. *Proceedings of the National Academy of Sciences***, 106(52)**, 22041-22048, doi:10.1073/pnas.0908286106.

Forbis Jr, R. and K. Hayhoe, 2018: Does Arctic governance hold the key to achieving climate policy targets? *Environmental Research Letters***, 13(2)**, 20201.

Ford, J.D., 2012: Indigenous health and climate change. *American Journal of Public Health***, 102(7)**, 1260-1266, doi:10.2105/AJPH.2012.300752.

Ford, J.D. and D. King, 2015: Coverage and framing of climate change adaptation in the media: A review of influential North American newspapers during 1993-2013. *Environmental Science and Policy***, 48**, 137-146, doi:10.1016/j.envsci.2014.12.003.

Ford, J.D. and L. Berrang-Ford, 2016: The 4Cs of adaptation tracking: consistency, comparability, comprehensiveness, coherency. *Mitigation and Adaptation Strategies for Global Change***, 21(6)**, 839-859, doi:10.1007/s11027-014-9627-7.

Ford, J.D., G. McDowell, and J. Jones, 2014a: The state of climate change adaptation in the Arctic. *Environmental Research Letters***, 9(10)**, 104005, doi:10.1088/1748-9326/9/10/104005.

Ford, J.D., G. McDowell, and T. Pearce, 2015a: The adaptation challenge in the Arctic. *Nature Climate Change***, 5(12)**, 1046-1053, doi:10.1038/nclimate2723.

Ford, J.D. et al., 2014b: Adapting to the effects of climate change on inuit health. *American Journal of Public Health***, 104(SUPPL. 3)**, e9-e17, doi:10.2105/AJPH.2013.301724.

Ford, J.D. et al., 2015b: Adaptation tracking for a post-2015 climate agreement. *Nature Climate Change***, 5(11)**, 967-969, doi:10.1038/nclimate2744.

Ford, J.D. et al., 2015c: Evaluating climate change vulnerability assessments: a case study of research focusing on the built environment in northern Canada. *Mitigation and Adaptation Strategies for Global Change***, 20(8)**, 1267-1288, doi:10.1007/s11027-014-9543-x.

Ford, J.D. et al., 2016: Community-based adaptation research in the Canadian Arctic. *Wiley Interdisciplinary Reviews: Climate Change***, 7(2)**, 175-191, doi:10.1002/wcc.376.

Ford, J.D. et al., 2018: Preparing for the health impacts of climate change in Indigenous communities: The role of community-based adaptation. *Global Environmental Change*, **49**, 129-139.

Forman, C., I.K. Muritala, R. Pardemann, and B. Meyer, 2016: Estimating the global waste heat potential. *Renewable and Sustainable Energy Reviews*, **57(Supplement C)**, 1568-1579, doi:https://doi.org/10.1016/j.rser.2015.12.192.

Fornell, R., T. Berntsson, and A. Åsblad, 2013: Techno-economic analysis of a kraft pulp-mill-based biorefinery producing both ethanol and dimethyl ether. *Energy*, **50(1)**, 83-92, doi:10.1016/j.energy.2012.11.041.

Forsell, N. et al., 2016: Assessing the INDCs' land use, land use change, and forest emission projections. *Carbon Balance and Management*, **11(1)**, 26, doi:10.1186/s13021-016-0068-3.

Forster, J., I.R. Lake, A.R. Watkinson, and J.A. Gill, 2011: Marine biodiversity in the Caribbean UK overseas territories: Perceived threats and constraints to environmental management. *Marine Policy*, **35(5)**, 647-657, doi:10.1016/j.marpol.2011.02.005.

Fouquet, R., 2016: Lessons from energy history for climate policy: Technological change, demand and economic development. *Energy Research & Social Science*, **22**, 79-93, doi:10.1016/j.erss.2016.09.001.

Francesch-Huidobro, M., M. Dabrowski, Y. Tai, F. Chan, and D. Stead, 2017: Governance challenges of flood-prone delta cities: Integrating flood risk management and climate change in spatial planning. *Progress in Planning*, **114**, 1-27, doi:10.1016/j.progress.2015.11.001.

Francis, R. and B. Bekera, 2014: A metric and frameworks for resilience analysis of engineered and infrastructure systems. *Reliability Engineering & System Safety*, **121**, 90-103, doi:10.1016/j.ress.2013.07.004.

Frank, S. et al., 2013: How effective are the sustainability criteria accompanying the European Union 2020 biofuel targets? *GCB Bioenergy*, **5(3)**, 306-314, doi:10.1111/j.1757-1707.2012.01188.x.

Fraser, A. et al., 2017: Meeting the challenge of risk-sensitive and resilient urban development in sub-Saharan Africa: Directions for future research and practice. *International Journal of Disaster Risk Reduction*, **26**, 106-109, doi:10.1016/j.ijdrr.2017.10.001.

Frederiks, E.R., K. Stenner, and E. Hobman, 2015: Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour. *Renewable and Sustainable Energy Reviews*, **41**, 1385-1394, doi:10.1016/j.rser.2014.09.026.

Freire, M.E., S. Lall, and D. Leipziger, 2014: *Africa's urbanization: challenges and opportunities*. Working Paper No. 7, The Growth Dialogue, Washington DC, USA, 44 pp.

Freire-González, J., 2017: Evidence of direct and indirect rebound effect in households in EU-27 countries. *Energy Policy*, **102**, 270-276, doi:10.1016/j.enpol.2016.12.002.

Fridahl, M., 2017: Socio-political prioritization of bioenergy with carbon capture and storage. *Energy Policy*, **104**, 89-99, doi:10.1016/J.ENPOL.2017.01.050.

Friedlingstein, P. et al., 2014: Uncertainties in CMIP5 climate projections due to carbon cycle feedbacks. *Journal of Climate*, **27(2)**, 511-526, doi:10.1175/JCLI-D-12-00579.1.

Fritz, S. et al., 2011: Highlighting continued uncertainty in global land cover maps for the user community. *Environmental Research Letters*, **6(4)**, 044005, doi:10.1088/1748-9326/6/4/044005.

Froud, J., C. Haslam, S. Johal, and K. Williams, 2000: Shareholder value and Financialization: consultancy promises, management moves. *Economy and Society*, **29(1)**, 80-110, doi:10.1080/030851400360578.

Fryer, E., 2017: Digital infrastructure: And the impacts of climate change. *Journal of the Institute of Telecommunications Professionals*, **11(2)**, 8-13.

Fu, G. et al., 2017: Integrated Approach to Assess the Resilience of Future Electricity Infrastructure Networks to Climate Hazards. *IEEE Systems Journal*, doi:10.1109/JSYST.2017.2700791.

Fudge, S., M. Peters, and B. Woodman, 2016: Local authorities as niche actors: the case of energy governance in the UK. *Environmental Innovation and Societal Transitions*, **18**, 1-17, doi:10.1016/j.eist.2015.06.004.

Fuhr, H., T. Hickmann, and K. Kern, 2018: The role of cities in multi-level climate governance: local climate policies and the 1.5 °C target. *Current Opinion in Environmental Sustainability*, **30**, 1-6, doi:10.1016/j.cosust.2017.10.006.

Fujii, S. and R. Kitamura, 2003: What does a one-month free bus ticket do to habitual drivers? An experimental analysis of habit and attitude change. *Transportation*, **30(1)**, 81-95, doi:10.1023/A:1021234607980.

Fujimori, S. et al., 2016: Implication of Paris Agreement in the context of long-term climate mitigation goals. *SpringerPlus*, **5(1)**, 1620, doi:10.1186/s40064-016-3235-9.

Fulton, L. et al., 2017: Three Revolutions in Urban Transportation. .

Fuss, S. et al., 2014: Betting on negative emissions. *Nature Climate Change*, **4(10)**, 850-853, doi:10.1038/nclimate2392.

Fuss, S. et al., 2018: Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Letters* (in press), doi:https://doi.org/10.1088/1748-9326/aabf9f.

Gajjar, S.P., C. Singh, and T. Deshpande, 2018: Tracing back to move ahead: a review of development pathways that constrain adaptation futures. *Climate and Development*, 1-15, doi:10.1080/17565529.2018.1442793.

Gambhir, A. et al., 2017: Assessing the Feasibility of Global Long-Term Mitigation Scenarios. *Energies*, **10(1)**.

Gandure, S., S. Walker, and J.J. Botha, 2013: Farmers' perceptions of adaptation to climate change and water stress in a

South African rural community. *Environmental Development*, **5(1)**, 39-53, doi:10.1016/j.envdev.2012.11.004.

Gao, C., 2018: The future of CRISPR technologies in agriculture. *Nature Reviews Molecular Cell Biology*, **19(5)**, 275-276, doi:10.1038/nrm.2018.2.

Gao, Y. and J. Kenworthy, 2015: Growth of a Giant: A Historical and Current Perspective on the Chinese Automobile Industry. *World Transport Policy and Practice*, **21**, 40-55.

Gao, Y. and J. Kenworthy, 2017: China. In: *The Urban Transport Crisis in Emerging Economies* [Pojani, D. and D. Stead (eds.)]. Springer, New York, NY, USA, pp. 33-58.

Gao, Y. and P. Newman, 2018: Beijing's Peak Car Transition: Hope for Emerging Cities in the 1.5 °C Agenda. *Urban Planning*, **3(2)**, 82, doi:10.17645/up.v3i2.1246.

García Romero, H. and A. Molina, 2015: *Agriculture and Adaptation to Climate Change: The Role of Insurance in Risk Management: The Case of Colombia*. Inter-American Development Bank, 49 pp.

García-Álvarez, M.T., L. Cabeza-García, and I. Soares, 2017: Analysis of the promotion of onshore wind energy in the EU: Feed-in tariff or renewable portfolio standard? *Renewable Energy*, **111**, 256-264, doi:10.1016/j.renene.2017.03.067.

Gardiner, S.M., 2013: Why geoengineering is not a 'global public good', and why it is ethically misleading to frame it as one. *Climatic Change*, **121(3)**, 513-525, doi:10.1007/s10584-013-0764-x.

Garg, A., J. Maheshwari, P.R. Shukla, and R. Rawal, 2017: Energy appliance transformation in commercial buildings in India under alternate policy scenarios. *Energy*, **140**, 952-965, doi:10.1016/j.energy.2017.09.004.

Gasc, F., D. Guerrier, S. Barrett, and S. Anderson, 2014: *Assessing the effectiveness of investments in climate information services*. IIED, London.

Gawith, D., A. Daigneault, and P. Brown, 2016: Does community resilience mitigate loss and damage from climaterelated disasters? Evidence based on survey data. *Journal of Environmental Planning and Management*, **59(12)**, 2102-2123, doi:10.1080/09640568.2015.1126241.

GCEC, 2014: *Better growth, Better Climate: The New Climate Economy Report*. The Global Commission of the Economy and Climate, New Climate Economy, Washington, DC, USA, 308 pp.

GEA, 2012: *Global Energy Assessment - Toward a sustainable future*. Global Energy Assessment (GEA). Cambridge University Press, Cambridge UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 113 pp.

Gebrehiwot, T. and A. van der Veen, 2015: Farmers Prone to Drought Risk: Why Some Farmers Undertake Farm-Level Risk-Reduction Measures While Others Not? *Environmental Management*, **55(3)**, 588-602, doi:10.1007/s00267-014-0415-7.

Gebru, B., P. Kibaya, T. Ramahaleo, K. Kwena, and P. Mapfumo, 2015: *Improving access to climate-related information for adaptation*. IDRC, Canada, 1-4 pp.

Geden, O., V. Scott, and J. Palmer, 2018: Integrating carbon dioxide removal into EU climate policy: Prospects for a paradigm shift. , 1-10, doi:10.1002/wcc.521.

Geels, F.W., 2014: Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective. *Theory, Culture & Society*, **31(5)**, 21-40, doi:10.1177/0263276414531627.

Geels, F.W. and J. Schot, 2007: Typology of sociotechnical transition pathways. *Research Policy*, **36(3)**, 399-417, doi:10.1016/j.respol.2007.01.003.

Geels, F.W., F. Berkhout, and D.P. van Vuuren, 2016a: Bridging analytical approaches for low-carbon transitions. *Nature Climate Change*, **6(6)**, 576-583, doi:10.1038/nclimate2980.

Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**, 1242-1244, doi:10.1126/science.aao3760.

Geels, F.W. et al., 2016b: The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990-2014). *Research Policy*, **45(4)**, 896-913, doi:10.1016/j.respol.2016.01.015.

Gemenne, F. and J. Blocher, 2017: How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal. *Geographical Journal*, doi:10.1111/geoj.12205.

Georgeson, L., M. Maslin, M. Poessinouw, and S. Howard, 2016: Adaptation responses to climate change differ between global megacities. *Nature Climate Change*, **6(6)**, 584-588.

Gerbens-Leenes, W., A.Y. Hoekstra, and T.H. van der Meer, 2009: The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, **106(25)**, 10219-10223, doi:10.1073/pnas.0812619106.

Gerber, P.J. et al., 2013: Tackling climate change through livestock - A global assessment of emissions and mitigation opportunities. , 133.

GeSI, 2015: *SMARTEer2030: ICT Solutions for 21st Century Challenges*. Global e-Sustainability Initiative (GeSI), Brussels, Belgium, 134 pp.

Gheewala, S.H., G. Berndes, and G. Jewitt, 2011: The bioenergy and water nexus. *Biofuels, Bioproducts and Biorefining*, **5(4)**, 353-360, doi:10.1002/bbb.295.

Ghorbani, N., A. Aghahosseini, and C. Breyer, 2017: Transition towards a 100% Renewable Energy System and the Role of Storage Technologies: A Case Study of Iran. *Energy Procedia*, **135(Supplement C)**, 23-36, doi:https://doi.org/10.1016/j.egypro.2017.09.484.

Gibbs, D. and K. O'Neill, 2014: Rethinking Sociotechnical Transitions and Green Entrepreneurship: The Potential for Transformative Change in the Green Building Sector. *Environment and Planning A*, **46(5)**, 1088-1107, doi:10.1068/a46259.

Gillard, R., 2016: Questioning the Diffusion of Resilience Discourses in Pursuit of Transformational Change. *Global Environmental Politics*, **16(1)**, 13-20, doi:10.1162/GLEP_a_00334.

Gillard, R., A. Gouldson, J. Paavola, and J. Van Alstine, 2016: Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **7(2)**, 251-265, doi:10.1002/wcc.384.

Gillingham, K. and K. Palmer, 2017: Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Review of Environmental Economics and Policy*, **8(1)**, 18-38, doi:10.1093/reep/ret021.

Gillingham, K., M.J. Kotchen, D.S. Rapson, and G. Wagner, 2013: Energy policy: The rebound effect is overplayed. *Nature*, **493(7433)**, 475-476, doi:10.1038/493475a.

Giménez-Gómez, J.–M., J. Teixidó-Figueras, and C. Vilella, 2016: The global carbon budget: a conflicting claims problem. *Climatic Change*, **136(3-4)**, 693-703, doi:10.1007/s10584-016-1633-1.

Girod, B., T. Stucki, and M. Woerter, 2017: How do policies for efficient energy use in the household sector induce energy-efficiency innovation? An evaluation of European countries. *Energy Policy*, **103**, 223-237, doi:10.1016/j.enpol.2016.12.054.

Glaas, E., E.C.H. Keskitalo, and M. Hjerpe, 2017: Insurance sector management of climate change adaptation in three Nordic countries: the influence of policy and market factors. *Journal of Environmental Planning and Management*, **60(9)**, 1601-1621, doi:10.1080/09640568.2016.1245654.

Glachant, M. and A. Dechezleprêtre, 2016: What role for climate negotiations on technology transfer? *Climate Policy*, 1-15, doi:10.1080/14693062.2016.1222257.

Glazebrook, G. and P. Newman, 2018a: The City of the Future. *Urban Planning*, **3(2)**, 1, doi:10.17645/up.v3i2.1247.

Glazebrook, G. and P. Newman, 2018b: The City of the Future. *Urban Planning*, **3(2)**, 1, doi:10.17645/up.v3i2.1247.

Global CCS Institute, 2017: *The Global Status of CCS 2016 Summary Report*. 28 pp.

Goeppert, A., M. Czaun, G.K. Surya Prakash, and G.A. Olah, 2012: Air as the renewable carbon source of the future: an overview of CO2 capture from the atmosphere. *Energy & Environmental Science*, **5(7)**, 7833, doi:10.1039/c2ee21586a.

Goldemberg, J., 2011: The Role of Biomass in the World's Energy System. In: *Routes to Cellulosic Ethanol* [Buckeridge, M.S. and G.H. Goldman (eds.)]. Springer, New York, NY, USA, pp. 3-14.

Gölz, S. and U.J.J. Hahnel, 2016: What motivates people to use energy feedback systems ? A multiple goal approach to predict long-term usage behaviour in daily life. *Energy Research & Social Science*, **21**, 155-166, doi:10.1016/j.erss.2016.07.006.

Gonzales, M.H., E. Aronson, and M.A. Costanzo, 1988: Using Social Cognition and Persuation to Promote Energy Conservation: A Quasi-Experiment. *Journal of Applied Social Psychology*, **18(12)**, 1049-1066.

González, M.F. and T. Ilyina, 2016: Impacts of artificial ocean alkalinization on the carbon cycle and climate in Earth system simulations. *Geophysical Research Letters*, **43(12)**, 6493-6502, doi:10.1002/2016GL068576.

Goodwin, P. and K. Van Dender, 2013: Peak Car' - Themes and Issues. *Transport Reviews*, **33(3)**, 243-254, doi:10.1080/01441647.2013.804133.

Göpfert, C., C. Wamsler, and W. Lang, 2018: A framework for the joint institutionalization of climate change mitigation and adaptation in city administrations. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-018-9789-9.

Gorayeb, A., C. Brannstrom, A.J. de Andrade Meireles, and J. de Sousa Mendes, 2018: Wind power gone bad: Critiquing wind power planning processes in northeastern Brazil. *Energy Research & Social Science*, **40**, 82-88, doi:https://doi.org/10.1016/j.erss.2017.11.027.

Gordon, D.J. and C.A. Johnson, 2017: The orchestration of global urban climate governance: conducting power in the post-Paris climate regime. *Environmental Politics*, **26(4)**, 694-714, doi:10.1080/09644016.2017.1320829.

Gota, S., C. Huizenga, K. Peet, N. Medimorec, and S. Bakker, 2018: Decarbonising transport to achieve Paris Agreement targets. *Energy Efficiency*, doi:10.1007/s12053-018-9671-3.

Goulder, L.H., 1995: Effects of Carbon Taxes in an Economy with Prior Tax Distortions: An Intertemporal General Equilibrium Analysis. *Journal of Environmental Economics and Management*, **29(3)**, 271-297, doi:10.1006/jeem.1995.1047.

Goulder, L.H., 2013: Climate change policy's interactions with the tax system. *Energy Economics*, **40, Supple**, S3-S11, doi:10.1016/j.eneco.2013.09.017.

Goytia, S., M. Pettersson, T. Schellenberger, W.J. van Doorn-Hoekveld, and S. Priest, 2016: Dealing with change and uncertainty within the regulatory frameworks for flood defense infrastructure in selected European countries. *Ecology and Society*, **21(4)**, doi:10.5751/ES-08908-210423.

Grace, J., E. Mitchard, and E. Gloor, 2014: Perturbations in the carbon budget of the tropics. *Global Change Biology*, **20(10)**, 3238-3255, doi:10.1111/gcb.12600.

Graham, S., J. Barnett, R. Fincher, C. Mortreux, and A. Hurlimann, 2015: Towards fair local outcomes in adaptation to sea-level rise. *Climatic Change*, **130(3)**, 411-424, doi:10.1007/s10584-014-1171-7.

Granderson, A.A., 2017: The Role of Traditional Knowledge in Building Adaptive Capacity for Climate Change: Perspectives from Vanuatu. *Weather, Climate, and Society*, **9(3)**, 545-561, doi:10.1175/WCAS-D-16-0094.1.

Grassi, G. et al., 2017: The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, **7(3)**, 220-226, doi:10.1038/nclimate3227.

Grecequet, M., J. DeWaard, J.J. Hellmann, and G.J. Abel, 2017: Climate Vulnerability and Human Migration in Global Perspective. *Sustainability*, **9(5)**, 720, doi:10.3390/su9050720.

Green, D. and L. Minchin, 2014: Living on climate-changed country: Indigenous health, well-being and climate change in remote Australian communities. *EcoHealth*, **11(2)**, 263-272, doi:10.1007/s10393-013-0892-9.

Green, J. and P. Newman, 2017a: Citizen utilities: The emerging power paradigm. *Energy Policy*, **105(February)**, 283-293, doi:10.1016/j.enpol.2017.02.004.

Green, J. and P. Newman, 2017b: Disruptive innovation, stranded assets and forecasting: the rise and rise of renewable energy. *Journal of Sustainable Finance & Investment*, **7(2)**, 169-187, doi:10.1080/20430795.2016.1265410.

Green, K.E., 2016: A political ecology of scaling: Struggles over power, land and authority. *Geoforum*, **74**, 88-97, doi:10.1016/j.geoforum.2016.05.007.

Green, O.O. et al., 2016: Adaptive governance to promote ecosystem services in urban green spaces. *Urban Ecosystems*, **19(1)**, 77-93, doi:10.1007/s11252-015-0476-2.

Greenblatt, J.B. and S. Saxena, 2015: Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. *Nature Climate Change*, **5(9)**, 860-863, doi:10.1038/nclimate2685.

Greene, C.H. et al., 2017: Earth ' s Future Geoengineering , marine microalgae , and climate stabilization in the 21st century Earth ' s Future. , doi:10.1002/eft2.194.

Greene, D.L., 2011: Uncertainty, loss aversion, and markets for energy efficiency. *Energy Economics*, **33(4)**, 608-616, doi:10.1016/j.eneco.2010.08.009.

Greening, L.A., D.L. Greene, and C. Difiglio, 2000: Energy efficiency and consumption - the rebound effect - a survey. *Energy Policy*, **28(6-7)**, 389-401, doi:10.1016/S0301-4215(00)00021-5.

Gregorio, M. et al., 2016: Integrating Mitigation and Adaptation in Climate and Land Use Policies in Brazil: A Policy Document Analysis. .

Gregory, R., S. Lichtenstein, and P. Slovic, 1993: Valuing environmental resources: A constructive approach. *Journal of Risk and Uncertainty*, **7(2)**, 177-197.

Grewe, V., E. Tsati, M. Mertens, C. Frömming, and P. Jöckel, 2017: Contribution of emissions to concentrations: the TAGGING 1.0 submodel based on the Modular Earth Submodel System (MESSy 2.52). *Geoscientific Model Development*, **10(7)**, 2615-2633, doi:10.5194/gmd-10-2615-2017.

Griscom, B.W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences*, **114(44)**, 11645-11650, doi:10.1073/pnas.1710465114.

Gross, R., W. Blyth, and P. Heptonstall, 2010: Risks, revenues and investment in electricity generation: Why policy needs to look beyond costs. *Energy Economics*, **32(4)**, 796-804, doi:10.1016/j.eneco.2009.09.017.

Grosse, G., S. Goetz, A.D. McGuire, V.E. Romanovsky, and E.A.G. Schuur, 2016: Changing permafrost in a warming world and feedbacks to the Earth system. *Environmental Research Letters*, **11(4)**, doi:10.1088/1748-9326/11/4/040201.

Grothmann, T. and F. Reusswig, 2006: People at risk of flooding: Why some residents take precautionary action while others do not. *Natural hazards*, **38(1)**, 101-120.

Grottera, C., W. Wills, and E.L. La Rovere, 2016: The Transition to a Low Carbon Economy and Its Effects on Jobs and Welfare - A Long-Term Scenario for Brazil. In: *The Fourth Green Growth Knowledge Platform Annual Conference, 6-7 September 2016, Jeju, Republic of Korea*. The Fourth Green Growth Knowledge Platform Annual Conference, 6-7 September 2016. Jeju, Republic of Korea, Geneva, Switzerland, pp. 7.

Grove, K.J., 2013: From emergency management to managing emergence: A genealogy of disaster management in Jamaica. *Annals of the Association of American Geographers*, **103(3)**, 570-588.

Grubb, M., 1990: The Greenhouse Effect: Negotiating Targets. *International Affairs*, **66(1)**, 67-89.

Grubb, M., J.C. Hourcade, and K. Neuhoff, 2014: *Planetary economics: energy, climate change and the three domains of sustainable development*. Routledge, Abingdon, Oxon, UK, 548 pp.

Grubler, A., 2010: The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, **38(9)**, 5174-5188, doi:https://doi.org/10.1016/j.enpol.2010.05.003.

Grubler, A. et al., 2012: Chapter 24 - Policies for the Energy Technology Innovation System (ETIS). In: *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1665-1744.

Grübler, A., 2018: A Global Scenario of Low Energy Demand for Sustainable Development below 1.5°C without Negative Emission Technologies. *Nature Energy* (in press).

Guerra, A., 2017: La Crisis como Oportunidad, Análisis de la sequía en la costa sur de Guatemala en 2016. *Red Nacional de Formacion e Investigacion Ambiental*, 21-27 pp.

Guivarch, C. and S. Hallegatte, 2011: Existing infrastructure and the 2°C target. *Climatic Change*, **109(3-4)**, 801-805, doi:10.1007/s10584-011-0268-5.

Gupta, J., 2014: *The History of Global Climate Governance*. Cambridge University Press, Cambridge, UK and New York, NY, USA, 262 pp.

Gupta, S. et al., 2007: Policies, Instruments and Co-operative Arrangements. In: *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Metz, B., O.R. Davidson, P.R. Bosch, R. Dave, and L.A. Meyer (eds.)]. pp. 746-807.

Gurara, D. et al., 2017: Trends and Challenges in Infrastructure Investment in Low-Income Developing Countries. IMF Working Paper, 31 pp.

GWA, 2016: *Statistics Digest 2015-16*. Department of Mines and Petroleum, Government of Western Australia (GWA), Perth, Australia, 74 pp.

Gwedla, N. and C.M. Shackleton, 2015: The development visions and attitudes towards urban forestry of officials responsible for greening in South African towns. *Land Use Policy*, **42**, 17-26, doi:10.1016/j.landusepol.2014.07.004.

Haas, W., F. Krausmann, D. Wiedenhofer, and M. Heinz, 2015: How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. *Journal of Industrial Ecology*, **19(5)**, 765-777, doi:10.1111/jiec.12244.

Haasnoot, M., J.H.J.H. Kwakkel, W.E.W.E. Walker, and J. ter Maat, 2013: Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, **23(2)**, 485-498, doi:10.1016/j.gloenvcha.2012.12.006.

Hackmann, H., S.C. Moser, and A.L. St. Clair, 2014: The social heart of global environmental change. *Nature Climate Change*, **4(8)**, 653-655, doi:10.1038/nclimate2320.

Hadarits, M. et al., 2017: The interplay between incremental, transitional, and transformational adaptation: a case study of Canadian agriculture. *Regional Environmental Change*, **17(5)**, 1515-1525, doi:10.1007/s10113-017-1111-y.

Hagen, A., L. Kähler, and K. Eisenack, 2017: *Transnational environmental agreements with heterogeneous actors*. Routledge.

Hagen, B., A. Middel, and D. Pijawka, 2016: European Climate Change Perceptions: Public support for mitigation and adaptation policies. *Environmental Policy and Governance*, **26(3)**, 170-183, doi:10.1002/eet.1701.

Hahnel, U.J.J. et al., 2015: The power of putting a label on it : green labels weigh heavier than contradicting product information for consumers ' purchase decisions and post-purchase behavior. *Frontiers in Psychology*, **6(September)**, 1392, doi:10.3389/fpsyg.2015.01392.

Haines, A. et al., 2017: Short-lived climate pollutant mitigation and the Sustainable Development Goals. *Nature Climate Change*, **7(12)**, 863-869, doi:10.1038/s41558-017-0012-x.

Hallegatte, S. and K.J. Mach, 2016: Make climate-change assessments more relevant. *Nature*, **534(7609)**, 613-615, doi:10.1038/534613a.

Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7**, 250-256, doi:10.1038/nclimate3253.

Hallegatte, S., J.–C. Hourcade, and P. Dumas, 2007: Why economic dynamics matter in assessing climate change damages: Illustration on extreme events. *Ecological Economics*, **62(2)**, 330-340, doi:10.1016/j.ecolecon.2006.06.006.

Hallegatte, S., C. Green, R.J. Nicholls, and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nature Climate Change*, **3(9)**, 802-806, doi:10.1038/nclimate1979.

Hallegatte, S., A. Vogt-Schilb, M. Bangalore, and J. Rozenberg, 2017: *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters*. The World Bank, Washington DC, USA, 201 pp.

Hallegatte, S. et al., 2016: *Shock waves: Managing the Impacts of Climate Change on Poverty*. World Bank Group, Washington DC, USA, 227 pp.

Halpern, B.S. et al., 2015: Spatial and temporal changes in cumulative human impacts on the world's ocean. *Nature Communications*, **6**, 7615, doi:10.1038/ncomms8615.

Hammill, A., R. Matthew, and E. McCarter, 2008: Microfinance and climate change adaptation. *IDS bulletin*, **39(4)**, 113-122.

Handgraaf, M.J.J., M.A. Lidth, D. Jeude, and K.C. Appelt, 2013: Public praise vs . private pay : Effects of rewards on energy conservation in the workplace. *Ecological Economics*, **86**, 86-92, doi:10.1016/j.ecolecon.2012.11.008.

Hangx, S.J.T. and C.J. Spiers, 2009: Coastal spreading of olivine to control atmospheric CO2 concentrations: A critical analysis of viability. *International Journal of Greenhouse Gas Control*, **3(6)**, 757-767, doi:10.1016/j.ijggc.2009.07.001.

Haoqi, Q., W. Libo, and T. Weiqi, 2017: "Lock-in" effect of emission standard and its impact on the choice of market based instruments. *Energy Economics*, **63**, 41-50, doi:10.1016/j.eneco.2017.01.005.

Harberger, A.C., 1984: Basic Needs versus Distributional Weights in Social Cost-Benefit Analysis. *Economic Development and Cultural Change*, **32(3)**, 455-474, doi:10.1086/451400.

Harding, A. and J.B. Moreno-Cruz, 2016: Solar geoengineering economics: From incredible to inevitable and half-way back. *Earth's Future*, **4(12)**, 569-577, doi:10.1002/2016EF000462.

Hardoy, J. and L.S. Velásquez Barrero, 2014: Re-thinking "Biomanizales": addressing climate change adaptation in Manizales, Colombia. *Environment and Urbanization*, **26(1)**, 53-68.

Hardoy, J. and L.S. Velásquez Barrero, 2016: Manizales, Colombia. *Cities on a finite planet: Towards transformative responses to climate change*, 274.

Harjanne, A., 2017: Servitizing climate science-Institutional analysis of climate services discourse and its implications. *Global Environmental Change*, **46(November 2016)**, 1-16, doi:10.1016/j.gloenvcha.2017.06.008.

Harris, Z.M., R. Spake, and G. Taylor, 2015: Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions. *Biomass and Bioenergy*, **82**, 27-39, doi:10.1016/J.BIOMBIOE.2015.05.008.

Harrison, D.P., 2017: Global negative emissions capacity of ocean macronutrient fertilization. *Environmental Research Letters*, **12(3)**, doi:10.1088/1748-9326/aa5ef5.

Hartley, P.R. and K.B. Medlock, 2013: The Valley of Death for New Energy Technologies. *The Energy Journal*, **38(3)**, 1-61.

Hartmann, J. and S. Kempe, 2008: What is the maximum potential for CO2 sequestration by "stimulated" weathering on the global scale? *Naturwissenschaften*, **95(12)**, 1159-1164, doi:10.1007/s00114-008-0434-4.

Hartmann, J. et al., 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification: Enhanced weathering. *Reviews of Geophysics*, **51(2)**, 113-149, doi:10.1002/rog.20004.

Harvey, C.A. et al., 2014: Climate-Smart Landscapes: Opportunities and Challenges for Integrating Adaptation and Mitigation in Tropical Agriculture. *Conservation Letters*, **7(2)**, 77-90, doi:10.1111/conl.12066.

Harvey, L.D.D., 2008: Mitigating the atmospheric CO 2 increase and ocean acidification by adding limestone powder to upwelling regions. *Journal of Geophysical Research*, **113(C4)**, C04028, doi:10.1029/2007JC004373.

Hasanbeigi, A., M. Arens, and L. Price, 2014: Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: A technical review. *Renewable and Sustainable Energy Reviews*, **33(Supplement C)**, 645-658, doi:https://doi.org/10.1016/j.rser.2014.02.031.

Haselip, J., U.E. Hansen, D. Puig, S. Trærup, and S. Dhar, 2015: Governance, enabling frameworks and policies for the transfer and diffusion of low carbon and climate adaptation technologies in developing countries. *Climatic Change*, **131(3)**, 363-370, doi:10.1007/s10584-015-1440-0.

Hauck, J., P. Köhler, D. Wolf-Gladrow, and C. Völker, 2016: Iron fertilisation and century-scale effects of open ocean dissolution of olivine in a simulated CO2 removal experiment. *Environmental Research Letters*, **11(2)**, doi:10.1088/1748-9326/11/2/024007.

Havet, A. et al., 2014: Review of livestock farmer adaptations to increase forages in crop rotations in western France. *Agriculture, ecosystems & environment*, **190**, 120-127.

Havlik, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111(10)**, 3709-3714, doi:10.1073/pnas.1308044111.

Hayashi, A., F. Sano, Y. Nakagami, and K. Akimoto, 2018: Changes in terrestrial water stress and contributions of major factors under temperature rise constraint scenarios. *Mitigation and Adaptation Strategies for Global Change*, 1-27, doi:10.1007/s11027-018-9780-5.

Heard, B.P., B.W. Brook, T.M.L. Wigley, and C.J.A. Bradshaw, 2017: Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. *Renewable and Sustainable Energy Reviews*, **76(March)**, 1122-1133, doi:10.1016/j.rser.2017.03.114.

Heck, V., D. Gerten, W. Lucht, and A. Popp, 2018: Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, **8(2)**, 151-155, doi:10.1038/s41558-017-0064-y.

Heckendorn, P. et al., 2009: The impact of geoengineering aerosols on stratospheric temperature and ozone. *Environmental Research Letters*, **4(4)**, 045108, doi:10.1088/1748-9326/4/4/045108.

Heede, R., 2014: Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854-2010. *Climatic Change*, **122(1)**, 229-241, doi:10.1007/s10584-013-0986-y.

Heidrich, O. et al., 2016: National climate policies across Europe and their impacts on cities strategies. *Journal of Environmental Management*, **168**, 36-45.

Hekkert, M.P., R.A.A. Suurs, S.O. Negro, S. Kuhlmann, and R.E.H.M. Smits, 2007: Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, **74(4)**, 413-432, doi:10.1016/j.techfore.2006.03.002.

Henly-Shepard, S., S.A. Gray, and L.J. Cox, 2015: The use of participatory modeling to promote social learning and facilitate community disaster planning. *Environmental Science & Policy*, **45**, 109-122, doi:10.1016/j.envsci.2014.10.004.

Henry, R.C. et al., 2018: Food supply and bioenergy production within the global cropland planetary boundary. *PLOS ONE*, **13(3)**, e0194695, doi:10.1371/journal.pone.0194695.

Henry, R.K., Z. Yongsheng, and D. Jun, 2006: Municipal solid waste management challenges in developing countries - Kenyan case study. *Waste Management*, **26(1)**, 92-100, doi:10.1016/j.wasman.2005.03.007.

Henstra, D., 2016: The tools of climate adaptation policy : analysing instruments and instrument selection The tools of climate adaptation policy : analysing instruments and instrument selection. *Climate Policy*, **16(4)**, 496-521, doi:10.1080/14693062.2015.1015946.

Hering, J.G., D.A. Dzombak, S.A. Green, R.G. Luthy, and D. Swackhamer, 2014: Engagement at the Science-Policy Interface. *Environmental Science and Technology*, **48(19)**, 1031-11033, doi:10.1021/es504225t.

Hermwille, L., 2016: Climate Change as a Transformation Challenge. A New Climate Policy Paradigm? *GAIA - Ecological Perspectives for Science and Society*, **25(1)**, 19-22, doi:10.14512/gaia.25.1.6.

Hermwille, L., W. Obergassel, H.E. Ott, and C. Beuermann, 2017: UNFCCC before and after Paris - what's necessary for an effective climate regime? *Climate Policy*, **17(2)**, 150-170, doi:10.1080/14693062.2015.1115231.

Hernández-Morcillo, M., P. Burgess, J. Mirck, A. Pantera, and T. Plieninger, 2018: Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environmental Science and Policy*, **80**, 44-52, doi:10.1016/j.envsci.2017.11.013.

Herrero, M. et al., 2015: Livestock and the Environment: What Have We Learned in the Past Decade? *Annual Review of Environment and Resources*, **40(1)**, 177-202, doi:10.1146/annurev-environ-031113-093503.

Herwehe, L. and C.A. Scott, 2017: Drought adaptation and development: small-scale irrigated agriculture in northeast Brazil. *Climate and Development*, 1-10, doi:10.1080/17565529.2017.1301862.

Hess, J. and I. Kelman, 2017: Tourism Industry Financing of Climate Change Adaptation: Exploring the Potential in Small Island Developing States. *Climate, Disaster and Development Journal*, **2(2)**, 34-45, doi:10.18783/cddj.v002.i02.a04.

Hesse, C., 2016: Decentralising climate finance to reach the most vulnerable. , 4.

Hetz, K., 2016: Contesting adaptation synergies: political realities in reconciling climate change adaptation with urban development in Johannesburg, South Africa. *Regional Environmental Change*, **16(4)**, 1171-1182, doi:10.1007/s10113-015-0840-z.

Heutel, G., J. Moreno-Cruz, and S. Shayegh, 2018: Solar geoengineering, uncertainty, and the price of carbon. *Journal of Environmental Economics and Management*, **87**, 24-41, doi:10.1016/j.jeem.2017.11.002.

Hewitt, C., S. Mason, and D. Walland, 2012: The Global Framework for Climate Services. *Nature Climate Change*, **2(12)**, 831-832, doi:10.1038/nclimate1745.

Heyen, D., T. Wiertz, and P.J. Irvine, 2015: Regional disparities in SRM impacts: the challenge of diverging preferences. *Climatic Change*, **133(4)**, 557-563, doi:10.1007/s10584-015-1526-8.

Hiç, C., P. Pradhan, D. Rybski, and J.P. Kropp, 2016: Food Surplus and Its Climate Burdens. *Environmental Science and Technology*, doi:10.1021/acs.est.5b05088.

Hill, J., E. Nelson, D. Tilman, S. Polasky, and D. Tiffany, 2006: Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences*, **103(30)**, 11206-11210, doi:10.1073/pnas.0604600103.

Hill Clarvis, M. and N.L. Engle, 2015: Adaptive capacity of water governance arrangements: a comparative study of barriers and opportunities in Swiss and US states. *Regional Environmental Change*, **15(3)**, 517-527, doi:10.1007/s10113-013-0547-y.

Hirschberg, S. et al., 2016: Health effects of technologies for power generation: Contributions from normal operation, severe accidents and terrorist threat. *Reliability Engineering and System Safety*, **145**, 373-387, doi:10.1016/j.ress.2015.09.013.

Hirth, L. and J.C. Steckel, 2016: The role of capital costs in decarbonizing the electricity sector. *Environmental Research Letters*, **11(11)**, 114010, doi:10.1088/1748-9326/11/11/114010.

Hiwasaki, L., E. Luna, Syamsidik, and J.A. Marçal, 2015: Local and indigenous knowledge on climate-related hazards of coastal and small island communities in Southeast Asia. *Climatic Change*, **128(1-2)**, 35-56, doi:10.1007/s10584-014-1288-8.

Hof, A.F. et al., 2017: Global and regional abatement costs of Nationally Determined Contributions (NDCs) and of enhanced action to levels well below 2 °C and 1.5 °C. *Environmental Science {&} Policy*, **71**, 30-40, doi:10.1016/j.envsci.2017.02.008.

Hogarth, J.R., 2017: Evolutionary models of sustainable economic change in Brazil: No-till agriculture, reduced deforestation and ethanol biofuels. *Environmental Innovation and Societal Transitions*, **24**, 130-141, doi:https://doi.org/10.1016/j.eist.2016.08.001.

Höglund-Isaksson, L., 2012: Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs. *Atmospheric Chemistry and Physics*, **12(19)**, 9079-9096, doi:10.5194/acp-12-9079-2012.

Höglund-Isaksson, L. et al., 2017: Cost estimates of the Kigali Amendment to phase-down hydrofluorocarbons. *Environmental Science & Policy*, **75**, 138-147, doi:10.1016/j.envsci.2017.05.006.

Högy, P. et al., 2009: Effects of elevated CO2 on grain yield and quality of wheat: results from a 3-year free-air CO2 enrichment experiment. *Plant Biology*, **11(s1)**, 60-69, doi:10.1111/j.1438-8677.2009.00230.x.

Höhne, N., H. Fekete, M.G.J. den Elzen, A.F. Hof, and T. Kuramochi, 2017: Assessing the ambition of post-2020 climate targets: a comprehensive framework. *Climate Policy*, 1-16, doi:10.1080/14693062.2017.1294046.

Holland, B., 2017: Procedural justice in local climate adaptation: political capabilities and transformational change. *Environmental Politics*, **26(3)**, 391-412, doi:10.1080/09644016.2017.1287625.

Holland, R.A. et al., 2015: A synthesis of the ecosystem services impact of second generation bioenergy crop production. *Renewable and Sustainable Energy Reviews***, 46**, 30-40, doi:10.1016/J.RSER.2015.02.003.

Holmes, G. and D.W. Keith, 2012: An air-liquid contactor for large-scale capture of CO2 from air. *Philosophical transactions. Series A, Mathematical, Physical, and Engineering sciences***, 370(1974)**, 4380-403, doi:10.1098/rsta.2012.0137.

Holmes, G. et al., 2013: Outdoor prototype results for direct atmospheric capture of carbon dioxide. *Energy Procedia***, 37**, 6079-6095.

Hölscher, K., N. Frantzeskaki, and D. Loorbach, 2018: Steering transformations under climate change: capacities for transformative climate governance and the case of Rotterdam, the Netherlands. *Regional Environmental Change*, 1-15, doi:10.1007/s10113-018-1329-3.

Holz, C., S. Kartha, and T. Athanasiou, 2018: Fairly sharing 1.5: national fair shares of a 1.5 °C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics***, 18(1)**, 117-134, doi:10.1007/s10784-017-9371-z.

Honegger, M., K. Sugathapala, and A. Michaelowa, 2013: Tackling climate change: where can the generic framework be located? *Carbon & Climate Law Review***, 7(2)**, 125-135, doi:10.5167/uzh-86551.

Hong, N.B. and M. Yabe, 2017: Improvement in irrigation water use efficiency: a strategy for climate change adaptation and sustainable development of Vietnamese tea production. *Environment, Development and Sustainability***, 19(4)**, 1247-1263, doi:10.1007/s10668-016-9793-8.

Höök, M., J. Li, N. Oba, and S. Snowden, 2011: Descriptive and Predictive Growth Curves in Energy System Analysis. *Natural Resources Research***, 20(2)**, 103-116, doi:10.1007/s11053-011-9139-z.

Hornsey, M.J., E.A. Harris, P.G. Bain, and K.S. Fielding, 2016: Meta-analyses of the determinants and outcomes of belief in climate change. *Nature Climate Change***, 6(6)**, 622-626, doi:10.1038/nclimate2943.

Horton, J.B., 2011: Geoengineering and the Myth of Unilateralism: Pressures and Prospects for International Cooperation. *Stanford Journal of Law Science Policy***, IV(May)**, 56-69, doi:10.1017/CBO9781139161824.010.

Horton, J.B., D.W. Keith, and M. Honegger, 2016: Implications of the Paris Agreement for Carbon Dioxide Removal and Solar Geoengineering. 1-10 pp.

Horton, J.B., J.L. Reynolds, and D.W. Keith, 2018: Solar Geoengineering and Democracy. *Global Environmental Politics*, 1-18.

Houghton, R.A., 2013: The emissions of carbon from deforestation and degradation in the tropics: past trends and future potential. *Carbon Management***, 4(5)**, 539-546, doi:10.4155/cmt.13.41.

Houghton, R.A., B. Byers, and A.A. Nassikas, 2015: A role for tropical forests in stabilizing atmospheric CO2. *Nature Clim. Change***, 5(12)**, 1022-1023.

Hourcade, J.–C., P.–R. Shukla, and C. Cassen, 2015: Climate policy architecture for the Cancun paradigm shift: building on the lessons from history. *International Environmental Agreements: Politics, Law and Economics***, 15(4)**, 353-367, doi:10.1007/s10784-015-9301-x.

Hourcade, J.–C. et al., 2001: Global, Regional, and National Costs and Ancillary Benefits of Mitigation. *Climate Change 2001: Mitigation. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*.

House, K.Z., C.H. House, D.P. Schrag, and M.J. Aziz, 2007: Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change. *Environmental Science & Technology***, 41(24)**, 8464-8470, doi:10.1021/es0701816.

House, K.Z. et al., 2011: Economic and energetic analysis of capturing CO2 from ambient air. *Proceedings of the National Academy of Sciences***, 108(51)**, 20428-20433, doi:10.1073/pnas.1012253108.

Hovi, J., D.F. Sprinz, H. Sælen, and A. Underdal, 2016: Climate change mitigation: a role for climate clubs? *Palgrave Communications***, 2**, 16020.

Howes, M. et al., 2015: Towards networked governance: improving interagency communication and collaboration for disaster risk management and climate change adaptation in Australia. *Journal of Environmental Planning and Management***, 58(5)**, 757-776, doi:10.1080/09640568.2014.891974.

Hoy, M.B., 2016: Smart Buildings: An Introduction to the Library of the Future. *Medical Reference Services Quarterly***, 35(3)**, 326-331, doi:10.1080/02763869.2016.1189787.

Hristov, A.N. et al., 2015: An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. *Proceedings of the National Academy of Sciences***, 112(34)**, 10663-10668, doi:10.1073/pnas.1504124112.

Hsu, A., A.J. Weinfurter, and K. Xu, 2017: Aligning subnational climate actions for the new post-Paris climate regime. *Climatic Change***, 142(3-4)**, 419-432, doi:10.1007/s10584-017-1957-5.

Hu, A., Y. Xu, C. Tebaldi, W.M. Washington, and V. Ramanathan, 2013: Mitigation of short-lived climate pollutants slows sea-level rise. *Nature Climate Change***, 3**, 730.

Huang, W., W. Chen, and G. Anandarajah, 2017a: The role of technology diffusion in a decarbonizing world to limit global warming to well below 2 °C: An assessment with application of Global TIMES model. *Applied Energy***,**

208, 291-301, doi:https://doi.org/10.1016/j.apenergy.2017.10.040.

Huang, W., D. Ma, and W. Chen, 2017b: Connecting water and energy: Assessing the impacts of carbon and water constraints on China's power sector. *Applied Energy***, 185**, 1497-1505, doi:10.1016/J.APENERGY.2015.12.048.

Huang-Lachmann, J.–T. and J.C. Lovett, 2016: How cities prepare for climate change: Comparing Hamburg and Rotterdam. *Cities***, 54**, 36-44.

HUD, 2013: Rebuild by Design Competition. http://www.rebuildbydesign.org.

Huebner, G.M. and D. Shipworth, 2017: All about size? - The potential of downsizing in reducing energy demand. *Applied Energy***, 186**, 226-233, doi:10.1016/j.apenergy.2016.02.066.

Hughes, A.D. et al., 2012: Does seaweed offer a solution for bioenergy with biological carbon capture and storage? *Greenhouse Gases: Science and Technology***, 2(6)**, 402-407, doi:10.1002/ghg.1319.

IAEA, 2017: *Nuclear Technology Review 2017*. IAEA.

IAEA, 2018: Power Reactor Information System - Country Statistics: France. https://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=FR (Accessed: 12 April 2018).

Ickowitz, A., E. Sills, and C. de Sassi, 2017: Estimating Smallholder Opportunity Costs of REDD+: A Pantropical Analysis from Households to Carbon and Back. *World Development***, 95**, 15-26, doi:10.1016/J.WORLDDEV.2017.02.022.

Idem, R. et al., 2015: Practical experience in post-combustion CO2 capture using reactive solvents in large pilot and demonstration plants. *International Journal of Greenhouse Gas Control***, 40(Supplement C)**, 6-25, doi:https://doi.org/10.1016/j.ijggc.2015.06.005.

IEA, 2014a: *World Energy Investment Outlook Special Report*. 190 pp.

IEA, 2014b: *World Energy Outlook 2014*. OECD, Paris, France, 748 pp.

IEA, 2016a: *20 Years of Carbon Capture and Storage - Accelerating Future Deployment*. International Energy Agency, Paris, France, 115 pp.

IEA, 2016b: *IEA 4E Solid State Lighting Annex Task 7: Smart Lighting - New Features Impacting Energy Consumption First Status Report*. 41 pp.

IEA, 2016c: *World Energy Outlook 2016*.

IEA, 2017a: *Digitalization & Energy*. 188 pp.

IEA, 2017b: *Energy Access Outlook 2017*. International Energy Agency, Paris, France, 144 pp.

IEA, 2017c: *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*. IEA, Paris, France, 443 pp.

IEA, 2017d: *Getting Wind and Sun onto the Grid A Manual for Policy Makers*. 64 pp.

IEA, 2017e: *The Future of Trucks*. International Energy Agency, Paris, France.

IEA, 2017f: *Tracking Clean Energy Progress 2017*. 1-82 pp.

IEA, 2017g: *World Energy Outlook 2017*. International Energy Agency, Paris, France, 748 pp.

IEA, 2018: *Global EV Outlook 2018: Towards cross-modal electrification*. International Energy Agency (IEA), Paris, France, 141 pp.

Iguma, H. and H. Kidoshi, 2015: *Why Toyota can sell Mirai at 7 million Yen?* Nikkan-Kogyo Press.

IIF, 2017: Global Debt Monitor. https://www.iif.com/publication/global-debt-monitor/global-debt-monitor-april-2018 (Accessed: 18 May 2018).

Iiyama, M. et al., 2017: Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. *Agroforestry Systems***, 91(2)**, 271-293, doi:10.1007/s10457-016-9926-y.

IMF, 2014: *World Economic Outlook October 2014: Legacies, Clouds, Uncertainties*. 243 pp.

IMO, 1972: *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter*. International Maritime Organization (IMO).

IMO, 1996: *1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972*. International Maritime Organization (IMO).

Inamara, A. and V. Thomas, 2017: Pacific climate change adaptation: The use of participatory media to promote indigenous knowledge. *Pacific Journalism Review***, 23(1)**, 113-132.

Ingold, K. and M. Fischer, 2014: Drivers of collaboration to mitigate climate change: An illustration of Swiss climate policy over 15 years. *Global Environmental Change***, 24**, 88-98, doi:10.1016/j.gloenvcha.2013.11.021.

Ingty, T., 2017: High mountain communities and climate change: adaptation, traditional ecological knowledge, and institutions. *Climatic Change***, 145(1-2)**, 41-55, doi:10.1007/s10584-017-2080-3.

IPCC, 1995: Climate Change 1995. , 339, doi:10.1016/S0959-3780(97)82915-9.

IPCC, 2001: Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of theIntegovernmental Panel on Climate Change. []. 398 pp.

IPCC, 2005: Special Report on Carbon Dioxide Capture and Storage. [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, UK, Cambridge, United Kingdom and New York, NY, USA, UK and New York, NY, USA, 442 pp.

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special

Report of Working Groups I and II of IPCC Intergovernmental Panel on Climate Change. [Field, C.B., V. Barros, T.F. Stocker, Q. Dahe, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.–K. Plattner, S.K. Allen, and Others (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 594 pp.

IPCC, 2014a: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014b: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1454 pp.

IPCC, 2014c: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Core Writing Team, R.K. Pachauri, and L.A. Meyer (eds.)]. 169 pp.

IRENA, 2013: *Smart Grids and Renewables - A Guide for Effective Deployment*. International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, 47 pp.

IRENA, 2015: *Renewable energy options for shipping: Technology Brief*. International Renewable Energy Agency (IRENA), Bonn, Germany, 1-58 pp.

IRENA, 2017a: *Electricity storage and renewables: Costs and markets to 2030*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates.

IRENA, 2017b: Renewable Energy and Jobs: Annual Review 2017. , 24.

IRENA, 2018: *Renewable Power Generation Costs in 2017*.

Irvine, P.J., A. Ridgwell, and D.J. Lunt, 2011: Climatic effects of surface albedo geoengineering. *Journal of Geophysical Research Atmospheres*, **116(24)**, n/a-n/a, doi:10.1029/2011JD016281.

Irvine, P.J., B. Kravitz, M.G. Lawrence, and H. Muri, 2016: An overview of the Earth system science of solar geoengineering. *Wiley Interdisciplinary Reviews: Climate Change*, **7(6)**, 815-833, doi:10.1002/wcc.423.

Isayama, K. and N. Ono, 2015: Steps towards sustainable and resilient disaster management in Japan: Lessons from Cuba. *International Journal of Health System and Disaster Management*, **3(2)**, 54, doi:10.4103/2347-9019.151300.

ISSC and UNESCO, 2013: *World Social Science Report 2013: Changing Global Environments*. 612 pp.

ITF, 2015: *Urban Mobility System Upgrade: How shared self-driving cars could change city traffic*. OECD Publishing, Paris, 1-36 pp.

Izrael, Y.A., E.M. Volodin, S. Kostrykin, A.P. Revokatova, and A.G. Ryaboshapko, 2014: The ability of stratospheric climate engineering in stabilizing global mean temperatures and an assessment of possible side effects. *Atmospheric Science Letters*, **15(2)**, 140-148, doi:10.1002/asl2.481.

Jabeen, H., 2014: Adapting the built environment : the role of gender in shaping vulnerability and resilience to climate extremes in Dhaka. *Environment & Urbanization*, **26(1)**, 147-165, doi:10.1177/0956247813517851.

Jaboyedoff, P., C.A. Roulet, V. Dorer, A. Weber, and A. Pfeiffer, 2004: Energy in air-handling units - results of the AIRLESS European Project. *Energy and Buildings*, **36(4)**, 391-399, doi:10.1016/j.enbuild.2004.01.047.

Jackson, L.S., J.A. Crook, and P.M. Forster, 2016: An intensified hydrological cycle in the simulation of geoengineering by cirrus cloud thinning using ice crystal fall speed changes. *Journal of Geophysical Research*, **121(12)**, 6822-6840, doi:10.1002/2015JD024304.

Jackson, L.S. et al., 2015: Assessing the controllability of Arctic sea ice extent by sulfate aerosol geoengineering. *Geophysical Research Letters*, **42(4)**, doi:10.1002/2014GL062240.

Jackson, T. and P. Senker, 2011: Prosperity without growth: Economics for a finite planet. *Energy & Environment*, **22(7)**, 1013-1016.

Jacobi, J., S. Rist, and M.A. Altieri, 2017: Incentives and disincentives for diversified agroforestry systems from different actors' perspectives in Bolivia. *International Journal of Agricultural Sustainability*, **15(4)**, 365-379, doi:10.1080/14735903.2017.1332140.

Jacobson, M.Z. and J.E. Ten Hoeve, 2012: Effects of urban surfaces and white roofs on global and regional climate. *Journal of Climate*, **25(3)**, 1028-1044, doi:10.1175/JCLI-D-11-00032.1.

Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, B.A. Frew, and S. Polasky, 2015: Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes. *Proceeding of the National Academy of Sciences of the United States of America*, 15060-15065, doi:10.1073/pnas.1510028112.

Jacobson, M.Z. et al., 2017: 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule*, **1(1)**, 108-121, doi:10.1016/j.joule.2017.07.005.

Jaeger, C.C., A. Haas, and K. Töpfer, 2013: Sustainability, Finance, and a Proposal from China. 1-35 pp.

Jägermeyr, J. et al., 2015: Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrology and Earth System Sciences*, **19(7)**, 3073-3091, doi:10.5194/hess-19-3073-2015.

Jaglin, S., 2014: Regulating Service Delivery in Southern Cities: Rethinking urban heterogeneity. In: *The Routledge Handbook on Cities of the Global South* [Parnell, S. and S. Oldfield (eds.)]. Routledge, Abingdon, UK, pp. 636.

Jahandideh-Tehrani, M., O. Bozorg Haddad, and H.A. Loáiciga, 2014: Hydropower Reservoir Management Under Climate Change: The Karoon Reservoir System. *Water Resources Management*, **29(3)**, 749-770, doi:10.1007/s11269-014-0840-7.

Jaiswal, D. et al., 2017: Brazilian sugarcane ethanol as an expandable green alternative to crude oil use. *Nature Climate Change*, **7(11)**, 788-792, doi:10.1038/nclimate3410.

Jakob, M. and J. Hilaire, 2015: Climate science: Unburnable fossil-fuel reserves. *Nature*, **517(7533)**, 150-152, doi:10.1038/517150a.

Jakob, M., C. Chen, S. Fuss, A. Marxen, and O. Edenhofer, 2015: Development incentives for fossil fuel subsidy reform. *Nature Climate Change*, **5(8)**, 709-712, doi:10.1038/nclimate2679.

Jakob, M. et al., 2016: Carbon Pricing Revenues Could Close Infrastructure Access Gaps. *World Development*, **84**, 254-265, doi:10.1016/j.worlddev.2016.03.001.

Jakovcevic, A. and L. Steg, 2013: Sustainable transportation in Argentina: Values, beliefs, norms and car use reduction. *Transportation Research Part F: Traffic Psychology and Behaviour*, **20**, 70-79, doi:10.1016/j.trf.2013.05.005.

James, R., R. Washington, C.–F. Schleussner, J. Rogelj, and D. Conway, 2017: Characterizing half-a-degree difference: a review of methods for identifying regional climate responses to global warming targets. *Wiley Interdisciplinary Reviews: Climate Change*, **8(2)**, e457, doi:10.1002/wcc.457.

Janif, S.Z. et al., 2016: Value of traditional oral narratives in building climate-change resilience: insights from rural communities in Fiji. *Ecology and Society*, **21(2)**, doi:10.5751/ES-08100-210207.

Jansson, J., 2011: Consumer eco-innovation adoption: Assessing attitudinal factors and perceived product characteristics. *Business Strategy and the Environment*, **20(3)**, 192-210, doi:10.1002/bse.690.

Jantke, K., J. Müller, N. Trapp, and B. Blanz, 2016: Is climate-smart conservation feasible in Europe? Spatial relations of protected areas, soil carbon, and land values. *Environmental Science & Policy*, **57(Supplement C)**, 40-49, doi:10.1016/j.envsci.2015.11.013.

Jasanoff, S., 2007: Technologies of humility. *Nature*, **450(7166)**, 33-33, doi:10.1038/450033a.

Jayachandran, S. et al., 2017: Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. *Science (New York, N.Y.)*, **357(6348)**, 267-273, doi:10.1126/science.aan0568.

Jenkins, K., B.K. Sovacool, and D. McCauley, 2018: Humanizing sociotechnical transitions through energy justice: An ethical framework for global transformative change. *Energy Policy*, **117**, 66-74, doi:10.1016/J.ENPOL.2018.02.036.

Jenkins, K., S. Surminski, J. Hall, and F. Crick, 2017: Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model. *Science of the Total Environment*, **595**, 159-168, doi:10.1016/j.scitotenv.2017.03.242.

Jennings, V., L. Larson, and J. Yun, 2016: Advancing Sustainability through Urban Green Space: Cultural Ecosystem Services, Equity, and Social Determinants of Health. *International Journal of Environmental Research and Public Health*, **13(2)**, 196, doi:10.3390/ijerph13020196.

Jensen, C.B. and J.J. Spoon, 2011: Testing the 'Party Matters' Thesis: Explaining Progress towards Kyoto Protocol Targets. *Political Studies*, **59(1)**, 99-115, doi:10.1111/j.1467-9248.2010.00852.x.

Jensen, N. and C. Barrett, 2017: Agricultural index insurance for development. *Applied Economic Perspectives and Policy*, **39(2)**, 199-219, doi:10.1093/aepp/ppw022.

Jeong, S. and Y.–Y. An, 2016: Climate change risk assessment method for electrical facility. In: *2016 International Conference on Information and Communication Technology Convergence, ICTC 2016*.

Jeuland, M., S.K. Pattanayak, and R. Bluffstone, 2015: The Economics of Household Air Pollution. *Annual Review of Resource Economics*, **7(1)**, 81-108, doi:10.1146/annurev-resource-100814-125048.

Ji, Z. and F. Sha, 2015: The challenges of the post-COP21 regime: interpreting CBDR in the INDC context. *International Environmental Agreements: Politics, Law and Economics*, **15**, 421-430, doi:10.1007/s10784-015-9303-8.

Jiang, K., K. Tamura, and T. Hanaoka, 2017: Can we go beyond INDCs: Analysis of a future mitigation possibility in China, Japan, EU and the U.S.. *Advances in Climate Change Research*, **8(2)**, 117-122, doi:10.1016/j.accre.2017.05.005.

Jiang, Y. et al., 2016: Importance of soil thermal regime in terrestrial ecosystem carbon dynamics in the circumpolar north. *Global and Planetary Change*, **142**, 28-40, doi:10.1016/j.gloplacha.2016.04.011.

Jiang, Z., T. Xiao, V.L. Kuznetsov, and P.P. Edwards, 2010: Turning carbon dioxide into fuel. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, **368(1923)**, 3343-3364, doi:10.1098/rsta.2010.0119.

Jimenez, R., 2017: *Development Effects of Rural Electrification*. Policy Brief No IDB-PB-261, Infrastructure and Energy Sector - Energy Division, Inter-American Development Bank, Washington DC, USA.

Jin, J., W. Wang, and X. Wang, 2016: Farmers' Risk Preferences and Agricultural Weather Index Insurance Uptake in Rural China. *International Journal of Disaster Risk Science*, **7(4)**, 366-373, doi:10.1007/s13753-016-0108-3.

Johannessen, S.C. and R.W. Macdonald, 2016: Geoengineering with seagrasses: is credit due where credit is given? *Environmental Research Letters*, **11(11)**, 113001, doi:10.1088/1748-9326/11/11/113001.

Johnson, C. and J. Walker, 2016: *Peak car ownership report*. 30 pp.

Johnson, N. et al., 2015: The contributions of Community-Based monitoring and traditional knowledge to Arctic observing networks: Reflections on the state of the field. *Arctic*, **68(5)**, 1-13, doi:10.14430/arctic4447.

Jones, A. and J.M. Haywood, 2012: Sea-spray geoengineering in the HadGEM2-ES earth-system model: Radiative impact and climate response. *Atmospheric Chemistry and Physics*, **12(22)**, 10887-10898, doi:10.5194/acp-12-10887-2012.

Jones, A., J. Haywood, and O. Boucher, 2011: A comparison of the climate impacts of geoengineering by stratospheric SO2 injection and by brightening of marine stratocumulus cloud. *Atmospheric Science Letters*, **12(2)**, 176-183, doi:10.1002/asl.291.

Jones, A. et al., 2013: The impact of abrupt suspension of solar radiation management (termination effect) in experiment G2 of the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, **118(17)**, 9743-9752, doi:10.1002/jgrd.50762.

Jones, A.C. et al., 2018: Regional climate impacts of stabilizing global warming at 1.5 K using solar geoengineering. *Earth's Future*, 1-22, doi:10.1002/2017EF000720.

Jones, A.D., K. Calvin, W.D. Collins, and J. Edmonds, 2015: Accounting for radiative forcing from albedo change in future global land-use scenarios. *Climatic Change*, **131(4)**, 691-703, doi:10.1007/s10584-015-1411-5.

Jones, C.D. et al., 2016: Simulating the Earth system response to negative emissions. *Environmental Research Letters*, **11(9)**, 095012, doi:10.1088/1748-9326/11/9/095012.

Jones, I.S.F., 2014: The cost of carbon management using ocean nourishment. *International Journal of Climate Change Strategies and Management*, **6(4)**, 391-400, doi:10.1108/ijccsm-11-2012-0063.

Jones, L., B. Harvey, and R. Godfrey-Wood, 2016: *The changing role of NGOs in supporting climate services*. 24 pp.

Jordan, A.J. et al., 2015: Emergence of polycentric climate governance and its future prospects. *Nature Climate Change*, **5(11)**, 977-982, doi:10.1038/nclimate2725.

Joyette, A.R.T., L.A. Nurse, and R.S. Pulwarty, 2015: Disaster risk insurance and catastrophe models in risk-prone small Caribbean islands. *Disasters*, **39(3)**, 467-492, doi:10.1111/disa.12118.

Juhl, H.J., M.H.J. Fenger, and J. Thøgersen, 2017: Will the Consistent Organic Food Consumer Step Forward? An Empirical Analysis. *Journal of Consumer Research*, 1-17, doi:10.1093/jcr/ucx052.

Juhola, S., E. Glaas, B.O. Linnér, and T.S. Neset, 2016: Redefining maladaptation. *Environmental Science and Policy*, **55**, 135-140, doi:10.1016/j.envsci.2015.09.014.

K Murthy, I., 2013: Carbon Sequestration Potential of Agroforestry Systems in India. *Journal of Earth Science & Climatic Change*, **04(01)**, 1-7, doi:10.4172/2157-7617.1000131.

K.Y., N.A., A. Jonathan, B. David, L. Yufeng, and B. Austin, 2018: Implications of climate change for shipping: Opening the Arctic seas. *Wiley Interdisciplinary Reviews: Climate Change*, **9(2)**, e507, doi:10.1002/wcc.507.

Kabir, E., K.–H. Kim, and J. Szulejko, 2017: Social Impacts of Solar Home Systems in Rural Areas: A Case Study in Bangladesh. *Energies*, **10(10)**, 1615, doi:10.3390/en10101615.

Kahan, D., 2010: Fixing the communications failure. *Nature*, **463(7279)**, 296-297, doi:10.1038/463296a.

Kahneman, D., 2003: A perspective on judgment and choice: Mapping bounded rationality. *American Psychologist*, **58(9)**, 697-720, doi:10.1037/0003-066X.58.9.697.

Kaika, M., 2017: Don't call me resilient again!' The New Urban Agenda as immunology … or ... what happens when communities refuse to be vaccinated with 'smart cities' and indicators. *Environment & Urbanization*, **29(1)**, 89-102, doi:10.1177/0956247816684763.

Kale, E., 2015: Problematic Uses and Practices of Farm Ponds in Maharashtra. *Economic and Political Weekly*, **52(3)**, 7-8.

Kammann, C. et al., 2017: Biochar as a tool to reduce the agricultural greenhouse-gas burden - knowns, unknowns and future research needs. *Journal of Environmental Engineering and Landscape Management*, **25(2)**, 114-139, doi:10.3846/16486897.2017.1319375.

Kärcher, B., 2017: Cirrus Clouds and Their Response to Anthropogenic Activities. *Current Climate Change Reports*, **3(1)**, 45-57, doi:10.1007/s40641-017-0060-3.

Kardooni, R., S.B. Yusoff, and F.B. Kari, 2016: Renewable energy technology acceptance in Peninsular Malaysia. *Energy Policy*, **88**, 1-10, doi:10.1016/j.enpol.2015.10.005.

Kärki, J., E. Tsupari, and A. Arasto, 2013: CCS feasibility improvement in industrial and municipal applications by heat utilization. *Energy Procedia*, **37**, 2611-2621, doi:10.1016/j.egypro.2013.06.145.

Karlin, B., J.F. Zinger, and R. Ford, 2015: The effects of feedback on energy conservation: A meta-analysis.. *Psychological Bulletin*, **141(6)**, 1205-1227, doi:10.1037/a0039650.

Kashima, Y., A. Paladino, and E.A. Margetts, 2014: Environmentalist identity and environmental striving. *Journal of Environmental Psychology*, **38**, 64-75, doi:10.1016/j.jenvp.2013.12.014.

Kashimura, H. et al., 2017: Shortwave radiative forcing, rapid adjustment, and feedback to the surface by sulfate geoengineering: Analysis of the Geoengineering Model Intercomparison Project G4 scenario. *Atmospheric Chemistry and Physics*, **17(5)**, 3339-3356, doi:10.5194/acp-17-3339-2017.

Kasser, T. and K.M. Sheldon, 2002: What Makes for a Merry Christmas? *Journal of Happiness Studies*, **3(4)**, 313-329, doi:10.1023/A:1021516410457.

Kasser, T., S. Cohn, A.D. Kanner, and R.M. Ryan, 2007: Some Costs of American Corporate Capitalism: A Psychological Exploration of Value and Goal Conflicts. *Psychological Inquiry*, **18(1)**, 1-22, doi:10.1080/10478400701386579.

Kastner, I. and P.C. Stern, 2015: Examining the decision-making processes behind household energy investments: A review. *Energy Research and Social Science*, **10**, 72-89, doi:10.1016/j.erss.2015.07.008.

Kates, R.W., W.R. Travis, and T.J. Wilbanks, 2012: Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, **109(19)**, 7156-61, doi:10.1073/pnas.1115521109.

Kato, T. and J. Ellis, 2016: Communicating Progress in National and Global Adaptation to Climate Change. OECD/IEA Climate Change Expert Group Papers No. 47, 47 pp.

Kauffman, S.A., 2002: Investigations. , 308.

KCCA, 2016: *Kampala Climate Change Action Plan*. Kampala Capital City Authority, Kampala, Uganda.

Keen, M., I. Parry, and J. Strand, 2013: Planes, ships and taxes: charging for international aviation and maritime emissions. *Economic Policy*, **28(76)**, 701-749, doi:10.1111/1468-0327.12019.

Keim, M.E., 2008: Adaptation to Climate Change. *American Journal of Preventive Medicine*, **35(5)**, 508-516, doi:10.1016/j.amepre.2008.08.022.

Keith, D.W. and P.J. Irvine, 2016: Solar geoengineering could substantially reduce climate risks - a research hypothesis for the next decade. *Earth's Future*, **4(11)**, 549-559, doi:10.1002/2016EF000465.

Keith, D.W., M. Ha-Duong, and J.K. Stolaroff, 2006: Climate Strategy with CO2 Capture from the Air. *Climatic Change*, **74(1-3)**, 17-45, doi:10.1007/s10584-005-9026-x.

Keith, D.W., G. Wagner, and C.L. Zabel, 2017: Solar geoengineering reduces atmospheric carbon burden. *Nature Climate Change*, **7(9)**, 617-619, doi:10.1038/nclimate3376.

Keller, D.P., E.Y. Feng, and A. Oschlies, 2014: Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications*, **5**, 3304, doi:10.1038/ncomms4304.

Keller, D.P. et al., 2018: The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6. *Geoscientific Model Development*, **11(3)**, 1133-1160, doi:10.5194/gmd-11-1133-2018.

Kelleway, J.J. et al., 2017: Review of the ecosystem service implications of mangrove encroachment into salt marshes. *Global Change Biology*, **23(10)**, 3967-3983, doi:10.1111/gcb.13727.

Kelman, I., 2015: Difficult decisions: Migration from Small Island Developing States under climate change. *Earth's Future*, **3(4)**, 133-142, doi:10.1002/2014EF000278.

Kelman, I., 2017: Linking disaster risk reduction, climate change, and the sustainable development goals. *Disaster Prevention and Management: An International Journal*, **26(3)**, 254-258, doi:10.1108/DPM-02-2017-0043.

Kelman, I., J.C. Gaillard, and J. Mercer, 2015: Climate Change's Role in Disaster Risk Reduction's Future: Beyond Vulnerability and Resilience. *International Journal of Disaster Risk Science*, **6(1)**, 21-27, doi:10.1007/s13753-015-0038-5.

Kemper, J., 2015: Biomass and carbon dioxide capture and storage: A review. *International Journal of Greenhouse Gas Control*, **40**, 401-430, doi:10.1016/j.ijggc.2015.06.012.

Kennedy, C., I.D. Stewart, M.I. Westphal, A. Facchini, and R. Mele, 2018: Keeping global climate change within 1.5 °C through net negative electric cities. *Current Opinion in Environmental Sustainability*, **30**, 18-25, doi:10.1016/j.cosust.2018.02.009.

Kennedy, C.A. et al., 2015: Energy and material flows of megacities. *Proceedings of the National Academy of Sciences*, **112(19)**, 5985-5990, doi:10.1073/pnas.1504315112.

Kenworthy, J. and P.L. Schiller, 2018: *An Introduction to Sustainable Transportortation: Policy, Planning and Implementation*. Routledge, Abingdon, Oxon; New York, NY, 442 pp.

Keohane, R.O. and D.G. Victor, 2011: The Regime Complex for Climate Change. *Perspectives on Politics*, **9(1)**, 7-23, doi:10.1017/S1537592710004068.

Kern, F. and K.S. Rogge, 2016: The pace of governed energy transitions: Agency, international dynamics and the global Paris agreement accelerating decarbonisation processes? *Energy Research and Social Science*, **22**, 13-17, doi:10.1016/j.erss.2016.08.016.

Kern, F., J. Gaede, J. Meadowcroft, and J. Watson, 2016: The political economy of carbon capture and storage: An analysis of two demonstration projects. *Technological Forecasting and Social Change*, **102**, 250-260, doi:10.1016/j.techfore.2015.09.010.

Kern, K. and G. Alber, 2009: Governing Climate Change in Cities: Modes of Urban Climate Governance in Multi-level Systems. In: *The international conference on Competitive Cities and Climate Change, Milan, Italy*. OECD, Paris, France, pp. 171-196.

Kerstholt, J., H. Duijnhoven, and D. Paton, 2017: Flooding in The Netherlands: How people's interpretation of personal, social and institutional resources influence flooding preparedness. *International Journal of Disaster Risk Reduction*, **24(August 2016)**, 52-57, doi:10.1016/j.ijdrr.2017.05.013.

Keskitalo, E.C.H., H. Dannevig, G.K. Hovelsrud, J.J. West, and G. Swartling, 2011: Adaptive capacity determinants in developed states: Examples from the Nordic countries and Russia. *Regional Environmental Change*, **11(3)**, 579-592, doi:10.1007/s10113-010-0182-9.

Kettle, N.P. et al., 2014: Integrating scientific and local knowledge to inform risk-based management approaches for climate adaptation. *Climate Risk Management*, **4**, 17-31.

Khan, M.R., 2013: Toward a binding climate change adaptation regime: a proposed framework. .

Kholod, N. and M. Evans, 2016: Reducing black carbon emissions from diesel vehicles in Russia: An assessment and policy recommendations. *Environmental Science & Policy*, **56**, 1-8, doi:10.1016/j.envsci.2015.10.017.

Kilpeläinen, A. et al., 2017: Effects of Initial Age Structure of Managed Norway Spruce Forest Area on Net Climate Impact of Using Forest Biomass for Energy. *BioEnergy Research*, **10(2)**, 499-508, doi:10.1007/s12155-017-9821-z.

Kim, S. and W. Shin, 2017: Understanding American and Korean Students ' Support for Pro-environmental Tax Policy : The Application of the Value - Belief - Norm Theory of Environmentalism. *Environmental Communication*, **11**, 311-331, doi:10.1080/17524032.2015.1088458.

Kim, S.C. and Y. Chung, 2017: Dynamics of Nuclear Power Policy in the Post-Fukushima Era: Interest Structure and Politicisation in Japan, Taiwan and Korea. *Asian Studies Review*, **42(1)**, 107-124, doi:10.1080/10357823.2017.1408569.

Kimball, S. et al., 2015: Cost-effective ecological restoration. *Restoration Ecology*, **23(6)**, 800-810, doi:10.1111/rec.12261.

Kimura, S., 2016: When a Seawall Is Visible: Infrastructure and Obstruction in Post-tsunami Reconstruction in Japan. *Science as Culture*, **25(1)**, 23-43, doi:10.1080/09505431.2015.1081501.

King, S.D., 2011: *Losing control: the emerging threats to Western prosperity*. Yale University Press, New Haven, CT, USA and London, UK, 304 pp.

Kinley, R., 2017: Climate change after Paris: from turning point to transformation. *Climate Policy*, **17(1)**, 9-15, doi:10.1080/14693062.2016.1191009.

Kirk, E.J., 2017: Alternatives-Dealing with the perfect storm: Cuban disaster management. *Studies in Political Economy*, **98(1)**, 93-103, doi:10.1080/07078552.2017.1297047.

Kita, S.M., 2017: "Government Doesn't Have the Muscle": State, NGOs, Local Politics, and Disaster Risk Governance in Malawi. *Risk, Hazards & Crisis in Public Policy*, **8(3)**, 244-267, doi:10.1002/rhc3.12118.

Kiunsi, R., 2013: The constraints on climate change adaptation in a city with a large development deficit: the case of Dar es Salaam. *Environment and Urbanization*, **25(2)**, 321-337, doi:10.1177/0956247813489617.

Kivimaa, P. and F. Kern, 2016: Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. *Research Policy*, **45(1)**, 205-217, doi:10.1016/j.respol.2015.09.008.

Klepper, G. and W. Rickels, 2014: Climate Engineering: Economic Considerations and Research Challenges. *Review of Environmental Economics and Policy*, **8(2)**, 270-289, doi:10.1093/reep/reu010.

Klimont, Z. et al., 2017: Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics*, **17(14)**, 8681-8723, doi:10.5194/acp-17-8681-2017.

Kline, K.L. et al., 2017: Reconciling food security and bioenergy: priorities for action. *GCB Bioenergy*, **9(3)**, 557-576, doi:10.1111/gcbb.12366.

Kloeckner, C.A., E. Matthies, and M. Hunecke, 2003: Operationalizing Habits and Integrating Habits in Normative Decision-Making Models. *Journal of Applied Social Psychology*, **33(2)**, 396-417.

Klotz, L., 2011: Cognitive biases in energy decisions during the planning, design, and construction of commercial buildings in the United States: An analytical framework and research needs. *Energy Efficiency*, **4(2)**, 271-284, doi:10.1007/s12053-010-9089-z.

Knight, P.J., T. Prime, J.M. Brown, K. Morrissey, and A.J. Plater, 2015: Application of flood risk modelling in a web-based geospatial decision support tool for coastal adaptation to climate change. *Natural Hazards and Earth System Sciences*, **15(7)**, doi:10.5194/nhess-15-1457-2015.

Knoop, K. and S. Lechtenböhmer, 2017: The potential for energy efficiency in the EU Member States - A comparison of studies. *Renewable and Sustainable Energy Reviews*, **68**, 1097-1105, doi:10.1016/j.rser.2016.05.090.

Knowlton, K. et al., 2014: Development and Implementation of South Asia's First Heat-Health Action Plan in Ahmedabad (Gujarat, India). *International Journal of Environmental Research and Public Health*, **11(4)**, doi:10.3390/ijerph110403473.

Koch, N., S. Fuss, G. Grosjean, and O. Edenhofer, 2014: Causes of the EU ETS price drop: Recession, CDM, renewable policies or a bit of everything? - New evidence. *Energy Policy*, **73**, 676-685, doi:10.1016/j.enpol.2014.06.024.

Koch, N., G. Grosjean, S. Fuss, and O. Edenhofer, 2016: Politics matters: Regulatory events as catalysts for price formation under cap-and-trade. *Journal of Environmental Economics and Management*, **78**, 121-139, doi:10.1016/j.jeem.2016.03.004.

Koerth, J., A.T. Vafeidis, and J. Hinkel, 2017: Household-Level Coastal Adaptation and Its Drivers: A Systematic Case Study Review. *Risk Analysis*, **37(4)**, 629-646, doi:10.1111/risa.12663.

Koezjakov, A., D. Urge-Vorsatz, W. Crijns-Graus, and M. van den Broek, 2018: The relationship between operational energy demand and embodied energy in Dutch residential buildings. *Energy and Buildings*, **165**, 233-245, doi:10.1016/j.enbuild.2018.01.036.

Köhler, P., J. Hartmann, and D.A. Wolf-Gladrow, 2010: Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proc Natl Acad Sci U S A*, **107(47)**, 20228-20233, doi:10.1073/pnas.1000545107.

Köhler, P., J.F. Abrams, C. Volker, J. Hauck, and D.A. Wolf-Gladrow, 2013: Geoengineering impact of open ocean dissolution of olivine on atmospheric CO2, surface ocean pH and marine biology. *Environmental Research Letters*, **8(1)**, doi:Artn 014009 10.1088/1748-9326/8/1/014009.

Kolstad, C. et al., 2014: Social, Economic and Ethical Concepts and Methods. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. pp. 207-282.

Komarnicki, P., 2016: Energy storage systems: power grid and energy market use cases. *Archives of Electrical Engineering*, **65**, 495, doi:10.1515/aee-2016-0036.

Kona, A., P. Bertoldi, G. Melica, and S. Rivas, 2018: Covenant of Mayors signatories leading the way towards 1.5 degree global warming pathway. *Sustainable Cities and Society* (in press).

Koomey, J., N.E. Hultman, and A. Grubler, 2017: A reply to "Historical construction costs of global nuclear power reactors". *Energy Policy*, **102**, 640-643, doi:https://doi.org/10.1016/j.enpol.2016.03.052.

Koomey, J.G., H.S. Matthews, and E. Williams, 2013: Smart everything: Will intelligent systems reduce resource use? *Annual Review of Environment and Resources*, **38**, 17.1-17.33.

Kossoy, A. et al., 2015: *State and Trends of Carbon Pricing October 2015*. The World Bank, Washington DC, 140 pp.

Kosugi, T., 2013: Fail-safe solar radiation management geoengineering. *Mitigation and Adaptation Strategies for Global Change*, **18(8)**, 1141-1166, doi:10.1007/s11027-012-9414-2.

Kothari, U., 2014: Political discourses of climate change and migration: resettlement policies in the Maldives. *The Geographical Journal*, **180(2)**, 130-140, doi:10.1111/geoj.12032.

Kotilainen, K. and U.A. Saari, 2018: Policy Influence on Consumers' Evolution into Prosumers-Empirical Findings from an Exploratory Survey in Europe. *Sustainability*, **2018(10)**, doi:10.3390/su10010186.

Kraucunas, I. et al., 2015: Investigating the nexus of climate, energy, water, and land at decision-relevant scales: the Platform for Regional Integrated Modeling and Analysis (PRIMA). *Climatic Change*, **129(3-4)**, 573-588, doi:10.1007/s10584-014-1064-9.

Kravitz, B. et al., 2011: The Geoengineering Model Intercomparison Project (GeoMIP). *Atmospheric Science Letters*, **12(2)**, 162-167, doi:10.1002/asl.316.

Kravitz, B. et al., 2013: Sea spray geoengineering experiments in the geoengineering model intercomparison project (GeoMIP): Experimental design and preliminary results. *Journal of Geophysical Research Atmospheres*, **118(19)**, 11175-11186, doi:10.1002/jgrd.50856.

Kraxner, F. et al., 2014: BECCS in South Korea - Analyzing the negative emissions potential of bioenergy as a mitigation tool. *Renewable Energy*, **61**, 102-108, doi:10.1016/J.RENENE.2012.09.064.

Kreidenweis, U. et al., 2016: Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environmental Research Letters*, **11(8)**, 085001, doi:10.1088/1748-9326/11/8/085001.

Kreuz, S. and F. Müsgens, 2017: The German Energiewende and its roll-out of renewable energies: An economic perspective. *Frontiers in Energy*, 1-9.

Kriegler, E., O. Edenhofer, L. Reuster, G. Luderer, and D. Klein, 2013: Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change*, **118(1)**, 45-57, doi:10.1007/s10584-012-0681-4.

Kristjánsson, J.E., H. Muri, and H. Schmidt, 2015: The hydrological cycle response to cirrus cloud thinning. *Geophysical Research Letters*, **42(24)**, 10807-10815, doi:10.1002/2015GL066795.

Krugman, P., 2009: *The Return of Depression Economics and the Crisis of 2008*. W.W. Norton & Company Inc, New York, NY, USA, 207 pp.

Kryvasheyeu, Y. et al., 2016: Rapid assessment of disaster damage using social media activity. *Science Advances*, **2(3)**, e1500779-e1500779, doi:10.1126/sciadv.1500779.

Kull, D. et al., 2016: Building Resilience: World Bank Group Experience in Climate and Disaster Resilient Development. *Climate Change Adaptation Strategies -- An Upstream-downstream Perspective*, 255-270, doi:10.1007/978-3-319-40773-9_14.

Kuramochi, T. et al., 2018: Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, **18(3)**, 287-305, doi:10.1080/14693062.2017.1397495.

Kurdgelashvili, L., J. Li, C.–H. Shih, and B. Attia, 2016: Estimating technical potential for rooftop photovoltaics in California, Arizona and New Jersey. *Renewable Energy*, **95(Supplement C)**, 286-302, doi:https://doi.org/10.1016/j.renene.2016.03.105.

Kuruppu, N. and D. Liverman, 2011: Mental preparation for climate adaptation: The role of cognition and culture in enhancing adaptive capacity of water management in Kiribati. *Global Environmental Change*, **21(2)**, 657-669, doi:10.1016/j.gloenvcha.2010.12.002.

Kuruppu, N. and R. Willie, 2015: Barriers to reducing climate enhanced disaster risks in Least Developed Country-Small Islands through anticipatory adaptation. *Weather and Climate Extremes*, **7**, 72-83, doi:10.1016/j.wace.2014.06.001.

Kverndokk, S. and K.E. Rosendahl, 2007: Climate policies and learning by doing: Impacts and timing of technology subsidies. *Resource and Energy Economics*, **29(1)**, 58-82, doi:10.1016/j.reseneeco.2006.02.007.

La Rovere, E.L., C. Gesteira, C. Grottera, and W. William, 2017a: Pathways to a low carbon economy in Brazil. In: *Brazil in the Anthropocene: Conflicts between predatory development and environmental policies* [Issberner, L.–R. and P. Léna (eds.)]. pp. 243-266.

La Rovere, E.L., J.–C. Hourcade, S. Priyadarshi, E. Espagne, and B. Perrissin-Fabert, 2017b: Social Value of Mitigation Activities and forms of Carbon Pricing. CIRED Working Papers: 2017-60, 8 pp.

Labanca, N. (ed.), 2017: *Complex Systems and Social Practices in Energy Transitions: Framing Energy Sustainability in the Time of Renewables*. Springer, 337 pp.

Labbé, J., J.D. Ford, M. Araos, and M. Flynn, 2017: The government-led climate change adaptation landscape in Nunavut, Canada. *Environmental Reviews*, **25(1)**, 12-25, doi:10.1139/er-2016-0032.

Lacasse, K., 2015: The Importance of Being Green. *Environment and Behavior*, **47(7)**, 754-781, doi:10.1177/0013916513520491.

Lacasse, K., 2016: Don't be satisfied, identify! Strengthening positive spillover by connecting pro-environmental behaviors to an "environmentalist" label. *Journal of Environmental Psychology*, **48**, 149-158, doi:10.1016/j.jenvp.2016.09.006.

Lachapelle, E., R. MacNeil, and M. Paterson, 2017: The political economy of decarbonisation: from green energy 'race' to green 'division of labour'. *New Political Economy*, **22(3)**, 311-327, doi:10.1080/13563467.2017.1240669.

Lackner, K.S. et al., 2012: The urgency of the development of CO2 capture from ambient air. *Proceedings of the National Academy of Sciences*, **109(33)**, 13156-13162, doi:10.1073/pnas.1108765109.

Läderach, P. et al., 2017: Climate change adaptation of coffee production in space and time. *Climatic Change*, **141(1)**, 47-62, doi:10.1007/s10584-016-1788-9.

Lahn, B., 2017: In the light of equity and science: scientific expertise and climate justice after Paris. *International Environmental Agreements: Politics, Law and Economics*, doi:10.1007/s10784-017-9375-8.

Lahn, B. and G. Sundqvist, 2017: Science as a "fixed point"? Quantification and boundary objects in international climate politics. *Environmental Science & Policy*, **67(Supplement C)**, 8-15, doi:https://doi.org/10.1016/j.envsci.2016.11.001.

Lam, N.S.–N., Y. Qiang, H. Arenas, P. Brito, and K.– Liu, 2015: Mapping and assessing coastal resilience in the Caribbean region. *Cartography and Geographic Information Science*, **42(4)**, 315-322, doi:10.1080/15230406.2015.1040999.

Lamb, W.F. et al., 2014: Transitions in pathways of human development and carbon emissions. *Environmental Research Letters*, **9(1)**, 014011, doi:10.1088/1748-9326/9/1/014011.

Lamond, J.E., C.B. Rose, and C.A. Booth, 2015: Evidence for improved urban flood resilience by sustainable drainage retrofit. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning*, **168(2)**, 101-111, doi:10.1680/udap.13.00022.

Lampert, D.J., H. Cai, and A. Elgowainy, 2016: Wells to wheels: water consumption for transportation fuels in the United States. *Energy & Environmental Science*, **9(3)**, 787-802, doi:10.1039/C5EE03254G.

Lampin, L.B.A., F. Nadaud, F. Grazi, and J.–C. Hourcade, 2013: Long-term fuel demand: Not only a matter of fuel price. *Energy Policy*, **62**, 780-787, doi:10.1016/j.enpol.2013.05.021.

Larsen, J.N. et al., 2014: Polar Regions. *Climate Change 2014: Impacts, Adaptation and Vulnerability*, 1567-1612, doi:10.1017/CBO9781107415386.008.

Larsen, K. and U. Gunnarsson-Östling, 2009: Climate change scenarios and citizen-participation: Mitigation and adaptation perspectives in constructing sustainable futures. *Habitat International*, **33(3)**, 260-266, doi:10.1016/j.habitatint.2008.10.007.

Larson, W. and W. Zhao, 2017: Telework: Urban Form, Energy Consumption, and Greenhouse Gas Implications. *Economic Inquiry*, **55(2)**, 714-735, doi:10.1111/ecin.12399.

Larsson, L., E.C.H. Keskitalo, and J. Åkermark, 2016: Climate Change Adaptation and Vulnerability Planning within the Municipal and Regional System: Examples from Northern Sweden. *Journal of Northern Studies*, **10(1)**, 61-90.

Lasco, R.D., R.J.P. Delfino, and M.L.O. Espaldon, 2014: Agroforestry systems: helping smallholders adapt to climate risks while mitigating climate change. *Wiley Interdisciplinary Reviews: Climate Change***, 5(6)**, 825-833, doi:10.1002/wcc.301.

Lashley, J.G. and K. Warner, 2015: Evidence of demand for microinsurance for coping and adaptation to weather extremes in the Caribbean. *Climatic Change***, 133(1)**, 101-112, doi:10.1007/s10584-013-0922-1.

Latham, J., B. Parkes, A. Gadian, and S. Salter, 2012: Weakening of hurricanes via marine cloud brightening (MCB). *Atmospheric Science Letters***, 13(4)**, 231-237, doi:10.1002/asl.402.

Latham, J., J. Kleypas, R. Hauser, B. Parkes, and A. Gadian, 2013: Can marine cloud brightening reduce coral bleaching? *Atmospheric Science Letters***, 14(4)**, 214-219, doi:10.1002/asl2.442.

Laurance, W.F. and G.B. Williamson, 2001: Positive Feedbacks among Forest Fragmentation, Drought, and Climate Change in the Amazon. *Conservation Biology***, 15(6)**, 1529-1535, doi:10.1046/j.1523-1739.2001.01093.x.

Lauren, N., K.S. Fielding, L. Smith, and W.R. Louis, 2016: You did, so you can and you will: Self-efficacy as a mediator of spillover from easy to more difficult pro-environmental behaviour. *Journal of Environmental Psychology***, 48**, 191-199, doi:10.1016/j.jenvp.2016.10.004.

Laurice Jamero, M. et al., 2017: Small-island communities in the Philippines prefer local measures to relocation in response to sea-level rise. *Nature Climate Change***, 7**, 581-586, doi:10.1038/nclimate3344.

Lauvset, S.K., J. Tjiputra, and H. Muri, 2017: Climate engineering and the ocean: effects on biogeochemistry and primary production. *Biogeosciences***, 14(24)**, 5675-5691, doi:10.5194/bg-14-5675-2017.

Lawrence, M.G. and P.J. Crutzen, 2017: Was breaking the taboo on research on climate engineering via albedo modification a moral hazard, or a moral imperative? *Earth's Future***, 5(2)**, 136-143, doi:10.1002/2016EF000463.

Lazurko, A. and H.D. Venema, 2017: Financing high performance climate adaptation in agriculture: Climate bonds for multi-functional water harvesting infrastructure on the Canadian Prairies. *Sustainability***, 9(7)**, doi:10.3390/su9071237.

Le Dang, H., E. Li, J. Bruwer, and I. Nuberg, 2014: Farmers' perceptions of climate variability and barriers to adaptation: lessons learned from an exploratory study in Vietnam. *Mitigation and adaptation strategies for global change***, 19(5)**, 531-548.

Le Page, Y. et al., 2013: Sensitivity of climate mitigation strategies to natural disturbances. *Environmental Research Letters***, 8(1)**, doi:10.1088/1748-9326/8/1/015018.

Leal Filho, W. et al., 2018: Implementing climate change research at universities: Barriers, potential and actions. *Journal of Cleaner Production***, 170(1)**, 269-277, doi:10.1016/j.jclepro.2017.09.105.

Leape, J., 2006: The London Congestion Charge. *Journal of Economic Perspectives***, 20(4)**, 157-176, doi:10.1257/jep.20.4.157.

Leck, H. and D. Roberts, 2015: What lies beneath: understanding the invisible aspects of municipal climate change governance. *Current Opinion in Environmental Sustainability***, 13**, 61-67, doi:10.1016/j.cosust.2015.02.004.

Leck, H., D. Conway, M. Bradshaw, and J. Rees, 2015: Tracing the Water-Energy-Food Nexus: Description, Theory and Practice. *Geography Compass***, 9(8)**, 445-460, doi:10.1111/gec3.12222.

Lecuyer, O. and P. Quirion, 2013: Can uncertainty justify overlapping policy instruments to mitigate emissions? *Ecological Economics***, 93**, 177-191, doi:10.1016/j.ecolecon.2013.05.009.

Lee, T. and M. Painter, 2015: Comprehensive local climate policy: The role of urban governance. *Urban Climate***, 14**, 566-577, doi:10.1016/j.uclim.2015.09.003.

Leeson, D., N. Mac Dowell, N. Shah, C. Petit, and P.S. Fennell, 2017: A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control***, 61**, 71-84, doi:https://doi.org/10.1016/j.ijggc.2017.03.020.

Lefevre, C.E. et al., 2015: Heat protection behaviors and positive affect about heat during the 2013 heat wave in the United Kingdom. *Social Science & Medicine***, 128**, 282-289, doi:10.1016/j.socscimed.2015.01.029.

Lefèvre, J., W. Wills, and J.–C. Hourcade, 2018: Combining low-carbon economic development and oil exploration in Brazil? An energy-economy assessment. *Climate Policy*, 1-10, doi:10.1080/14693062.2018.1431198.

Leijten, F.R.M. et al., 2014: Factors that influence consumers' acceptance of future energy systems: the effects of adjustment type, production level, and price. *Energy Efficiency***, 7(6)**, 973-985e, doi:10.1007/s12053-014-9271-9.

Lemos, M.C., 2015: Usable climate knowledge for adaptive and co-managed water governance. *Current Opinion in Environmental Sustainability***, 12**, 48-52, doi:10.1016/j.cosust.2014.09.005.

Lemos, M.C., Y.J. Lo, D.R. Nelson, H. Eakin, and A.M. Bedran-Martins, 2016: Linking development to climate adaptation: Leveraging generic and specific capacities to reduce vulnerability to drought in NE Brazil. *Global Environmental Change***, 39**, 170-179, doi:10.1016/j.gloenvcha.2016.05.001.

Lempert, R.J. and D. Prosnitz, 2011: *Governing geoengineering research: a political and technical vulnerability analysis of potential near-term options*. RAND Corporation, Santa Monica, CA, 93 pp.

Lenferna, G.A., R.D. Russotto, A. Tan, S.M. Gardiner, and T.P. Ackerman, 2017: Relevant climate response tests for stratospheric aerosol injection: A combined ethical and scientific analysis. *Earth's Future*, 577-591, doi:10.1002/2016EF000504.

Lenton, T.M., 2010: The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. *Carbon Management*, **1(1)**, 145-160, doi:10.4155/cmt.10.12.

Lenton, T.M., 2014: The Global Potential for Carbon Dioxide Removal. *Geoengineering of the Climate System*, 52-79, doi:10.1039/9781782621225-00052.

Lesnikowski, A., J.D. Ford, R. Biesbroek, L. Berrang-Ford, and S.J. Heymann, 2016: National-level progress on adaptation. *Nature Climate Change*, **6**, 261-266, doi:10.1038/nclimate2863.

Lesnikowski, A. et al., 2017: What does the Paris Agreement mean for adaptation? *Climate Policy*, **17(7)**, 825-831, doi:10.1080/14693062.2016.1248889.

Lesnikowski, A.C., J.D. Ford, L. Berrang-Ford, M. Barrera, and J. Heymann, 2015: How are we adapting to climate change? A global assessment. *Mitigation and Adaptation Strategies for Global Change*, **20(2)**, 277-293, doi:10.1007/s11027-013-9491-x.

Levy, D.L. and D. Egan, 2003: A Neo-Gramscian Approach to Corporate Political Strategy: Conflict and Accommodation in the Climate Change Negotiations. *Journal of Management Studies*, **40(4)**, 803-829.

Lewandowski, M., 2016: Designing the Business Models for Circular Economy-Towards the Conceptual Framework. *Sustainability*, **8(1)**, 43, doi:10.3390/su8010043.

Li, F. et al., 2017: Urban ecological infrastructure: an integrated network for ecosystem services and sustainable urban systems. *Journal of Cleaner Production*, **163(S1)**, S12-S18, doi:10.1016/j.jclepro.2016.02.079.

Li, H., J. He, Z.P. Bharucha, R. Lal, and J. Pretty, 2016: Improving China's food and environmental security with conservation agriculture. *International Journal of Agricultural Sustainability*, **14(4)**, 377-391, doi:10.1080/14735903.2016.1170330.

Li, J. and X. Wang, 2012: Energy and climate policy in China's twelfth five-year plan: A paradigm shift. *Energy Policy*, **41**, 519-528, doi:http://dx.doi.org/10.1016/j.enpol.2011.11.012.

Li, L. and B.P.Y. Loo, 2017: Railway Development and Air Patronage in China, 1993-2012: Implications for Low-Carbon Transport. *Journal of Regional Science*, **57(3)**, 507-522, doi:10.1111/jors.12276.

Li, N., D. Ma, and W. Chen, 2017: Quantifying the impacts of decarbonisation in China's cement sector: A perspective from an integrated assessment approach. *Applied Energy*, **185**, 1840-1848, doi:https://doi.org/10.1016/j.apenergy.2015.12.112.

Lilford, R.J. et al., 2017: Improving the health and welfare of people who live in slums.. *Lancet*, **389(10068)**, 559-570.

Lillemo, S., 2014: Measuring the effect of procrastination and environmental awareness on households' energy-saving behaviours: An empirical approach. *Energy Policy*, **66**, 249-256, doi:https://doi.org/10.1016/j.enpol.2013.10.077.

Lim-Camacho, L. et al., 2015: Facing the wave of change: stakeholder perspectives on climate adaptation for Australian seafood supply chains. *Regional Environmental Change*, **15(4)**, 595-606, doi:10.1007/s10113-014-0670-4.

Lin, A.C., 2013: Does Geoengineering Present a Moral Hazard? *Ecology Law Quarterly*, **40**, 673-712, doi:10.2307/24113611.

Lin, B.B. et al., 2017: How green is your garden?: Urban form and socio-demographic factors influence yard vegetation, visitation, and ecosystem service benefits. *Landscape and Urban Planning*, **157**, 239-246, doi:10.1016/j.landurbplan.2016.07.007.

Lin, C.S.K. et al., 2013: Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective. *Energy & Environmental Science*, doi:10.1039/c2ee23440h.

Lindenberg, S. and L. Steg, 2013: What makes organizations in market democracies adopt environmentally-friendly policies? In: *Green Organizations: Driving Change with I-O Psychology* [Huffmann, A.H. and S.R. Klein (eds.)]. Routledge, New York, pp. 93-114.

Linder, M. and M. Williander, 2017: Circular Business Model Innovation: Inherent Uncertainties. *Business Strategy and the Environment*, **26(2)**, 182-196, doi:10.1002/bse.1906.

Lindoso, D.P. et al., 2014: Integrated assessment of smallholder farming's vulnerability to drought in the Brazilian Semi-arid: a case study in Ceará. *Climatic Change*, **127(1)**, 93-105, doi:10.1007/s10584-014-1116-1.

Linnenluecke, M.K., A. Griffiths, and P.J. Mumby, 2015: Executives' engagement with climate science and perceived need for business adaptation to climate change. *Climatic Change*, **131(2)**, 321-333, doi:10.1007/s10584-015-1387-1.

Linnér, B.–O. and V. Wibeck, 2015: Dual high-stake emerging technologies: a review of the climate engineering research literature. *Wiley Interdisciplinary Reviews: Climate Change*, **6(2)**, 255-268, doi:10.1002/wcc.333.

Linnerooth-Bayer, J. and S. Hochrainer-Stigler, 2015: Financial instruments for disaster risk management and climate change adaptation. *Climatic Change*, **133(1)**, 85-100, doi:10.1007/s10584-013-1035-6.

Liu, W., W. Chen, and C. Peng, 2014: Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study. *Ecological Modelling*, **291(Supplement C)**, 6-14, doi:https://doi.org/10.1016/j.ecolmodel.2014.07.012.

Liu, W., Z. Yu, X. Xie, K. von Gadow, and C. Peng, 2018: A critical analysis of the carbon neutrality assumption in life cycle assessment of forest bioenergy systems. *Environmental Reviews*, **26(1)**, 93-101, doi:10.1139/er-2017-

0060.

Liu, X. et al., 2017: Microgrids for Enhancing the Power Grid Resilience in Extreme Conditions. *IEEE Transactions on Smart Grid*, **8(2)**, 589-597, doi:10.1109/TSG.2016.2579999.

Lizarralde, G. et al., 2015: A systems approach to resilience in the built environment: the case of Cuba. *Disasters*, **39(s1)**, s76-s95, doi:10.1111/disa.12109.

Lloyd, I.D. and M. Oppenheimer, 2014: On the Design of an International Governance Framework for Geoengineering. *Global Environmental Politics*, **14(2)**, 45-63, doi:10.1162/GLEP_a_00228.

Loboda, T., 2014: Adaptation strategies to climate change in the Arctic: a global patchwork of reactive community-scale initiatives. *Environmental Research Letters*, **9(11)**, 7-10, doi:10.1088/1748-9326/9/11/111006.

Locatelli, B., V. Evans, A. Wardell, A. Andrade, and R. Vignola, 2011: Forests and Climate Change in Latin America: Linking Adaptation and Mitigation. *Forests*, **2(4)**, 431-450, doi:10.3390/f2010431.

Locatelli, B. et al., 2015: Tropical reforestation and climate change: beyond carbon. *Restoration Ecology*, **23(4)**, 337-343, doi:10.1111/rec.12209.

Lockley, A., 2012: Comment on "Review of Methane Mitigation Technologies with Application to Rapid Release of Methane from the Arctic". *Environmental Science & Technology*, **46(24)**, 13552-13553, doi:10.1021/es303074j.

Lockley, A. and D.M. Coffman, 2016: Distinguishing morale hazard from moral hazard in geoengineering. *Environmental Law Review*, **18(3)**, 194-204, doi:10.1177/1461452916659830.

Loftus, P., A. Cohen, J.C. Long, and J.D. Jenkins, 2014: A critical review of global decarbonization scenarios: what do they tell us about feasibility? *Wiley Interdisciplinary Reviews: Climate Change*, **6(1)**, 93-112, doi:10.1002/wcc.324.

Lohmann, U. and B. Gasparini, 2017: A cirrus cloud climate dial? *Science*, **357(6348)**, 248-249, doi:10.1126/science.aan3325.

Lokhorst, A.M., C. Werner, H. Staats, E. van Dijk, and J.L. Gale, 2013: Commitment and Behavior Change: A Meta-Analysis and Critical Review of Commitment-Making Strategies in Environmental Research. *Environment and Behavior*, **45(1)**, 3-34, doi:10.1177/0013916511411477.

Loladze, I., 2014: Hidden shift of the ionome of plants exposed to elevated CO2 depletes minerals at the base of human nutrition. *eLife*, **2014(3)**, 1-29, doi:10.7554/eLife.02245.

Lomax, G., M. Workman, T. Lenton, and N. Shah, 2015: Reframing the policy approach to greenhouse gas removal technologies. *Energy Policy*, **78(Supplement C)**, 125-136, doi:https://doi.org/10.1016/j.enpol.2014.10.002.

Lombardi, M., P. Pazienza, and R. Rana, 2016: The EU environmental-energy policy for urban areas: The Covenant of Mayors, the ELENA program and the role of ESCos. *Energy Policy*, **93(December)**, 33-40, doi:10.1016/j.enpol.2016.02.040.

Long, J. and J. Shepherd, 2014: The Strategic Value of Geoengineering Research. In: *Global Environmental Change. Handbook of Global Environmental Pollution* [Freedman, B. (ed.)]. Springer Netherlands, Dordrecht, The Netherlands, pp. 757-770.

Loock, C.–, T. Staake, and F. Thiesse, 2013: Motivating energy-efficient behavior with green IS: An investigation of goal setting and the role of defaults. *MIS Quarterly*, **37(4)**, 1313-1332.

Loring, P.A., S.C. Gerlach, and H.J. Penn, 2016: "Community work" in a climate of adaptation: Responding to change in rural Alaska. *Human Ecology*, **44(1)**, 119-128, doi:10.1007/s10745-015-9800-y.

Lourenço, T.C., R. Swart, H. Goosen, and R. Street, 2016: The rise of demand-driven climate services. *Nature Climate Change*, **6(1)**, 13-14, doi:10.1038/nclimate2836.

Lövbrand, E., M. Hjerpe, and B.–O. Linnér, 2017: Making climate governance global: how UN climate summitry comes to matter in a complex climate regime. *Environmental Politics*, **26(4)**, 1-20, doi:10.1080/09644016.2017.1319019.

Lovering, J.R., A. Yip, and T. Nordhaus, 2016: Historical construction costs of global nuclear power reactors. *Energy Policy*, **91**, 371-382, doi:10.1016/j.enpol.2016.01.011.

Lovins, A.B., T. Palazzi, R. Laemel, and E. Goldfield, 2018: Relative deployment rates of renewable and nuclear power: A cautionary tale of two metrics. *Energy Research & Social Science*, **38**, 188-192, doi:10.1016/J.ERSS.2018.01.005.

LTA, 2013: *Land Transport Master Plan 2013*. 58 pp.

LTA, 2015: *Singapore Land Transport Statistics In Brief 2014*. 2 pp.

LTA, 2017: *Annual Vehicle Statistics 2016: Motor vehicle population by vehicle type*. 1 pp.

Luderer, G. et al., 2012: The economics of decarbonizing the energy system - results and insights from the RECIPE model intercomparison. *Climatic Change*, **114(1)**, 9-37, doi:10.1007/s10584-011-0105-x.

Luderer, G. et al., 2016: *Deep decarbonisation towards 1.5 °C - 2 °C stabilisation. Policy findings from the ADVANCE project (first edition)*. The ADVANCE Consortium, 42 pp.

Luderer, G. et al., 2018: Residual fossil CO2 determining carbon dioxide removal requirements in 1.5-2°C pathways. *Nature Climate Change* (in press).

Lupíšek, A., M. Vaculíková, ManĽík, J. Hodková, and J. RůžiĽka, 2015: Design Strategies for Low Embodied Carbon and Low Embodied Energy Buildings: Principles and Examples. *Energy Procedia*, **83**, 147-156, doi:10.1016/j.egypro.2015.12.205.

Lusiana, B., M. van Noordwijk, and G. Cadisch, 2012: Land sparing or sharing? Exploring livestock fodder options in combination with land use zoning and consequences for livelihoods and net carbon stocks using the FALLOW model. *Agriculture, Ecosystems & Environment*, **159**, 145-160, doi:10.1016/j.agee.2012.07.006.

Lustick, I.S., D. Nettle, D.S. Wilson, H. Kokko, and B.A. Thayer, 2011: Institutional rigidity and evolutionary theory: Trapped on a local maximum. *Cliodynamics: The Journal of Theoretical and Mathematical History*, **2(2)**.

Lutz, W. and R. Muttarak, 2017: Forecasting societies' adaptive capacities through a demographic metabolism model. *Nature Climate Change*, **7(3)**, 177-184, doi:10.1038/nclimate3222.

Lwasa, S., 2010: Adapting urban areas in Africa to climate change: the case of Kampala. *Current Opinion in Environmental Sustainability*, **2(3)**, 166-171, doi:10.1016/j.cosust.2010.06.009.

Lwasa, S., 2017: Options for reduction of greenhouse gas emissions in the low-emitting city and metropolitan region of Kampala. *Carbon Management*, **8(3)**, 263-276, doi:10.1080/17583004.2017.1330592.

Lwasa, S. et al., 2014: Urban and peri-urban agriculture and forestry: Transcending poverty alleviation to climate change mitigation and adaptation. *Urban Climate*, **7(Supplement C)**, 92-106, doi:10.1016/j.uclim.2013.10.007.

Lwasa, S. et al., 2015: A meta-analysis of urban and peri-urban agriculture and forestry in mediating climate change. *Current Opinion in Environmental Sustainability*, **13**, 68-73, doi:10.1016/j.cosust.2015.02.003.

Ma, D., A. Hasanbeigi, L. Price, and W. Chen, 2015: Assessment of energy-saving and emission reduction potentials in China's ammonia industry. *Clean Technologies and Environmental Policy*, **17(6)**, 1633-1644, doi:10.1007/s10098-014-0896-3.

Ma, Y., 2014: A Study on Carbon Financing Innovation of Financial Institutions in China. *International Journal of Business Administration*, **5(103)**, 1923-4007, doi:10.5430/ijba.v5n4p103.

Mac Dowell, N., P.S. Fennell, N. Shah, and G.C. Maitland, 2017: The role of CO2 capture and utilization in mitigating climate change. *Nature Climate Change*, **7(4)**, 243-249, doi:10.1038/nclimate3231.

MacDonald, A.E. et al., 2016: Future cost-competitive electricity systems and their impact on US CO2 emissions. *Nature Climate Change*, **6(5)**, 526-531, doi:10.1038/nclimate2921.

MacDonald, J.P. et al., 2015: Protective factors for mental health and well-being in a changing climate: Perspectives from Inuit youth in Nunatsiavut, Labrador. *Social Science & Medicine*, **141**, 133-141, doi:10.1016/j.socscimed.2015.07.017.

Macedo, I.C., J.E.A. Seabra, and J.E.A.R. Silva, 2008: Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy*, **32(7)**, 582-595, doi:10.1016/j.biombioe.2007.12.006.

MacKay, D.J.C., 2013: Could energy-intensive industries be powered by carbon-free electricity? *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **371(1986)**, doi:10.1098/rsta.2011.0560.

Mackerron, G., 2014: Costs and economics of geoengineering. Climate Geoengineering Governance Working Paper Series: 013, 28 pp.

Maclean, J., J. Tan, D. Tirpak, V. Sonntag-O'Brien, and E. Usher, 2008: *Public Finance Mechanisms to Mobilise Investment in Climate Change Mitigation*. 40 pp.

MacMartin, D.G., K. Caldeira, and D.W. Keith, 2014: Solar geoengineering to limit the rate of temperature change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **372(2031)**, 20140134-20140134, doi:10.1098/rsta.2014.0134.

MacMartin, D.G., K.L. Ricke, and D.W. Keith, 2018: Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160454, doi:10.1098/rsta.2016.0454.

Maggioni, V. et al., 2016: A Review of Merged High-Resolution Satellite Precipitation Product Accuracy during the Tropical Rainfall Measuring Mission (TRMM) Era. *Journal of Hydrometeorology*, **17(4)**, 1101-1117, doi:10.1175/JHM-D-15-0190.1.

Maghari, B.M. and A.M. Ardekani, 2011: Genetically modified foods and social concerns. *Avicenna journal of medical biotechnology*, **3(3)**, 109-17.

Magnan, A., T. Ribera, and S. Treyer, 2015: National adaptation is also a global concern. Working Papers N°04/15, 16 pp.

Magnan, A.K. and T. Ribera, 2016: Global adaptation after Paris. *Science*, **352(6291)**, 1280-1282, doi:10.1126/science.aaf5002.

Magnan, A.K. et al., 2016: Addressing the risk of maladaptation to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **7(5)**, 646-665, doi:10.1002/wcc.409.

Magni, G., 2017: Indigenous knowledge and implications for the sustainable development agenda. *European Journal of Education*, **52(4)**, 437-447, doi:10.1111/ejed.12238.

Mahlkow, N. and J. Donner, 2017: From Planning to Implementation? The Role of Climate Change Adaptation Plans to

Tackle Heat Stress: A Case Study of Berlin, Germany. *Journal of Planning Education and Research*, **37(4)**, 385-396, doi:10.1177/0739456X16664787.

Mahoo, H. et al., 2013: Seasonal weather forecasting: integration of indigenous and scientific knowledge. In: *Innovation in smallholder farming in Africa: recent advances and recommendations. Proceedings of the International Workshop on Agricultural Innovation Systems in Africa*.

Mahoo, H. et al., 2015: Integrating indigenous knowledge with scientific seasonal forecasts for climate risk management in Lushoto district in Tanzania. CCAFS Working Paper no. 103, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark, 32 pp.

Majzoobi, A. and A. Khodaei, 2017: Application of microgrids in providing ancillary services to the utility grid. *Energy*, **123**, 555-563, doi:10.1016/j.energy.2017.01.113.

Maki, A., R.J. Burns, L. Ha, and A.J. Rothman, 2016: Paying people to protect the environment: A meta-analysis of financial incentive interventions to promote proenvironmental behaviors. *Journal of Environmental Psychology*, **47**, 242-255, doi:10.1016/j.jenvp.2016.07.006.

Malmodin, J., D. Lunden, A. Moberg, G. Andersson, and M. Nilsson, 2014: Life Cycle Assessment of ICT Carbon Footprint and Operational Electricity Use from the Operator, National, and Subscriber Perspective in Sweden. *JOURNAL OF INDUSTRIAL ECOLOGY*, **18(6)**, 829-845, doi:10.1111/jiec.12145.

Manning, D.A. and P. Renforth, 2013: Passive sequestration of atmospheric CO2 through coupled plant-mineral reactions in urban soils. *Environ Sci Technol*, **47(1)**, 135-141, doi:10.1021/es301250j.

Mannke, F., 2011: Key themes of local adaptation to climate change: results from mapping community-based initiatives in Africa. In: *Experiences of Climate Change Adaptation in Africa* [Walter Leal Filho (ed.)]. pp. 17-32.

Manville, M., D.A. King, and M.J. Smart, 2017: The Driving Downturn: A Preliminary Assessment. *Journal of the American Planning Association*, **83(1)**, 42-55, doi:10.1080/01944363.2016.1247653.

Maor, M., J. Tosun, and A. Jordan, 2017: Proportionate and disproportionate policy responses to climate change: core concepts and empirical applications. *Journal of Environmental Policy & Planning*, 1-13, doi:10.1080/1523908X.2017.1281730.

Mapfumo, P., F. Mtambanengwe, and R. Chikowo, 2016: Building on indigenous knowledge to strengthen the capacity of smallholder farming communities to adapt to climate change and variability in southern Africa. *Climate and Development*, **8(1)**, 72-82, doi:10.1080/17565529.2014.998604.

Maréchal, K., 2010: Not irrational but habitual: The importance of "behavioural lock-in" in energy consumption. *Ecological Economics*, **69(5)**, 1104-1114, doi:10.1016/j.ecolecon.2009.12.004.

Marengo, J.A. and J.C. Espinoza, 2016: Extreme seasonal droughts and floods in Amazonia: causes, trends and impacts. *International Journal of Climatology*, **36(3)**, 1033-1050, doi:10.1002/joc.4420.

Marengo, J.A. et al., 2013: Recent Extremes of Drought and Flooding in Amazonia: Vulnerabilities and Human Adaptation. *American Journal of Climate Change*, **02(02)**, 87-96, doi:10.4236/ajcc.2013.22009.

Margerum, R.D. and C.J. Robinson, 2015: Collaborative partnerships and the challenges for sustainable water management. *Current Opinion in Environmental Sustainability*, **12**, 53-58, doi:10.1016/j.cosust.2014.09.003.

Maru, Y.T., M. Stafford Smith, A. Sparrow, P.F. Pinho, and O.P. Dube, 2014: A linked vulnerability and resilience framework for adaptation pathways in remote disadvantaged communities. *Global Environmental Change*, **28**, 337-350, doi:10.1016/j.gloenvcha.2013.12.007.

Massey, E. and D. Huitema, 2016: The emergence of climate change adaptation as a new field of public policy in Europe. *Regional Environmental Change*, **16(2)**, 553-564, doi:10.1007/s10113-015-0771-8.

Massey, E., R. Biesbroek, D. Huitema, and A. Jordan, 2014: Climate policy innovation: The adoption and diffusion of adaptation policies across Europe. *Global Environmental Change*, **29**, 434-443, doi:10.1016/j.gloenvcha.2014.09.002.

Mathioudakis, V., P.W. Gerbens-Leenes, T.H. Van der Meer, and A.Y. Hoekstra, 2017: The water footprint of second-generation bioenergy: A comparison of biomass feedstocks and conversion techniques. *Journal of Cleaner Production*, **148**, 571-582, doi:10.1016/J.JCLEPRO.2017.02.032.

Mathy, S., P. Criqui, K. Knoop, M. Fischedick, and S. Samadi, 2016: Uncertainty management and the dynamic adjustment of deep decarbonization pathways. *Climate Policy*, **16(sup1)**, S47-S62, doi:10.1080/14693062.2016.1179618.

Mavhura, E., A. Collins, and P.P. Bongo, 2017: Flood vulnerability and relocation readiness in Zimbabwe. *Disaster Prevention and Management: An International Journal*, **26(1)**, 41-54, doi:10.1108/DPM-05-2016-0101.

Mazzucato, M., 2013: *The entrepreneurial state*. Anthem Press, London, UK and New York, NY, USA, 237 pp.

Mazzucato, M., 2018: *Mission-Oriented Research & Innovation in the European Union: A problem-solving approach to fuel innovation-led growth*. European Commission, Brussels, Belgium, 36 pp.

Mazzucato, M. and G. Semieniuk, 2017: Public financing of innovation: new questions. *Oxford Review of Economic Policy*, **33(1)**, 24-48, doi:10.1093/oxrep/grw036.

Mbow, C., P. Smith, D. Skole, L. Duguma, and M. Bustamante, 2014: Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Current Opinion in Environmental Sustainability*, **6(1)**, 8-14, doi:10.1016/j.cosust.2013.09.002.

McCarl, B.A., C. Peacocke, R. Chrisman, C.–C. Kung, and R.D. Sands, 2009: Economics of biochar production, utilization and greenhouse gas offsets. In: *Biochar for environmental management: Science and technology*. Earthscan: London, UK, pp. 341-358.

McClellan, J., D.W. Keith, and J. Apt, 2012: Cost analysis of stratospheric albedo modification delivery systems. *Environmental Research Letters***, 7(3)**, 034019, doi:10.1088/1748-9326/7/3/034019.

McCormick, K. and T. Kåberger, 2007: Key barriers for bioenergy in Europe: Economic conditions, know-how and institutional capacity, and supply chain co-ordination. *Biomass and Bioenergy***, 31(7)**, 443-452, doi:10.1016/j.biombioe.2007.01.008.

McCright, A.M. and R.E. Dunlap, 2011: Cool dudes: The denial of climate change among conservative white males in the United States. *Global Environmental Change***, 21(4)**, 1163-1172, doi:10.1016/j.gloenvcha.2011.06.003.

McCright, A.M., R.E. Dunlap, and C. Xiao, 2013: Perceived scientific agreement and support for government action on climate change in the USA. *Climatic Change***, 119**, 511-518, doi:10.1007/s10584-013-0704-9.

Mccubbin, S.G., T. Pearce, J.D. Ford, and B. Smit, 2017: Social - ecological change and implications for food security in Funafuti, Tuvalu. *Ecology and Society***, 22(1)**, 53-65, doi:10.5751/ES-09129-220153.

McCusker, K.E., K.C. Armour, C.M. Bitz, and D.S. Battisti, 2014: Rapid and extensive warming following cessation of solar radiation management. *Environmental Research Letters***, 9(2)**, 024005, doi:10.1088/1748-9326/9/2/024005.

McGlade, C. and P. Ekins, 2015: The geographical distribution of fossil fuels unused when limiting global warming to 2°C. *Nature***, 517(7533)**, 187-190.

McGlashan, N., N. Shah, B. Caldecott, and M. Workman, 2012: High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection***, 90(6)**, 501-510, doi:10.1016/j.psep.2012.10.004.

McGranahan, G., D. Schensul, and G. Singh, 2016: Inclusive urbanization: Can the 2030 Agenda be delivered without it? *Environment and Urbanization***, 28(1)**, 13-34, doi:10.1177/0956247815627522.

McKay, B., S. Sauer, B. Richardson, and R. Herre, 2016: The political economy of sugarcane flexing: initial insights from Brazil, Southern Africa and Cambodia. *The Journal of Peasant Studies***, 43(1)**, 195-223, doi:10.1080/03066150.2014.992016.

McKinnon, C., 2018: Sleepwalking into lock-in? Avoiding wrongs to future people in the governance of solar radiation management research. *Environmental Politics,* 1-19, doi:10.1080/09644016.2018.1450344.

McLaren, D., 2012: A comparative global assessment of potential negative emissions technologies. *Special Issue: Negative emissions technology***, 90(6)**, 489-500, doi:10.1016/j.psep.2012.10.005.

McLaren, D., 2016: Mitigation deterrence and the "moral hazard" of solar radiation management. *Earth's Future***, 4(12)**, 596-602, doi:10.1002/2016EF000445.

McMillen, H.L. et al., 2014: Small islands, valuable insights: Systems of customary resource use and resilience to climate change in the Pacific. *Ecology and Society***, 19(4)**, doi:10.5751/ES-06937-190444.

McNamara, K.E. and S.S. Prasad, 2014: Coping with extreme weather: Communities in Fiji and Vanuatu share their experiences and knowledge. *Climatic Change***, 123(2)**, 121-132, doi:10.1007/s10584-013-1047-2.

McPhearson, T. et al., 2016: Scientists must have a say in the future of cities. *Nature***, 538(7624)**, 165-166, doi:10.1038/538165a.

MDB, 2016: *Joint Report on Multilateral Development Banks' Climate Finance*. 45 pp.

Measham, T.G. et al., 2011: Adapting to climate change through local municipal planning: barriers and challenges. *Mitigation and Adaptation Strategies for Global Change***, 16(8)**, 889-909, doi:10.1007/s11027-011-9301-2.

Medek, D.E., J. Schwartz, and S.S. Myers, 2017: Estimated Effects of Future Atmospheric CO2 Concentrations on Protein Intake and the Risk of Protein Deficiency by Country and Region. *Environmental Health Perspectives***, 125(8)**, 1-8, doi:10.1289/EHP41.

Mehta, L. et al., 2014: The politics of IWRM in Southern Africa. *International Journal of Water Resources Development***, 30(3)**, 528-542, doi:10.1080/07900627.2014.916200.

Meijer, S.S., D. Catacutan, O.C. Ajayi, G.W. Sileshi, and M. Nieuwenhuis, 2015: The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. *International Journal of Agricultural Sustainability***, 13(1)**, 40-54, doi:10.1080/14735903.2014.912493.

Méjean, A., F. Lecocq, and Y. Mulugetta, 2015: Equity, burden sharing and development pathways: reframing international climate negotiations. *International Environmental Agreements: Politics, Law and Economics***, 15(4)**, 387-402, doi:10.1007/s10784-015-9302-9.

Melde, S., F. Laczko, and F. Gemenne, 2017: *Making mobility work for adaptation to environmental changes: Results from the MECLEP global research*. International Organization for Migration.

Melica, G. et al., 2018: Multilevel governance of sustainable energy policies: The role of regions and provinces to support the participation of small local authorities in the Covenant of Mayors. *Sustainable Cities and Society***, 39**, 729-739, doi:10.1016/j.scs.2018.01.013.

Melvin, A.M. et al., 2017: Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. *Proceedings of the National Academy of Sciences*, **114(2)**, E122-E131, doi:10.1073/pnas.1611056113.

Mercado, L.M. et al., 2009: Impact of changes in diffuse radiation on the global land carbon sink. *Nature*, **458(7241)**, 1014-1017, doi:10.1038/nature07949.

Mercer, D.E., 2004: Adoption of agroforestry innovations in the tropics: A review. *Agroforestry Systems*, **61-62(1-3)**, 311-328, doi:10.1023/B:AGFO.0000029007.85754.70.

Mercure, J.–F. et al., 2018: Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy Strategy Reviews*, **20**, 195-208, doi:10.1016/j.esr.2018.03.003.

Merk, C., G. Pönitzsch, and K. Rehdanz, 2016: Knowledge about aerosol injection does not reduce individual mitigation efforts. *Environmental Research Letters*, **11(5)**, 054009, doi:10.1088/1748-9326/11/5/054009.

Merk, C., G. Pönitzsch, C. Kniebes, K. Rehdanz, and U. Schmidt, 2015: Exploring public perceptions of stratospheric sulfate injection. *Climatic Change*, **130(2)**, 299-312, doi:10.1007/s10584-014-1317-7.

Merrey, D.J., 2009: African models for transnational river basin organisations in Africa: An unexplored dimension. *Water Alternatives*, **2(2)**, 183-204.

Methmann, C. and A. Oels, 2015: From 'fearing' to 'empowering' climate refugees: Governing climate-induced migration in the name of resilience. *Security Dialogue*, **46(1)**, 51-68, doi:10.1177/0967010614552548.

Meze-Hausken, E., 2004: Contrasting climate variability and meteorological drought with perceived drought and climate change in northern Ethiopia. *Climate Research*, **27**, 19-31.

Mguni, P., L. Herslund, and M.B. Jensen, 2016: Sustainable urban drainage systems: examining the potential for green infrastructure-based stormwater management for Sub-Saharan cities. *Natural Hazards*, **82(S2)**, 241-257, doi:10.1007/s11069-016-2309-x.

Michaelowa, A., 2013: The politics of climate change in Germany: ambition versus lobby power. *Wiley Interdisciplinary Reviews: Climate Change*, **4(4)**, 315-320, doi:10.1002/wcc.224.

Michaelowa, A., M. Allen, and F. Sha, 2018: Policy instruments for limiting global temperature rise to 1.5°C - can humanity rise to the challenge? *Climate Policy*, **18(3)**, 275-286, doi:10.1080/14693062.2018.1426977.

Michaelowa, K. and A. Michaelowa, 2017: Transnational Climate Governance Initiatives: Designed for Effective Climate Change Mitigation? *International Interactions*, **43(1)**, 129-155, doi:10.1080/03050629.2017.1256110.

Midden, C. and J. Ham, 2012: Persuasive technology to promote pro-environmental behaviour. In: *Environmental psychology: An introduction* [Steg, L., A.E. Berg, and J.I.M.E. de Groot (eds.)]. John Wiley & Sons, Oxford, UK, pp. 243-254.

Middlemiss, L., 2011: The effects of community-based action for sustainability on participants' lifestyles. *Local Environment*, **16(3)**, 265-280, doi:10.1080/13549839.2011.566850.

Mikunda, T. et al., 2014: Designing policy for deployment of CCS in industry. *Climate Policy*, **14(5)**, 665-676, doi:10.1080/14693062.2014.905441.

Miles, D., 1993: Testing for Short Termism in the UK Stock Market. *The Economic Journal*, **103(421)**, 1379-1396, doi:10.2307/2234472.

Milinski, M., D. Semmann, H.–J. Krambeck, and J. Marotzke, 2006: Stabilizing the Earth ' s climate is not a losing game :. *Proceeding of the National Academy of Sciences of the United States of America (PNAS)*, **103(11)**, 3994-3998.

Millard-Ball, A. and L. Schipper, 2011: Are We Reaching Peak Travel? Trends in Passenger Transport in Eight Industrialized Countries. *Transport Reviews*, **31(3)**, 357-378, doi:10.1080/01441647.2010.518291.

Mills, M.P., 2015: Shale 2.0: Technology and the Coming Big-Data Revolution in America's Shale Oil Fields. *Trends Magazine*, 21-26.

Milner, A.M. et al., 2017: Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences*, **114(37)**, 9770-9778, doi:10.1073/pnas.1619807114.

Mimura, N. et al., 2014: Adaptation Planning and Implementation. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, and M.D. Mastrandrea (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 869-898.

Minville, M., F. Brissette, S. Krau, and R. Leconte, 2009: Adaptation to climate change in the management of a Canadian water-resources system exploited for hydropower. *Water Resources Management*, **23(14)**, 2965-2986, doi:10.1007/s11269-009-9418-1.

Minx, J., W.F. Lamb, M.W. Callaghan, L. Bornmann, and S. Fuss, 2017: Fast growing research on negative emissions. *Environmental Research Letters*, **12(3)**.

Minx, J.C. et al., 2018: Negative emissions: Part 1 - research landscape and synthesis. *Environmental Research Letters* (in press), doi:10.1088/1748-9326/aabf9b.

Mir-Artigues, P. and P. del Río, 2014: Combining tariffs, investment subsidies and soft loans in a renewable electricity deployment policy. *Energy Policy*, **69**, 430-442, doi:10.1016/j.enpol.2014.01.040.

Mistry, J. and A. Berardi, 2016: Bridging indigenous and scientific knowledge. *Science*, **352(6291)**, 1274-1275, doi:10.1126/science.aaf1160.

Mitchell, D. et al., 2017: Half a degree additional warming, prognosis and projected impacts (HAPPI): background and experimental design. *Geoscientific Model Development***, 10(2)**, 571-583, doi:10.5194/gmd-10-571-2017.

Mitchell, R., 2013: *Agreement on the Establishment of the Limpopo Watercourse Commission*. South African Department of Foreign Affairs, Office of the Chief State Law Adviser (IL), Treaty and Information Management Section.

Mitlin, D., 2005: Understanding chronic poverty in urban areas. *International Planning Studies***, 10(1)**, 3-19, doi:10.1080/13563470500159220.

Mitlin, D. and D. Satterthwaite, 2013: *Urban poverty in the global South: scale and nature*. Routledge, Abingdon, UK and New York, NY, USA.

Mittal, S., H. Dai, and P.R. Shukla, 2016: Low carbon urban transport scenarios for China and India: A comparative assessment. *Transportation Research Part D: Transport and Environment***, 44**, 266-276, doi:10.1016/j.trd.2015.04.002.

Moffatt, S., 2014: Resilience and competing temporalities in cities. *Building Research & Information***, 42(2)**, 202-220, doi:10.1080/09613218.2014.869894.

Möllersten, K., J. Yan, and J. R. Moreira, 2003: Potential market niches for biomass energy with CO2 capture and storage-Opportunities for energy supply with negative CO2 emissions. *Biomass and Bioenergy***, 25(3)**, 273-285, doi:https://doi.org/10.1016/S0961-9534(03)00013-8.

Monstadt, J. and A. Wolff, 2015: Energy transition or incremental change? Green policy agendas and the adaptability of the urban energy regime in Los Angeles. *Energy Policy***, 78**, 213-224, doi:10.1016/j.enpol.2014.10.022.

Montserrat, F. et al., 2017: Olivine Dissolution in Seawater: Implications for CO2 Sequestration through Enhanced Weathering in Coastal Environments. *Environ Sci Technol***, 51(7)**, 3960-3972, doi:10.1021/acs.est.6b05942.

Montzka, S.A., E.J. Dlugokencky, and J.H. Butler, 2011: Non-CO2 Greenhouse Gases and Climate Change. *Nature***, 476**, 43-50, doi:10.1038/nature10322.

Mooij, R.A., 2000: *Environmental Taxation and the Double Dividend*. Emerald Group Publishing Ltd, Bingley, UK, 292 pp.

Moore, J.C., S. Jevrejeva, and A. Grinsted, 2010: Efficacy of geoengineering to limit 21st century sea-level rise. *Proceedings of the National Academy of Sciences***, 107(36)**, 15699-15703, doi:10.1073/pnas.1008153107.

Moreno-Cruz, J.B. and D.W. Keith, 2013: Climate policy under uncertainty: a case for solar geoengineering. *Climatic Change***, 121(3)**, 431-444, doi:10.1007/s10584-012-0487-4.

Morita, K. and K. Matsumoto, 2015: Financing Adaptation to Climate Change in Developing Countries. *Handbook of Climate Change Adaptation*, 983-1005, doi:10.1007/978-3-642-38670-1_22.

Moriyama, R. et al., 2016: The cost of stratospheric climate engineering revisited. *Mitigation and Adaptation Strategies for Global Change*, 1-22, doi:10.1007/s11027-016-9723-y.

Morrow, D.R., 2014: Starting a flood to stop a fire? Some moral constraints on solar radiation management. *Ethics, Policy & Environment***, 17(2)**, 123-138, doi:10.1080/21550085.2014.926056.

Mortreux, C. and J. Barnett, 2009: Climate change, migration and adaptation in Funafuti, Tuvalu. *Global Environmental Change***, 19(1)**, 105-112, doi:10.1016/j.gloenvcha.2008.09.006.

Moser, S.C., 2014: Communicating adaptation to climate change: The art and science of public engagement when climate change comes home. *Wiley Interdisciplinary Reviews: Climate Change***, 5(3)**, 337-358, doi:10.1002/wcc.276.

Moss, R.H. et al., 2013: Hell and High Water: Practice-Relevant Adaptation Science. *Science***, 342(6159)**, 696-698, doi:10.1126/science.1239569.

Mota-Babiloni, A., P. Makhnatch, and R. Khodabandeh, 2017: Recent investigations in HFCs substitution with lower GWP synthetic alternatives: Focus on energetic performance and environmental impact. *International Journal of Refrigeration***, 82**, 288-301, doi:10.1016/j.ijrefrig.2017.06.026.

Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy***, 64**, 48-58, doi:10.1016/J.ENVSCI.2016.06.007.

Mousavi, B. and M. Blesl, 2018: Analysis of the Relative Roles of Supply-Side and Demand-Side Measures in Tackling the Global 1.5 °C Target. In: *Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development* [Giannakidis, G., K. Karlsson, M. Labriet, and B. Gallachóir (eds.)]. Springer International Publishing, Cham, Switzerland, pp. 67-83.

Muench, S., S. Thuss, and E. Guenther, 2014: What hampers energy system transformations? The case of smart grids. *Energy Policy***, 73**, 80-92, doi:10.1016/J.ENPOL.2014.05.051.

Mullaney, J., T. Lucke, and S.J. Trueman, 2015: A review of benefits and challenges in growing street trees in paved urban environments. *Landscape and Urban Planning***, 134**, 157-166, doi:10.1016/j.landurbplan.2014.10.013.

Mulville, M., K. Jones, G. Huebner, and J. Powell-Greig, 2017: Energy-saving occupant behaviours in offices: change strategies. *Building Research & Information***, 45(8)**, 861-874, doi:10.1080/09613218.2016.1212299.

Munck, J., J.G. Rozema, and L.A. Frye-levine, 2014: Institutional inertia and climate change: a review of the new institutionalist literature. *WIREs Clim Change*, **5(October)**, 639-648, doi:10.1002/wcc.292.

Mundaca, L., 2007: Transaction costs of Tradable White Certificate schemes : The Energy Efficiency Commitment as case study. *Energy Policy*, **35**, 4340-4354, doi:10.1016/j.enpol.2007.02.029.

Mundaca, L. and A. Markandya, 2016: Assessing regional progress towards a 'Green Energy Economy'. *Applied Energy*, **179**, 1372-1394, doi:10.1016/j.apenergy.2015.10.098.

Murphy, A.G., J. Hartell, V. Cárdenas, and J.R. Skees, 2012: *Risk Management Instruments for Food Price Volatility and Weather Risk in Latin America and the Caribbean: The Use of Risk Management Instruments*. Discussion Paper, Inter-American Development Bank, 110 pp.

Murrant, D., A. Quinn, and L. Chapman, 2015: The water-energy nexus: Future water resource availability and its implications on UK thermal power generation. *Water and Environment Journal*, **29(3)**, 307-319, doi:10.1111/wej.12126.

Musall, F.D. and O. Kuik, 2011: Local acceptance of renewable energy-A case study from southeast Germany. *Energy Policy*, **39(6)**, 3252-3260, doi:10.1016/j.enpol.2011.03.017.

Mushtaq, S., 2016: Economic and policy implications of relocation of agricultural production systems under changing climate: Example of Australian rice industry. *Land Use Policy*, **52**, 277-286, doi:10.1016/J.LANDUSEPOL.2015.12.029.

Mushtaq, S., 2018: Managing climate risks through transformational adaptation: Economic and policy implications for key production regions in Australia. *Climate Risk Management*, **19**, 48-60, doi:10.1016/J.CRM.2017.12.001.

Mycoo, M., 2017: *A Blue Urban Agenda: Adapting to Climate Change in the Coastal Cities of Caribbean and Pacific Small Island Developing States*.

Myers, C.D., T. Ritter, and A. Rockway, 2017: Community Deliberation to Build Local Capacity for Climate Change Adaptation: The Rural Climate Dialogues Program. In: *Climate Change Adaptation in North America: Fostering Resilience and the Regional Capacity to Adapt* [Leal Filho, W. and J.M. Keenan (eds.)]. Springer International Publishing, Cham, pp. 9-26.

Myers, T.A., E.W. Maibach, C. Roser-Renouf, K. Akerlof, and A.A. Leiserowitz, 2012: The relationship between personal experience and belief in the reality of global warming. *Nature Climate Change*, **3**, 343-347, doi:10.1038/nclimate1754.

Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-740.

Nabernegg, S. et al., 2017: The Deployment of Low Carbon Technologies in Energy Intensive Industries: A Macroeconomic Analysis for Europe, China and India. *Energies*, **10(3)**, 360, doi:10.3390/en10030360.

Nadaï, A. and O. Labussière, 2017: Landscape commons, following wind power fault lines. The case of Seine-et-Marne (France). *Energy Policy*, **109**, 807-816, doi:10.1016/j.enpol.2017.06.049.

Nägele, F., T. Kasper, and B. Girod, 2017: Turning up the heat on obsolete thermostats: A simulation-based comparison of intelligent control approaches for residential heating systems. *Renewable and Sustainable Energy Reviews*, **75(January)**, 1254-1268, doi:10.1016/j.rser.2016.11.112.

Nair, S., B. George, H.M. Malano, M. Arora, and B. Nawarathna, 2014: Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods. *Resources, Conservation and Recycling*, **89**, 1-10, doi:10.1016/j.resconrec.2014.05.007.

Nakashima, D.J., K. Galloway McLean, H.D. Thulstrup, A. Ramos Castillo, and J.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation*. UNESCO, and Darwin, UNU, Paris, 120 pp.

Nakhooda, S. and C. Watson, 2016: Adaptation finance and the infrastructure agenda. Overseas Development Institute, London, UK, 40 pp.

Nalau, J., B.L. Preston, and M.C. Maloney, 2015: Is adaptation a local responsibility? *Environmental Science & Policy*, **48**, 89-98.

Napp, T. et al., 2017: Exploring the Feasibility of Low-Carbon Scenarios Using Historical Energy Transitions Analysis. *Energies*, **10(1)**.

Napp, T.A., A. Gambhir, T.P. Hills, N. Florin, and P.S. Fennell, 2014: A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. *Renewable and Sustainable Energy Reviews*, **30(Supplement C)**, 616-640, doi:https://doi.org/10.1016/j.rser.2013.10.036.

Natcher, D.C. et al., 2007: Notions of time and sentience: Methodological considerations for Arctic climate change research. *Arctic Anthropology*, **44(2)**, 113-126, doi:10.1353/arc.2011.0099.

NCE, 2016: *The Sustainable Infrastructure Imperative: Financing for Better Grown and Development*. The New Climate Economy (NCE), 1-12 pp.

NEC, 2011: *Second National Communication to the UNFCCC*. National Environment Commission, Royal Government of Bhutan, Thimphu, Bhutan, 160 pp.

NEC, 2015: *Communication of INDC of the Kingdom of Bhutan*. 8 pp.

Nemet, G., 2014: Solar Photovoltaics: Multiple Drivers of Technological Improvement. In: *Energy Technology Innovation* [Grubler, A. and C. Wilson (eds.)]. Cambridge University Press, Cambridge, UK, pp. 400.

Nemet, G.F., M. Jakob, J.C. Steckel, and O. Edenhofer, 2017: Addressing policy credibility problems for low-carbon investment. *Global Environmental Change*, **42**, 47-57, doi:10.1016/j.gloenvcha.2016.12.004.

Nemet, G.F. et al., 2018: Negative emissions - Part 3: Innovation and upscaling. *Environmental Research Letters* (in press), doi:10.1088/1748-9326/aabff4.

Newell, P. and M. Paterson, 1998: A Climate For Business: Global Warming, the State and Capital. *Review of International Political Economy*, **5**, 679-703.

Newell, R.G. and W.A. Pizer, 2003: Regulating stock externalities under uncertainty. *Journal of Environmental Economics and Management*, **45(2)**, 416-432, doi:10.1016/S0095-0696(02)00016-5.

Newham, M. and B. Conradie, 2013: A Critical Review of South Africa's Carbon Tax Policy Paper: Recommendations for the Implementation of an Offset Mechanism. CSSR Working Paper.

Newman, P., 2017: Decoupling Economic Growth from Fossil Fuels. *Modern Economy*, **08(06)**, 791-805.

Newman, P. and J. Kenworthy, 2011: Peak Car Use': Understanding the Demise of Automobile Dependence. *Journal of World Transport Policy and Practice*, **17(2)**, 31-42.

Newman, P. and J. Kenworthy, 2015: The End of Automobile Dependence: How Cities are Moving Beyond Car-based Planning. In: *The End of Automobile Dependence*. Island Press/Center for Resource Economics, Washington, DC, pp. 201-226.

Newman, P., L. Kosonen, and J. Kenworthy, 2016: Theory of urban fabrics: planning the walking, transit/public transport and automobile/motor car cities for reduced car dependency. *Town Planning Review*, **87(4)**, 429-458, doi:10.3828/tpr.2016.28.

Newman, P., T. Beatley, and H. Boyer, 2017: *Resilient Cities: Overcoming Fossil Fuel Dependence*. Island Press, Washington DC, USA, 264 pp.

Ngendakumana, S. et al., 2017: Implementing REDD+ : learning from forest conservation policy and social safeguards frameworks in Cameroon. *International Forestry Review*, **19(2)**, 209-223, doi:10.1505/146554817821255187.

Nguyen, T.T.T., P.J. Bowman, M. Haile-Mariam, J.E. Pryce, and B.J. Hayes, 2016: Genomic selection for tolerance to heat stress in Australian dairy cattle. *Journal of Dairy Science*, **99(4)**, 2849-2862, doi:10.3168/jds.2015-9685.

Nicholson, S., 2013: The Promises and Perils of Geoengineering. In: *State of the World 2013: Is Sustainability Still Possible?* [Worldwatch Institute (ed.)]. Island Press/Center for Resource Economics, Washington DC, USA, pp. 317-331.

Nicholson, S., S. Jinnah, and A. Gillespie, 2018: Solar radiation management: a proposal for immediate polycentric governance. *Climate Policy*, **18(3)**, 322-334, doi:10.1080/14693062.2017.1400944.

Nicolson, M., G. Huebner, and D. Shipworth, 2017: Are consumers willing to switch to smart time of use electricity tariffs? The importance of loss-aversion and electric vehicle ownership. *Energy Research and Social Science*, **23**, 82-96, doi:10.1016/j.erss.2016.12.001.

Niemeier, U. and C. Timmreck, 2015: What is the limit of climate engineering by stratospheric injection of SO2? *Atmospheric Chemistry and Physics*, **15(16)**, 9129-9141, doi:10.5194/acp-15-9129-2015.

Nierop, S.C.A., 2014: Envisioning resilient electrical infrastructure: A policy framework for incorporating future climate change into electricity sector planning. *Environmental Science and Policy*, **40**, doi:10.1016/j.envsci.2014.04.011.

Nieto, J., Carpintero, and L.J. Miguel, 2018: Less than 2 °C? An Economic-Environmental Evaluation of the Paris Agreement. *Ecological Economics*, **146**, 69-84, doi:10.1016/j.ecolecon.2017.10.007.

Nightingale, A.J., 2017: Power and politics in climate change adaptation efforts: Struggles over authority and recognition in the context of political instability. *Geoforum*, **84**, 11-20, doi:10.1016/j.geoforum.2017.05.011.

Nijland, H. and J. Meerkerk, 2017: Environmental Innovation and Societal Transitions Mobility and environmental impacts of car sharing in the Netherlands. *Environmental Innovation and Societal Transitions*, **23**, 84-91, doi:10.1016/j.eist.2017.02.001.

Nikiforos, M. and G. Zezza, 2017: Stock-flow Consistent Macroeconomic Models: A Survey. LEI Working Paper No. 891, 71 pp.

Nissinen, A. et al., 2015: Combinations of policy instruments to decrease the climate impacts of housing, passenger transport and food in Finland. *Journal of Cleaner Production*, **107**, 455-466, doi:10.1016/j.jclepro.2014.08.095.

NITI Aayog and RMI, 2017: *India Leaps Ahead: Transformative Mobility Solutions for All*. NITI Aayog and Rocky Mountain Institute (RMI), New Delhi and Colorado, 134 pp.

Nitschke, M., A. Krackowizer, L.A. Hansen, P. Bi, and R.G. Tucker, 2017: Heat Health Messages: A Randomized Controlled Trial of a Preventative Messages Tool in the Older Population of South Australia. *International Journal of Environmental Research and Public Health*, **14(9)**, doi:10.3390/ijerph14090992.

Nitschke, M. et al., 2016: Evaluation of a heat warning system in Adelaide, South Australia, using case-series analysis. *BMJ open*, **6(7)**, e012125, doi:10.1136/bmjopen-2016-012125.

Noble, I. et al., 2014: Adaptation needs and options. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-708.

Nolan, J.M., P.W. Schultz, R.B. Cialdini, N.J. Goldstein, and V. Griskevicius, 2008: Normative Social Influence is Underdetected. *Personality and Social Psychology Bulletin*, **34(7)**, 913-923, doi:10.1177/0146167208316691.

Noppers, E.H., K. Keizer, J.W. Bolderdijk, and L. Steg, 2014: The adoption of sustainable innovations : Driven by symbolic and environmental motives. *Global Environmental Change*, **25**, 52-62.

Nordhaus, W., 2015: Climate clubs: Overcoming free-riding in international climate policy. *American Economic Review*, **105(4)**, 1339-1370, doi:10.1257/aer.15000001.

North, D.C., 1990: *Institutions, institutional change and economic performance*. Cambridge Univeristy Press, Cambridge, UK, 152 pp.

Nowak, D.J., D.E. Crane, and J.C. Stevens, 2006: Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, **4(3-4)**, 115-123, doi:10.1016/j.ufug.2006.01.007.

NPCC, 2015: *A Knowledge Base for Climate Resilience in New York City: Post-Hurricane Sandy Science and Assessment*.

NRC, 2015a: *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. National Academies Press, Washington DC, USA, 154 pp.

NRC, 2015b: *Climate Intervention: Reflecting Sunlight to Cool Earth*. National Research Council (NRC). The National Academies Press, Washington DC, USA, 260 pp.

NRC, 2015c: Governance of Research and Other Sociopolitical Considerations. In: *Climate Intervention: Reflecting Sunlight to Cool Earth*. The National Academies Press, Washington DC, USA, pp. 149-175.

Nunn, P.D., J. Runman, M. Falanruw, and R. Kumar, 2017: Culturally grounded responses to coastal change on islands in the Federated States of Micronesia, northwest Pacific Ocean. *Regional Environmental Change*, **17(4)**, 959-971, doi:10.1007/s10113-016-0950-2.

Nurse, L.A. et al., 2014: Small islands. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1613-1654.

Nyagwambo, N.L., E. Chonguiça, D. Cox, and F. Monggae, 2008: *Local Governments and IWRM in the SADC Region*. Institute of Water and Sanitation Development (IWSD), Harare, Zimbabwe, 58 pp.

Nyantakyi-Frimpong, H. and R. Bezner-Kerr, 2015: The relative importance of climate change in the context of multiple stressors in semi-arid Ghana. *Global Environmental Change*, **32**, 40-56, doi:10.1016/j.gloenvcha.2015.03.003.

NYC Parks, 2010: *Designing the Edge: Creating a Living Urban Shore at Harlem River Park*. NYC Department of Parks & Recreation, Metropolitan Waterfront Alliance, Harlem River Park Task Force, NY Department of State Divison of Coastal Resources, New York, NY, USA, 52 pp.

Nyholm, E., M. Odenberger, and F. Johnsson, 2017: An economic assessment of distributed solar PV generation in Sweden from a consumer perspective - The impact of demand response. *Renewable Energy*, **108(Supplement C)**, 169-178, doi:https://doi.org/10.1016/j.renene.2017.02.050.

Nykvist, B. and M. Nilsson, 2015: Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change*, **5(4)**, 329-332.

Nyong, A., F. Adesina, and B. Osman Elasha, 2007: The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 787-797, doi:10.1007/s11027-007-9099-0.

Obergassel, W. et al., 2016: *Phoenix from the Ashes - An Analysis of the Paris Agreement to the United Nations Framework Convention on Climate Change - Part II*. Wuppertal Institute for Climate, Environment and Energy, Wuppertal, 10 pp.

Ockwell, D. and R. Byrne, 2016: Improving technology transfer through national systems of innovation: climate relevant innovation-system builders (CRIBs). *Climate Policy*, **16(7)**, 836-854, doi:10.1080/14693062.2015.1052958.

Ockwell, D., A. Sagar, and H. de Coninck, 2015: Collaborative research and development (R&D) for climate technology transfer and uptake in developing countries: towards a needs driven approach. *Climatic Change*, **131(3)**, 401-415, doi:10.1007/s10584-014-1123-2.

OECD, 2015: *Climate Finance in 2013-14 and the USD 100 billion goal: A Report by the OECD in Collaboration with Climate Policy Initiative*. OECD Publishing, Paris, France.

OECD, 2016a: *2020 Projections of Climate Finance Towards the USD 100 Billion Goal: Technical Note*. OECD Publishing, Paris, France.

OECD, 2016b: *African Economic Outlook 2016*. OECD Publishing, 400 pp.

OECD, 2017a: Investing in Climate, Investing in Growth. , 314, doi:10.1787/9789264273528-1-en.

OECD, 2017b: *Mobilising Bond Markets for a Low-Carbon Transition*. OECD Publishing, Paris, 132 pp.

OECD, 2017c: *The Next Production Revolution : Implications for Governments and Business (Summary)*. OECD Publishing, Paris.

OECD/FAO, 2017: *OECD-FAO Agricultural Outlook 2017-2026*.

OECD/IEA/NEA/ITF, 2015: *Aligning Policies for a Low-carbon Economy*. OECD Publishing, Paris.

Ogunbode, C.A., Y. Liu, and N. Tausch, 2017: The moderating role of political affiliation in the link between flooding experience and preparedness to reduce energy use. *Climatic Change*, doi:10.1007/s10584-017-2089-7.

O'Hare, P., I. White, and A. Connelly, 2016: Insurance as maladaptation: Resilience and the 'business as usual' paradox. *Environment and Planning C: Government and Policy*, **34(6)**, 1175-1193, doi:10.1177/0263774X15602022.

Ohndorf, M., J. Blasch, and R. Schubert, 2015: Emission budget approaches for burden sharing: some thoughts from an environmental economics point of view. *Climatic Change*, **133(3)**, 385-395, doi:10.1007/s10584-015-1442-y.

Ölander, F. and J. Thøgersen, 2014: Informing Versus Nudging in Environmental Policy. *Journal of Consumer Policy*, **37(3)**, 341-356, doi:10.1007/s10603-014-9256-2.

Oldenbroek, V., L.A. Verhoef, and A.J.M. van Wijk, 2017: Fuel cell electric vehicle as a power plant: Fully renewable integrated transport and energy system design and analysis for smart city areas. *International Journal of Hydrogen Energy*, **42(12)**, 8166-8196, doi:10.1016/j.ijhydene.2017.01.155.

O'Leary, J.K. et al., 2017: The Resilience of Marine Ecosystems to Climatic Disturbances. *BioScience*, **67(3)**, 208-220, doi:10.1093/biosci/biw161.

Oliver, T.H. and M.D. Morecroft, 2014: Interactions between climate change and land use change on biodiversity: attribution problems, risks, and opportunities. *Wiley Interdisciplinary Reviews: Climate Change*, **5(3)**, 317-335, doi:10.1002/wcc.271.

O'Neill, B.C. et al., 2015: The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42(January)**, 169-180, doi:10.1016/j.gloenvcha.2015.01.004.

O'Neill, B.C. et al., 2017: IPCC reasons for concern regarding climate change risks. *Nature Climate Change*, **7(1)**, doi:10.1038/nclimate3179.

O'Neill, S. and S. Nicholson-Cole, 2009: "Fear Won't Do It" Visual and Iconic Representations. *Science Communication*, **30(3)**, 355-379.

O'Neill, S.J., M. Boykoff, S. Niemeyer, and S.A. Day, 2013: On the use of imagery for climate change engagement. *Global Environmental Change*, **23**, 413-421.

OneNYC Team, 2015: *One New York: The Plan for a Strong and Just City*. Office of the Mayor of New York City, New York, NY, USA, 354 pp.

Opio, C. et al., 2013: Greenhouse gas emissions from ruminant supply chains-A global life cycle assessment. *Food and agriculture organization of the United Nations (FAO), Rome*, 1-214.

Osbaldiston, R. and J.P. Schott, 2012: Environmental Sustainability and Behavioral Science: Meta-Analysis of Proenvironmental Behavior Experiments. *Environment and Behavior*, **44(2)**, 257-299, doi:10.1177/0013916511402673.

Osei, P.D., 2007: Policy responses, institutional networks management and post-Hurricane Ivan reconstruction in Jamaica. *Disaster Prevention and Management: An International Journal*, **16(2)**, 217-234.

Ostrom, E., 2009: A general framework for analyzing sustainability of social-ecological systems. *Science*, **325(5939)**, 419-422, doi:10.1126/science.1172133.

Ostrom, E. and J. Walker (eds.), 2005: *Trust and Reciprocity: Interdisciplinary Lessons for Experimental Research*. Russell Sage Foundation, New York, NY, USA, 424 pp.

Ostrom, E., J. Burger, C.B. Field, R.B. Norgaard, and D. Policansky, 1999: Revisiting the Commons: Local Lessons, Global Challenges. *Science*, **284(5412)**, 278-282, doi:10.1126/science.284.5412.278.

Oteros-Rozas, E. et al., 2015: Participatory scenario planning in place-based social-ecological research: insights and experiences from 23 case studies. *Ecology and Society*, **20(4)**, doi:10.5751/es-07985-200432.

Ouyang, M. and L. Dueñas-Osorio, 2014: Multi-dimensional hurricane resilience assessment of electric power systems. *Structural Safety*, **48(Supplement C)**, 15-24, doi:10.1016/j.strusafe.2014.01.001.

Overmars, K.P. et al., 2014: Estimating the opportunity costs of reducing carbon dioxide emissions via avoided deforestation, using integrated assessment modelling. *Land Use Policy*, **41(Supplement C)**, 45-60, doi:https://doi.org/10.1016/j.landusepol.2014.04.015.

Owen, R., 2014: *Solar radiation management: the governance of research*. 212-248 pp.

Pablo-Romero, M.P., A. Sánchez-Braza, J. Salvador-Ponce, and N. Sánchez-Labrador, 2017: An overview of feed-in tariffs, premiums and tenders to promote electricity from biogas in the EU-28. *Renewable and Sustainable Energy Reviews*, **73**, 1366-1379, doi:10.1016/j.rser.2017.01.132.

Pahl, S., J. Goodhew, C. Boomsma, and S.R.J. Sheppard, 2016: The Role of Energy Visualization in Addressing

Energy Use : Insights from the eViz Project. *Frontiers in Psychology*, **7(February)**, 92, doi:10.3389/fpsyg.2016.00092.

PAHO/WHO, 2016: *Strategy for Technical Cooperation with the United Kingdom Overseas Territories (UKOTs) in the Caribbean 2016-2022*. World Health Organization Regional Office for the Americas, Washington DC, USA, 57 pp.

Pan, X., M. Elzen, N. Höhne, F. Teng, and L. Wang, 2017: Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environmental Science & Policy*, **74**, 49-56, doi:10.1016/j.envsci.2017.04.020.

Panagopoulos, T., J.A. González Duque, and M. Bostenaru Dan, 2016: Urban planning with respect to environmental quality and human well-being. *Environmental Pollution*, **208**, 137-144, doi:10.1016/j.envpol.2015.07.038.

Pant, L.P., B. Adhikari, and K.K. Bhattarai, 2015: Adaptive transition for transformations to sustainability in developing countries. *Current Opinion in Environmental Sustainability*, **14**, 206-212, doi:10.1016/j.cosust.2015.07.006.

Panteli, M. and P. Mancarella, 2015: Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research*, **127**, 259-270, doi:10.1016/j.epsr.2015.06.012.

Panteli, M., D.N. Trakas, P. Mancarella, and N.D. Hatziargyriou, 2016: Boosting the Power Grid Resilience to Extreme Weather Events Using Defensive Islanding. *IEEE Transactions on Smart Grid*, **7(6)**, 2913-2922, doi:10.1109/TSG.2016.2535228.

Papargyropoulou, E., R. Lozano, J. K. Steinberger, N. Wright, and Z. Ujang, 2014: The food waste hierarchy as a framework for the management of food surplus and food waste. *Journal of Cleaner Production*, **76**, 106-115, doi:10.1016/j.jclepro.2014.04.020.

Parag, Y. and B.K. Sovacool, 2016: Electricity market design for the prosumer era. *Nature Energy*, **1(4)**, 16032, doi:10.1038/nenergy.2016.32.

Paraiso, M.L.S. and N. Gouveia, 2015: Health risks due to pre-harvesting sugarcane burning in São Paulo State, Brazil. *Revista Brasileira de Epidemiologia*, **18(3)**, 691-701, doi:10.1590/1980-5497201500030014.

Pardo, P. et al., 2014: A review on high temperature thermochemical heat energy storage. *Renewable and Sustainable Energy Reviews*, **32**, 591-610, doi:10.1016/j.rser.2013.12.014.

Parikh, K.S. and J.K. Parikh, 2016: Realizing potential savings of energy and emissions from efficient household appliances in India. *Energy Policy*, **97**, 102-111, doi:10.1016/j.enpol.2016.07.005.

Parker, A., 2014: Governing solar geoengineering research as it leaves the laboratory. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **372(2031)**, 20140173-20140173, doi:10.1098/rsta.2014.0173.

Parkes, B., A. Challinor, and K. Nicklin, 2015: Crop failure rates in a geoengineered climate: impact of climate change and marine cloud brightening. *Environmental Research Letters*, **10(8)**, 084003, doi:10.1088/1748-9326/10/8/084003.

Parkhill, K., N. Pidgeon, A. Corner, and N. Vaughan, 2013: Deliberation and Responsible Innovation: A Geoengineering Case Study. In: *Responsible Innovation* [Owen, R., J. Bessant, and M. Heintz (eds.)]. John Wiley & Sons Ltd, Chichester, UK, pp. 219-239.

Parkinson, S.C. and N. Djilali, 2015: Robust response to hydro-climatic change in electricity generation planning. *Climatic Change*, **130(4)**, 475-489, doi:10.1007/s10584-015-1359-5.

Parnell, S., 2015: Fostering Transformative Climate Adaptation and Mitigation in the African City: Opportunities and Constraints of Urban Planning. In: *Urban Vulnerability and Climate Change in Africa: A Multidisciplinary Approach*. Springer, Cham, Switzerland, pp. 349-367.

Parry, I.W.H., D. Evans, and W.E. Oates, 2014: Are energy efficiency standards justified? *Journal of Environmental Economics and Management*, **67(2)**, 104-125, doi:10.1016/j.jeem.2013.11.003.

Parson, E.A., 2017: Starting the Dialogue on Climate Engineering Governance: A World Commission. Fixing Climate Governance Series Policy Brief No. 8, Centre for International Governance Innovation, Waterloo.

Pasimeni, M.R. et al., 2014: Scales, strategies and actions for effective energy planning: A review. *Energy Policy*, **65**, 165-174, doi:10.1016/j.enpol.2013.10.027.

Pasquini, L., G. Ziervogel, R.M. Cowling, and C. Shearing, 2015: What enables local governments to mainstream climate change adaptation? Lessons learned from two municipal case studies in the Western Cape, South Africa. *Climate and Development*, **7(1)**, 60-70, doi:10.1080/17565529.2014.886994.

Patel, R., G. Walker, M. Bhatt, and V. Pathak, 2017: The Demand for Disaster Microinsurance for Small Businesses in Urban Slums: The Results of Surveys in Three Indian Cities. *PLOS Currents Disasters*, **9**, doi:10.1371/currents.dis.83315629ac7cae7e2c4f78c589a3ce1c.

Patt, A., 2017: Beyond the tragedy of the commons: Reframing effective climate change governance. *Energy Research & Social Science*, **34**, 1-3, doi:10.1016/j.erss.2017.05.023.

Patt, A.G. and D. Schröter, 2008: Perceptions of climate risk in Mozambique: Implications for the success of adaptation strategies. *Global Environmental Change*, **18(3)**, 458-467, doi:10.1016/j.gloenvcha.2008.04.002.

Pattanayak, S.K., D.E. Mercer, E. Sills, and J.C. Yang, 2003: Taking stock of agroforestry adoption studies.

Agroforestry Systems, **57(3)**, 173-186, doi:10.1023/A:1024809108210.

Patterson, J.J. et al., 2018: Political feasibility of 1.5 C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*, **31**, 1-9, doi:10.1016/j.cosust.2017.11.002.

Paul, K.I. et al., 2016: Managing reforestation to sequester carbon, increase biodiversity potential and minimize loss of agricultural land. *Land Use Policy*, **51**, 135-149, doi:https://doi.org/10.1016/j.landusepol.2015.10.027.

Pauw, W.P., R.J.T. Klein, P. Vellinga, and F. Biermann, 2016a: Private finance for adaptation: do private realities meet public ambitions? *Climatic Change*, **134(4)**, 489-503, doi:10.1007/s10584-015-1539-3.

Pauw, W.P. et al., 2016b: NDC Explorer. https://klimalog.die-gdi.de/ndc (Accessed: 14 December 2017).

Pauw, W.P. et al., 2018: Beyond headline mitigation numbers: we need more transparent and comparable NDCs to achieve the Paris Agreement on climate change. *Climatic Change*, **147(1-2)**, 23-29, doi:10.1007/s10584-017-2122-x.

Peake, S. and P. Ekins, 2017: Exploring the financial and investment implications of the Paris Agreement. *Climate Policy*, **17(7)**, 832-852, doi:10.1080/14693062.2016.1258633.

Pearce, T., J. Ford, A.C. Willox, and B. Smit, 2015: Inuit Traditional Ecological Knowledge (TEK), Subsistence Hunting and Adaptation to Climate Change in the Canadian Arctic. *Arctic*, **68(2)**, 233-245.

Pearce, T., R. Currenti, A. Mateiwai, and B. Doran, 2017: Adaptation to climate change and freshwater resources in Vusama village, Viti Levu, Fiji. *Regional Environmental Change*, 1-10, doi:10.1007/s10113-017-1222-5.

Pearce, T.C.L., 2018: Incorporating Indigenous Knowledge in Research. In: *Routledge Handbook of Environmental Migration and Displacement* [McLeman, R. and F. Gemenne (eds.)]. Taylor & Francis Group, New York and London, pp. 125-134.

Pellegrino, M., M. Simonetti, and G. Chiesa, 2016: Reducing thermal discomfort and energy consumption of Indian residential buildings: Model validation by in-field measurements and simulation of low-cost interventions. *Energy and Buildings*, **113**, 145-158, doi:10.1016/j.enbuild.2015.12.015.

Pelletier, L.G., K.M. Tuson, I. Green-Demers, K. Noels, and A.M. Beaton, 1998: Why Are You Doing Things for the Environment? The Motivation Toward the Environment Scale (MTES). *Journal of Applied Social Psychology*, **28(5)**, 437-468, doi:10.1111/j.1559-1816.1998.tb01714.x.

Pelling, M., K. O'Brien, and D. Matyas, 2015: Adaptation and transformation. *Climatic Change*, **133(1)**, 113-127, doi:10.1007/s10584-014-1303-0.

Pelling, M. et al., 2018: Africa's urban adaptation transition under a 1.5° climate. *Current Opinion in Environmental Sustainability*, **31**, 10-15, doi:10.1016/j.cosust.2017.11.005.

Peng, J. et al., 2016: Markedly enhanced absorption and direct radiative forcing of black carbon under polluted urban environments. *Proceedings of the National Academy of Sciences of the United States of America*, 1602310113-, doi:10.1073/pnas.1602310113.

Perlaviciute, G. and L. Steg, 2014: Contextual and psychological factors shaping evaluations and acceptability of energy alternatives: Integrated review and research agenda. *Renewable and Sustainable Energy Reviews*, **35**, 361-381, doi:10.1016/j.rser.2014.04.003.

Perrels, A., T. Frei, F. Espejo, L. Jamin, and A. Thomalla, 2013: Socio-economic benefits of weather and climate services in Europe. *Advances in Science & Research*, doi:10.5194/asr-1-1-2013.

Perrier, Q., 2016: A robust nuclear strategy for France.

Persson, U.M., 2015: The impact of biofuel demand on agricultural commodity prices: a systematic review. *Wiley Interdisciplinary Reviews: Energy and Environment*, **4(5)**, 410-428, doi:10.1002/wene.155.

Perugini, L. et al., 2017: Biophysical effects on temperature and precipitation due to land cover change. *Environmental Research Letters*, **12(5)**, doi:10.1088/1748-9326/aa6b3f.

Peters, A.M., E. van der Werff, and L. Steg, 2018: Beyond purchasing: Electric vehicle adoption motivation and consistent sustainable energy behaviour in the Netherlands. *Energy Research & Social Science*, **39**, 234-247.

Peters, G.P. and O. Geden, 2017: Catalysing a political shift from low to negative carbon. *Nature Clim. Change*, **7(9)**, 619-621, doi:10.1038/nclimate3369.

Peters, G.P. et al., 2017: Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Climate Change*, **7(2)**, 118-122, doi:10.1038/nclimate3202.

Pfeiffer, A., R. Millar, C. Hepburn, and E. Beinhocker, 2016: The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Applied Energy*, **179**, 1395-1408, doi:10.1016/j.apenergy.2016.02.093.

Pfeiffer, L. and C.–Y.C. Lin, 2014: Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. *Journal of Environmental Economics and Management*, **67(2)**, 189-208, doi:10.1016/j.jeem.2013.12.002.

Philibert, C., 2017: *Renewable Energy for Industry. From green energy to green materials and fuels*. IEA, Paris, France, 72 pp.

Pichert, D. and K. Katsikopoulos, 2008: Green defaults: Information presentation and pro-environmental behaviour. *Journal of Environmental Psychology*, **28(1)**, 63-73, doi:10.1016/j.jenvp.2007.09.004.

Pichler, A. and E. Striessnig, 2013: Differential vulnerability to hurricanes in Cuba, Haiti, and the Dominican Republic:

the contribution of education. *Ecology and society*, **18(3)**.

Pichler, M., A. Schaffartzik, H. Haberl, and C. Görg, 2017: Drivers of society-nature relations in the Anthropocene and their implications for sustainability transformations. *Current Opinion in Environmental Sustainability*, **26-27**, 32-36, doi:10.1016/j.cosust.2017.01.017.

Pickering, N.K. et al., 2015: Animal board invited review: genetic possibilities to reduce enteric methane emissions from ruminants. *animal*, **9(09)**, 1431-1440, doi:10.1017/S1751731115000968.

Pielke, R.A., 2009: An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy. *environmental science & policy*, **12(3)**, 216-225.

Pierpaoli, E., G. Carli, E. Pignatti, and M. Canavari, 2013: Drivers of Precision Agriculture Technologies Adoption: A Literature Review. *Procedia Technology*, **8(Haicta)**, 61-69, doi:10.1016/j.protcy.2013.11.010.

Pierrehumbert, R.T., 2014: Short-Lived Climate Pollution. *Annual Review of Earth and Planetary Sciences*, **42**, 341-79, doi:10.1146/annurev-earth-060313-054843.

Piketty, T., 2014: *Capital in the Twenty-first Century*. The Belknap Press of Harvard University Press, Cambridge, MA, USA, 696 pp.

Pindyck, 2017: The Use and Misuse of Models for Climate Policy. *Review of Environmental Economics and Policy*, **11(1)**, 100-114.

Pinho, P.F., J.A. Marengo, and M.S. Smith, 2015: Complex socio-ecological dynamics driven by extreme events in the Amazon. *Regional Environmental Change*, **15(4)**, doi:10.1007/s10113-014-0659-z.

Pinho, P.F. et al., 2014: Ecosystem protection and poverty alleviation in the tropics: Perspective from a historical evolution of policy-making in the Brazilian Amazon. *Ecosystem Services*, **8**, 97-109, doi:10.1016/j.ecoser.2014.03.002.

Pisano, I. and M. Lubell, 2017: Environmental Behavior in Cross-National Perspective : A Multilevel Analysis of 30 Countries. *Environment & Behavior*, **49(1)**, 31-58, doi:10.1177/0013916515600494.

Pitari, G. et al., 2014: Stratospheric ozone response to sulfate geoengineering: Results from the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research: Atmospheres*, **119(5)**, 2629-2653, doi:10.1002/2013JD020566.

Pittelkow, C.M. et al., 2014: Productivity limits and potentials of the principles of conservation agriculture. *Nature*, **517(7534)**, 365-368, doi:10.1038/nature13809.

Pittock, J., H. Bjornlund, R. Stirzaker, and A. van Rooyen, 2017: Communal irrigation systems in South-Eastern Africa: findings on productivity and profitability. *International Journal of Water Resources Development*, **33(5)**, 839-847, doi:10.1080/07900627.2017.1324768.

Pizer, W.A., 2002: Combining price and quantity controls to mitigate global climate change. *Journal of Public Economics*, **85(3)**, 409-434, doi:10.1016/S0047-2727(01)00118-9.

Place, F. et al., 2012: Improved Policies for Facilitating the Adoption of Agroforestry. *Agroforestry for Biodiversity and Ecosystem Services - Science and Practice*, doi:10.5772/34524.

Platinga, A. and B. Scholtens, 2016: *The Financial Impact of Divestment from Fossil Fuels*. 47 pp.

Plazzotta, M., R. Séférian, H. Douville, B. Kravitz, and J. Tjiputra, 2018: Land surface cooling induced by sulfate geoengineering constrained by major volcanic eruptions. *Geophysical Research Letters*, doi:10.1029/2018GL077583.

Plevin, R.J., M. O'Hare, A.D. Jones, M.S. Torn, and H.K. Gibbs, 2010: Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated. *Environmental Science & Technology*, **44(21)**, 8015-8021, doi:10.1021/es101946t.

Poeplau, C. and A. Don, 2015: Carbon sequestration in agricultural soils via cultivation of cover crops - A meta-analysis. *Agriculture, Ecosystems & Environment*, **200**, 33-41, doi:https://doi.org/10.1016/j.agee.2014.10.024.

Poff, N.L.R. et al., 2016: Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nature Climate Change*, **6(1)**, 25-34, doi:10.1038/nclimate2765.

Pollak, M., B. Meyer, and E. Wilson, 2011: Reducing greenhouse gas emissions: Lessons from state climate action plans. *Energy Policy*, **39(9)**, 5429-5439, doi:10.1016/j.enpol.2011.05.020.

Pollitt, H., 2018: Policies for limiting climate change to well below 2°C. (in press).

Pollitt, H. and J.–F. Mercure, 2017: The role of money and the financial sector in energy-economy models used for assessing climate and energy policy. *Climate Policy*, 1-14, doi:10.1080/14693062.2016.1277685.

Poortinga, W., L. Steg, and C. Vlek, 2002: Environmental Risk Concern and Preferences for Energy-Saving Measures. *Environment & Behavior*, **34(4)**, 455-478.

Poortinga, W., L. Steg, C. Vlek, and G. Wiersma, 2003: Household preferences for energy-saving measures: A conjoint analysis. *Journal of Economic Psychology*, **24(1)**, 49-64.

Popp, A. et al., 2014a: Land-use protection for climate change mitigation. *Nature Climate Change*, **4(12)**, 1095-1098, doi:10.1038/nclimate2444.

Popp, A. et al., 2014b: Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3-4)**, 495-509, doi:10.1007/s10584-013-0926-x.

Pradhan, A., C. Chan, P.K. Roul, J. Halbrendt, and B. Sipes, 2018: Potential of conservation agriculture (CA) for climate change adaptation and food security under rainfed uplands of India: A transdisciplinary approach. *Agricultural Systems*, **163**, 27-35, doi:10.1016/j.agsy.2017.01.002.

Preston, B.L., J. Mustelin, and M.C. Maloney, 2013: Climate adaptation heuristics and the science/policy divide. *Mitigation and Adaptation Strategies for Global Change*, **20(3)**, 467-497, doi:10.1007/s11027-013-9503-x.

Preston, B.L., L. Rickards, H. Fünfgeld, and R.J. Keenan, 2015: Toward reflexive climate adaptation research. *Current Opinion in Environmental Sustainability*, **14**, 127-135, doi:10.1016/j.cosust.2015.05.002.

Preston, C.J., 2013: Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal. *Wiley Interdisciplinary Reviews: Climate Change*, **4(1)**, 23-37, doi:10.1002/wcc.198.

Preston, C.J. (ed.), 2016: *Climate Justice and Geoengineering: Ethics and Policy in the Atmospheric Anthropocene*. Rowman & Littlefield International, London, UK, 234 pp.

Pretty, J. and Z.P. Bharucha, 2014: Sustainable intensification in agricultural systems. *Annals of Botany*, **114(8)**, 1571-1596, doi:10.1093/aob/mcu205.

Pretzsch, H. et al., 2017: Climate change accelerates growth of urban trees in metropolises worldwide. *Scientific Reports*, **7(1)**, 15403, doi:10.1038/s41598-017-14831-w.

Pritchard, C., A. Yang, P. Holmes, and M. Wilkinson, 2015: Thermodynamics, economics and systems thinking: What role for air capture of CO2? *Process Safety and Environmental Protection*, **94**, 188-195, doi:10.1016/j.psep.2014.06.011.

Pritoni, M., A.K. Meier, C. Aragon, D. Perry, and T. Peffer, 2015: Energy efficiency and the misuse of programmable thermostats: The effectiveness of crowdsourcing for understanding household behavior. *Energy Research & Social Science*, **8**, 190-197, doi:10.1016/j.erss.2015.06.002.

Proost, S. and D. Van Regemorter, 1995: The double dividend and the role of inequality aversion and macroeconomic regimes. *International Tax and Public Finance*, **2(2)**, 207-219, doi:10.1007/BF00877497.

Pueyo, A. and R. Hanna, 2015: *What level of electricity access is required to enable and sustain poverty reduction? Annex 1 Literature review*. Practical Action Consulting, Bourton-on-Dunsmore, UK, 65 pp.

Puppim de Oliveira, J.A. et al., 2013: Promoting win-win situations in climate change mitigation, local environmental quality and development in Asian cities through co-benefits. *Journal of Cleaner Production*, **58**, 1-6, doi:10.1016/j.jclepro.2013.08.011.

Pyörälä, P. et al., 2014: Effects of Management on Economic Profitability of Forest Biomass Production and Carbon Neutrality of Bioenergy Use in Norway Spruce Stands Under the Changing Climate. *Bioenergy Research*, **7(1)**, 279-294, doi:10.1007/s12155-013-9372-x.

Qazi, S. and W. Young Jr., 2014: Disaster relief management and resilience using photovoltaic energy.

Qin, Z., J.B. Dunn, H. Kwon, S. Mueller, and M.M. Wander, 2016: Soil carbon sequestration and land use change associated with biofuel production: empirical evidence. *GCB Bioenergy*, **8(1)**, 66-80, doi:10.1111/gcbb.12237.

Quaas, M.F., J. Quaas, W. Rickels, and O. Boucher, 2017: Are there reasons against open-ended research into solar radiation management? A model of intergenerational decision-making under uncertainty. *Journal of Environmental Economics and Management*, **84**, 1-17, doi:10.1016/j.jeem.2017.02.002.

Quandt, A., H. Neufeldt, and J.T. McCabe, 2017: The role of agroforestry in building livelihood resilience to floods and drought in semiarid Kenya. *Ecology and Society*, **22(3)**, doi:10.5751/ES-09461-220310.

Quitzow, R., 2015: Assessing policy strategies for the promotion of environmental technologies: A review of India's National Solar Mission. *Research Policy*, **44(1)**, 233-243, doi:https://doi.org/10.1016/j.respol.2014.09.003.

Rabitz, F., 2016: Going rogue? Scenarios for unilateral geoengineering. *Futures*, **84**, 98-107, doi:10.1016/j.futures.2016.11.001.

Radhakrishnan, M., A. Pathirana, R.M. Ashley, B. Gersonius, and C. Zevenbergen, 2018: Flexible adaptation planning for water sensitive cities. *Cities*, doi:10.1016/J.CITIES.2018.01.022.

Rai, V., D.C. Reeves, and R. Margolis, 2016: Overcoming barriers and uncertainties in the adoption of residential solar PV. *Renewable Energy*, **89**, 498-505, doi:10.1016/j.renene.2015.11.080.

Rajamani, L., 2016: Ambition and Differentiation in the 2015 Paris Agreement: Interpretative Possibilities and Underlying Politics. *International and Comparative Law Quarterly*, **65(02)**, 493-514, doi:10.1017/S0020589316000130.

Rajan, R.G., 2011: *Fault Lines: How Hidden Fractures Still Threaten the World Economy*. Princeton University Press, Princeton, NJ, USA and Woodstock, UK, 280 pp.

Rakatama, A., R. Pandit, C. Ma, and S. Iftekhar, 2017: The costs and benefits of REDD+: A review of the literature. *Forest Policy and Economics*, **75(Supplement C)**, 103-111, doi:https://doi.org/10.1016/j.forpol.2016.08.006.

Ramachandran, S., V. Ramaswamy, G.L. Stenchikov, and A. Robock, 2000: Radiative impact of the Mount Pinatubo volcanic eruption: Lower stratospheric response. *Journal of Geophysical Research*, **105(D19)**, 24409, doi:10.1029/2000JD900355.

Ramage, M.H. et al., 2017: The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, **68**, 333-359, doi:10.1016/j.rser.2016.09.107.

Ramankutty, N. et al., 2018: Trends in Global Agricultural Land Use: Implications for Environmental Health and Food

Security. *Annual Review of Plant Biology*, **69(1)**, annurev-arplant-042817-040256, doi:10.1146/annurev-arplant-042817-040256.

Ran, F.A. et al., 2013: Genome engineering using the CRISPR-Cas9 system. *Nature Protocols*, **8(11)**, 2281-2308, doi:10.1038/nprot.2013.143.

Rand, J. and B. Hoen, 2017: Thirty years of North American wind energy acceptance research: What have we learned? *Energy Research & Social Science*, **29(Supplement C)**, 135-148, doi:https://doi.org/10.1016/j.erss.2017.05.019.

Ranganathan, J. et al., 2016: Shifting Diets for a Sustainable Food Future. Installment 11 of Creating a Sustainable Food Future, 90 pp.

Ranjan, M. and H.J. Herzog, 2011: Feasibility of air capture. *Energy Procedia*, **4**, 2869-2876.

Rasul, G. and B. Sharma, 2016: The nexus approach to water-energy-food security: an option for adaptation to climate change. *Climate Policy*, **16(6)**, 682-702, doi:10.1080/14693062.2015.1029865.

Rathore, D., A.–S. Nizami, A. Singh, and D. Pant, 2016: Key issues in estimating energy and greenhouse gas savings of biofuels: challenges and perspectives. *Biofuel Research Journal*, **3(2)**, 380-393, doi:10.18331/BRJ2016.3.2.3.

Rau, G.H. et al., 2013: Direct electrolytic dissolution of silicate minerals for air CO2 mitigation and carbon-negative H2 production.. *Proceedings of the National Academy of Sciences of the United States of America*, **110(25)**, 10095-100, doi:10.1073/pnas.1222358110.

Ray, A., L. Hughes, D.M. Konisky, and C. Kaylor, 2017: Extreme weather exposure and support for climate change adaptation. *Global Environmental Change*, **46(June)**, 104-113, doi:10.1016/j.gloenvcha.2017.07.002.

RCI, 2008: *Rotterdam Climate Proof: The Rotterdam Challenge on Water and Climate Adaptation*. Rotterdam Climate Initiative (RCI), Rotterdam, Amsterdam, 11 pp.

RCI, 2013: *Rotterdam Climate Change Adaptation Strategy*. Rotterdam Climate Initiative (RCI), Rotterdam, 70 pp.

RCI, 2017: Rotterdam Climate Intitiative. http://www.rotterdamclimateinitiative.nl (Accessed: 23 November 2017).

Reckien, D., J. Flacke, M. Olazabal, and O. Heidrich, 2015: The Influence of drivers and barriers on urban adaptation and mitigation plans - An empirical analysis of european cities. *PLOS ONE*, **10(8)**, e0135597.

Reckien, D. et al., 2014: Climate change response in Europe: what's the reality? Analysis of adaptation and mitigation plans from 200 urban areas in 11 countries. *Climatic Change*, **122(1)**, 331-340, doi:10.1007/s10584-013-0989-8.

Reckien, D. et al., 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environment & Urbanization*, **29(1)**, 159-182, doi:10.1177/0956247816677778.

Refsgaard, K. and K. Magnussen, 2009: Household behaviour and attitudes with respect to recycling food waste - experiences from focus groups. *Journal of Environmental Management*, doi:10.1016/j.jenvman.2008.01.018.

Rehmatulla, N. and T. Smith, 2015: Barriers to energy efficiency in shipping: A triangulated approach to investigate the principal agent problem. *Energy Policy*, **84(Supplement C)**, 44-57, doi:10.1016/j.enpol.2015.04.019.

Reid, H., 2016: Ecosystem- and community-based adaptation: learning from community-based natural resource management. *Climate and Development*, **8(1)**, 4-9, doi:10.1080/17565529.2015.1034233.

Reid, H. et al., 2009: Community-based adaptation to climate change: An overview. *Participatory Learning and Action*, **60**, 11-38.

REN21, 2012: *Renwables 2017: Global Status Report*. 302 pp.

Renforth, P., 2012: The potential of enhanced weathering in the UK. *International Journal of Greenhouse Gas Control*, **10**, 229-243, doi:10.1016/j.ijggc.2012.06.011.

Renforth, P. and G. Henderson, 2017: Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*, n/a-n/a, doi:10.1002/2016RG000533.

Repo, A., J.–P. Tuovinen, and J. Liski, 2015: Can we produce carbon and climate neutral forest bioenergy? *GCB Bioenergy*, **7(2)**, 253-262, doi:10.1111/gcbb.12134.

Revi, A., 2016: Afterwards: Habitat III and the Sustainable Development Goals. *Urbanisation*, **1(2)**, x-xiv, doi:10.1177/2455747116682899.

Revi, A., 2017: Re-imagining the United Nations ' Response to a Twenty-first-century Urban World. *Urbanisation*, **2(2)**, 1-7, doi:10.1177/2455747117740438.

Revi, A. and C. Rosenzweig, 2013: *The urban opportunity: Enabling transformative and sustainable development*.

Revi, A. et al., 2014a: Towards transformative adaptation in cities: the IPCC's Fifth Assessment. *Environment and Urbanization*, **26(1)**, 11-28.

Revi, A. et al., 2014b: Urban Areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612.

Rey Benayas, J.M. et al., 2009: Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. *Science*, **325(5944)**, 1121-4, doi:10.1126/science.1172460.

Reynolds, J.L., 2015: An Economic Analysis of Liability and Compensation for Harm from Large-Scale Field Research in Solar Climate Engineering. *Climate Law*, **5(2-4)**, 182-209, doi:10.1163/18786561-00504004.

Reynolds, J.L., J.L. Contreras, and J.D. Sarnoff, 2018: Intellectual property policies for solar geoengineering. *Wiley Interdisciplinary Reviews: Climate Change*, **9(2)**, 1-7, doi:10.1002/wcc.512.

Reynolds, T.W., A. Bostrom, D. Read, and M.G. Morgan, 2010: Now What Do People Know About Global Climate Change? Survey Studies of Educated Laypeople. *Risk Analysis*, **30(10)**, 1520-1538, doi:10.1111/j.1539-6924.2010.01448.x.

RGoB, 2012: The Report of the High-Level Meeting on Wellbeing and Happiness: Defining a New Economic Paradigm. , 166.

RGoB, 2013: Eleventh Five Year Plan Volume I : Main Document. .

RGoB, 2016: Economic Development Policy. , 49.

Riahi, K. et al., 2015: Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change*, **90(PA)**, 8-23, doi:10.1016/j.techfore.2013.09.016.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, **42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009.

Ribeiro, H., 2008: Sugar cane burning in Brazil: respiratory health effects. *Revista de Saúde Pública*, **42(2)**, 1-6.

Rickards, L. and S.M. Howden, 2012: Transformational adaptation: agriculture and climate change. *Crop and Pasture Science*, **63(3)**, 240, doi:10.1071/CP11172.

Ricke, K.L., J.B. Moreno-Cruz, and K. Caldeira, 2013: Strategic incentives for climate geoengineering coalitions to exclude broad participation. *Environmental Research Letters*, **8(1)**, 014021, doi:10.1088/1748-9326/8/1/014021.

Ricke, K.L., J.B. Moreno-Cruz, J. Schewe, A. Levermann, and K. Caldeira, 2015: Policy thresholds in mitigation. *Nature Geoscience*, **9(1)**, 5-6, doi:10.1038/ngeo2607.

Ringel, M., 2017: Energy efficiency policy governance in a multi-level administration structure - evidence from Germany. *Energy Efficiency*, **10(3)**, 753-776, doi:10.1007/s12053-016-9484-1.

Rinkevich, B., 2014: Rebuilding coral reefs: does active reef restoration lead to sustainable reefs? *Current Opinion in Environmental Sustainability*, **7**, 28-36, doi:10.1016/j.cosust.2013.11.018.

Rippke, U. et al., 2016: Timescales of transformational climate change adaptation in sub-Saharan African agriculture. *Nature Climate Change*, **6(6)**, 605-609, doi:10.1038/nclimate2947.

Ritzenhofen, I. and S. Spinler, 2016: Optimal design of feed-in-tariffs to stimulate renewable energy investments under regulatory uncertainty - A real options analysis. *Energy Economics*, **53**, 76-89, doi:10.1016/j.eneco.2014.12.008.

Rivas, S. et al., 2015: *The Covenant of Mayors: In-depth Analysis of Sustainable Energy Action Plans*. EUR 27526 EN, 170 pp.

Robert, A. et al., 2014: Cities and the New Climate Economy: the transformative role of global urban growth. The New Climate Economy (NCE), 1-70 pp.

Roberts, D., 2016: The New Climate Calculus: 1.5°C = Paris Agreement, Cities, Local Government, Science and Champions (PLSC^2). *Urbanisation*, **1(2)**, 71-78, doi:10.1177/2455747116672474.

Roberts, J.T. and B. Parks, 2006: *A climate of injustice: Global inequality, north-south politics, and climate policy*. MIT press.

Roberts, J.T. and R. Weikmans, 2017: Postface: fragmentation, failing trust and enduring tensions over what counts as climate finance. *International Environmental Agreements: Politics, Law and Economics*, **17(1)**, 129-137.

Roberts, J.T. et al., 2017: How Will We Pay for Loss and Damage? *Ethics, Policy & Environment*, **20(2)**, 208-226.

Robertson, J.L. and J.E. Barling, 2015: The psychology of green organizations. .

Robinson, S.–, 2017: Climate change adaptation trends in small island developing states. *Mitigation and Adaptation Strategies for Global Change*, **22(4)**, 669-691.

Robinson, S.– and M. Dornan, 2017: International financing for climate change adaptation in small island developing states. *Regional Environmental Change*, **17(4)**, 1103-1115, doi:10.1007/s10113-016-1085-1.

Robiou du Pont, Y. et al., 2017: Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, **7(1)**, 38-43, doi:10.1038/nclimate3186.

Robledo-Abad, C. et al., 2017: Bioenergy production and sustainable development: science base for policymaking remains limited. *GCB Bioenergy*, **9(3)**, 541-556, doi:10.1111/gcbb.12338.

Robock, A., 2012: Is Geoengineering Research Ethical? *Peace and Security*, 1-11.

Robock, A., 2016: Albedo enhancement by stratospheric sulfur injections: More research needed. *Earth's Future*, **4(12)**, 644-648, doi:10.1002/2016EF000407.

Robock, A., L. Oman, and G.L. Stenchikov, 2008: Regional climate responses to geoengineering with tropical and Arctic SO2 injections. *Journal of Geophysical Research: Atmospheres*, **113(D16)**, D16101, doi:10.1029/2008JD010050.

Robock, A., A. Marquardt, B. Kravitz, and G. Stenchikov, 2009: Benefits, risks, and costs of stratospheric geoengineering. *Geophysical Research Letters*, **36(19)**.

Rochedo, P.R.R. et al., 2016: Carbon capture potential and costs in Brazil. *Journal of Cleaner Production*, **131**, 280-295, doi:10.1016/j.jclepro.2016.05.033.

Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science*, **355(6331)**, 1269-1271, doi:10.1126/science.aah3443.

Rode, P. et al., 2014: Accessibility in Cities: Transport and Urban Form. The New Climate Economy, 1-61 pp.

Rodríguez, H., 2015: Risk and Trust in Institutions That Regulate Strategic Technological Innovations: Challenges for a Socially Legitimate Risk Analysis. In: *New Perspectives on Technology, Values, and Ethics* [Gonzalez, W. (ed.)]. Springer, Cham, pp. 147-166.

Roe, M.J., 2001: *Strong Managers, Weak Owners: The Political Roots of American Corporate Finance*. Princeton University Press, Princeton, NJ, USA, 342 pp.

Roelfsema, M., M. Harmsen, J.J.G. Olivier, A.F. Hof, and D.P. van Vuuren, 2018: Integrated assessment of international climate mitigation commitments outside the UNFCCC. *Global Environmental Change*, **48**, 67-75, doi:10.1016/j.gloenvcha.2017.11.001.

Rogelj, J. et al., 2014: Disentangling the effects of CO2 and short-lived climate forcer mitigation. *Proceedings of the National Academy of Sciences*, **111(46)**, 16325-16330, doi:10.1073/pnas.1415631111.

Rogelj, J. et al., 2016: Perspective : Paris Agreement climate proposals need boost to keep warming well below 2 ° C. *Nature*, **534(June)**, 631-639, doi:10.1038/nature18307.

Rogelj, J. et al., 2017: Understanding the origin of Paris Agreement emission uncertainties. *Nature Communications*, **8**, 15748, doi:10.1038/ncomms15748.

Rogers, D. and V. Tsirkunov, 2010: *Costs and Benefits of Early Warning Systems*.

Rogge, K.S., F. Kern, and M. Howlett, 2017: Conceptual and empirical advances in analysing policy mixes for energy transitions. *Energy Research & Social Science*, **33**, 1-10, doi:10.1016/j.erss.2017.09.025.

Roh, S., 2017: Big Data Analysis of Public Acceptance of Nuclear Power in Korea. *Nuclear Engineering and Technology*, **49(4)**, 850-854, doi:https://doi.org/10.1016/j.net.2016.12.015.

Romero-Lankao, P., S. Hughes, A. Rosas-Huerta, R. Borquez, and D.M. Gnatz, 2013: Institutional capacity for climate change responses: An examination of construction and pathways in Mexico City and Santiago. *Environment and Planning C: Government and Policy*, **31(5)**, 785-805, doi:10.1068/c12173.

Romero-Lankao, P. et al., 2018: Governance and policy. In: *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network* [Rosenzweig, C., W. Solecki, P. Romero-Lankao, S. Mehrotra, S. Dhakal, and S. Ali Ibrahim (eds.)]. Cambridge Unviersity Press.

Röös, E. et al., 2017: Protein futures for Western Europe: potential land use and climate impacts in 2050. *Regional Environmental Change*, **17(2)**, 367-377, doi:10.1007/s10113-016-1013-4.

Roques, F.A., D.M. Newbery, and W.J. Nuttall, 2008: Fuel mix diversification incentives in liberalized electricity markets: A Mean--Variance Portfolio theory approach. *Energy Economics*, **30(4)**, 1831-1849, doi:10.1016/j.eneco.2007.11.008.

Rosa, E.A. and T. Dietz, 2012: Human drivers of national greenhouse-gas emissions. *Nature Climate Change*, **2**, 581-586, doi:10.1038/nclimate1506.

Rose, A., 2016: Capturing the co-benefits of disaster risk management on the private sector side. 33 pp.

Rose, S.K., R. Richels, G. Blanford, and T. Rutherford, 2017: The Paris Agreement and next steps in limiting global warming. *Climatic Change*, **142(1-2)**, 255-270, doi:10.1007/s10584-017-1935-y.

Rosenbloom, D., 2017: Pathways: An emerging concept for the theory and governance of low-carbon transitions. *Global Environmental Change*, **43**, 37-50, doi:10.1016/j.gloenvcha.2016.12.011.

Rosenow, J., F. Kern, and K. Rogge, 2017: The need for comprehensive and well targeted instrument mixes to stimulate energy transitions: The case of energy efficiency policy. *Energy Research & Social Science*, **33**, 95-104, doi:https://doi.org/10.1016/j.erss.2017.09.013.

Rosenzweig, C. and W. Solecki, 2014: Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. *Global Environmental Change*, **28**, 395-408, doi:10.1016/J.GLOENVCHA.2014.05.003.

Rosenzweig, C. et al., 2015: *ARC3.2 Summary for city leaders*. Urban Climate Change Research Network. Columbia University, New York, NY, USA, 28 pp.

Roser, D., C. Huggel, M. Ohndorf, and I. Wallimann-Helmer, 2015: Advancing the interdisciplinary dialogue on climate justice. *Climatic Change*, **133(3)**, 349-359, doi:10.1007/s10584-015-1556-2.

Ross, M.L., 2015: What Have We Learned about the Resource Curse? *Annual Review of Political Science*, **18(1)**, 239-259, doi:10.1146/annurev-polisci-052213-040359.

Rothman, D.S., P. Romero-Lankao, V.J. Schweizer, and B.A. Bee, 2014: Challenges to adaptation: a fundamental concept for the shared socio-economic pathways and beyond. *Climatic Change*, **122(3)**, 495-507, doi:10.1007/s10584-013-0907-0.

Roudier, P., A. Alhassane, C. Baron, S. Louvet, and B. Sultan, 2016: Assessing the benefits of weather and seasonal forecasts to millet growers in Niger. *Agricultural and Forest Meteorology*, **223**, 168-180, doi:10.1016/j.agrformet.2016.04.010.

Rozenberg, J., S. Hallegatte, B. Perrissin-Fabert, and J.–C. Hourcade, 2013: Funding low-carbon investments in the absence of a carbon tax. *Climate Policy*, **13(1)**, 134-141, doi:10.1080/14693062.2012.691222.

Rubin, E.S., J.E. Davison, and H.J. Herzog, 2015: The cost of CO2 capture and storage. *International Journal of Greenhouse Gas Control*, **40**, 378-400, doi:10.1016/j.ijggc.2015.05.018.

Ruepert, A. et al., 2016: Environmental considerations in the organizational context: A pathway to pro-environmental behaviour at work. *Energy Research and Social Science*, **17**, doi:10.1016/j.erss.2016.04.004.

Ruparathna, R., K. Hewage, and R. Sadiq, 2016: Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews*, **53**, 1032-1045.

Ryaboshapko, A.G. and A.P. Revokatova, 2015: Technical Capabilities for Creating an Aerosol Layer In the Stratosphere for Climate Stabilization Purpose. *Problems of environmental monitoring and ecosystem modeling*, **T 26(2)**, 115-127.

Sælen, H. and S. Kallbekken, 2011: A choice experiment on fuel taxation and earmarking in Norway. *Ecological Economics*, **70(11)**, 2181-2190, doi:10.1016/j.ecolecon.2011.06.024.

Safarzyńska, K. and J.C.J.M. van den Bergh, 2017: Financial stability at risk due to investing rapidly in renewable energy. *Energy Policy*, **108(October 2016)**, 12-20, doi:10.1016/j.enpol.2017.05.042.

Salon, D., M.G. Boarnet, S. Handy, S. Spears, and G. Tal, 2012: How do local actions affect VMT? A critical review of the empirical evidence. *Transportation Research Part D: Transport and Environment*, **17(7)**, 495-508, doi:10.1016/j.trd.2012.05.006.

Salter, S., G. Sortino, and J. Latham, 2008: Sea-going hardware for the cloud albedo method of reversing global warming. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, **366(1882)**, 3989-4006, doi:10.1098/rsta.2008.0136.

Salvo, A., J. Brito, P. Artaxo, and F.M. Geiger, 2017: Reduced ultrafine particle levels in São Paulo's atmosphere during shifts from gasoline to ethanol use. *Nature Communications*, **8(77)**, 1-14.

Samset, B.H. et al., 2018: Climate Impacts From a Removal of Anthropogenic Aerosol Emissions. *Geophysical Research Letters*, **45(2)**, 1020-1029, doi:10.1002/2017GL076079.

Sanchez, D.L. and V. Sivaram, 2017: Saving innovative climate and energy research: Four recommendations for Mission Innovation. *Energy Research and Social Science*, **29(May)**, 123-126, doi:10.1016/j.erss.2017.05.022.

Sand, M. et al., 2015: Response of Arctic temperature to changes in emissions of short-lived climate forcers. *Nature Climate Change*, **6(3)**, 286-289, doi:10.1038/nclimate2880.

Sanderson, B.M., B.C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris temperature targets? *Geophysical Research Letters*, **43(13)**, 7133-7142, doi:10.1002/2016GL069563.

Sandler, T., 2017: Collective action and geoengineering. *The Review of International Organizations*, 1-21, doi:10.1007/s11558-017-9282-3.

Sands, R., 2018: U.S. Carbon Tax Scenarios and Bioenergy. *Climate Change Economics (CCE)*, **9(1)**, 1-12, doi:10.1142/S2010007818400109.

Sanesi, G., G. Colangelo, R. Lafortezza, E. Calvo, and C. Davies, 2017: Urban green infrastructure and urban forests: a case study of the Metropolitan Area of Milan. *Landscape Research*, **42(2)**, 164-175, doi:10.1080/01426397.2016.1173658.

Sanna, A., M. Dri, M.R. Hall, and M. Maroto-Valer, 2012: Waste materials for carbon capture and storage by mineralisation (CCSM) - A UK perspective. *Applied Energy*, **99**, 545-554, doi:10.1016/J.APENERGY.2012.06.049.

Santangeli, A. et al., 2016: Global change synergies and trade-offs between renewable energy and biodiversity. *GCB Bioenergy*, **8(5)**, 941-951, doi:10.1111/gcbb.12299.

Santos, G., 2008: The London experience. In: *Pricing in Road Transport: A Multi-Disciplinary Perspective* [Verhoef, E., M. Bliemer, L. Steg, and B. van Wee (eds.)]. Edward Elgar Publishing, Cheltenham, UK, pp. 273-292.

Sanz-Pérez, E.S., C.R. Murdock, S.A. Didas, and C.W. Jones, 2016: Direct Capture of CO2 from Ambient Air. *Chemical Reviews*, **116(19)**, 11840-11876, doi:10.1021/acs.chemrev.6b00173.

Sarmiento, H. and C. Tilly, 2018: Governance Lessons from Urban Informality. *Politics and Governance*, **6(1)**, 199, doi:10.17645/pag.v6i1.1169.

Sarmiento, J.L. and J.C. Orr, 1991: Three-dimensional simulations of the impact of Southern Ocean nutrient depletion on atmospheric CO2 and ocean chemistry. *Limnology and Oceanography*, **36(8)**, 1928-1950.

Sartor, O., 2013: Carbon Leakage in the Primary Aluminium Sector: What Evidence after 6.5 Years of the EU ETS? USAEE Working Paper No. 13-106, Social Science Research Network, Rochester, NY, USA, 20 pp.

Satterthwaite, D. and S. Bartlett, 2017: Editorial: The full spectrum of risk in urban centres: changing perceptions, changing priorities. *Environment and Urbanization*, **29(1)**, 3-14, doi:10.1177/0956247817691921.

Satterthwaite, D., D. Archer, S. Colenbrander, D. Dodman, and J. Hardoy, 2018: Responding to climate change in cities and in their informal settlements and economies. 1-61 pp.

Saunders, M.I. et al., 2014: Interdependency of tropical marine ecosystems in response to climate change. *Nature*

*Climate Change***, 4(8)**, 724-729, doi:10.1038/NCLIMATE2274.

Savo, V. et al., 2016: Observations of climate change among subsistence-oriented communities around the world. *Nature Climate Change***, 6(5)**, 462-473, doi:10.1038/nclimate2958.

Schaeffer, R. et al., 2012: Energy sector vulnerability to climate change: A review. *Energy***, 38(1)**, 1-12, doi:10.1016/j.energy.2011.11.056.

Schaeffer, S.M. and P.A. Nakata, 2015: Plant Science Review article CRISPR / Cas9-mediated genome editing and gene replacement in plants : Transitioning from lab to field. *Plant Science***, 240**, 130-142, doi:10.1016/j.plantsci.2015.09.011.

Schäfer, S. et al., 2013: Field tests of solar climate engineering. *Nature Climate Change***, 3**, 766.

Scheben, A., Y. Yuan, and D. Edwards, 2016: Advances in genomics for adapting crops to climate change. *Current Plant Biology***, 6**, 2-10, doi:10.1016/j.cpb.2016.09.001.

Scheer, D. and O. Renn, 2014: Public Perception of geoengineering and its consequences for public debate. *Climatic Change***, 125(3-4)**, 305-318, doi:10.1007/s10584-014-1177-1.

Schelling, T.C., 1991: Cooperative Approaches to Global Warming. In: *Global Warming, Economic Policy Responses* [Dornbusch, R. and J.M. Poterba (eds.)]. MIT Press.

Schimmelpfennig, D. and R. Ebel, 2016: Sequential adoption and cost savings from precision agriculture. *Journal of Agricultural and Resource Economics***, 41(1)**, 97-115.

Schlenker, W. and M.J. Roberts, 2009: Nonlinear temperature effects indicate severe damages to US crop yields under climate change. *Proceedings of the National Academy of Sciences***, 106(37)**, 15594.

Schleussner, C.–F. et al., 2016: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 &deg;C and 2 &deg;C. *Earth System Dynamics***, 7(2)**, 327-351, doi:10.5194/esd-7-327-2016.

Schmale, J., D. Shindell, E. von Schneidemesser, I. Chabay, and M. Lawrence, 2014: Clean up our skies. *Nature***, 515**, 335-337, doi:10.1038/515335a.

Schmeier, S., 2014: International River Basin Organizations Lost in Translation? Transboundary River Basin Governance Between Science and Policy. In: *The Global Water System in the Anthropocene*. Springer International Publishing, Cham, pp. 369-383.

Schmitt, M.T., L.B. Aknin, J. Axsen, and R.L. Shwom, 2018: Unpacking the Relationships Between Pro-environmental Behavior, Life Satisfaction, and Perceived Ecological Threat. *Ecological Economics***, 143**, 130-140, doi:10.1016/j.ecolecon.2017.07.007.

Schneider, M. et al., 2017: *The World Nuclear Industry Status Report 2017*. Mycle Schneider Consulting, Paris, France, 267 pp.

Schoenefeld, J.J., M. Hildén, and A.J. Jordan, 2016: The challenges of monitoring national climate policy: learning lessons from the EU. *Climate Policy*, 1-11, doi:10.1080/14693062.2016.1248887.

Schoenmaker, D. and R. van Tilburg, 2016: Financial risks and opportunities in the time of climate change. Bruegel Policy Brief 2016/02, 8 pp.

Schroeder, R. and K. Schroeder, 2014: Happy Environments: Bhutan, Interdependence and the West. *Sustainability***, 6(6)**, doi:10.3390/su6063521.

Schubert, J.E., M. Burns, B.F. Sanders, and T. Flethcher, 2016: To what extent can green infrastructure mitigate downstream flooding in a peri-urban catchment?.

Schuiling, R.D. and P. Krijgsman, 2006: Enhanced Weathering: An Effective and Cheap Tool to Sequester Co2. *Climatic Change***, 74(1)**, 349-354, doi:10.1007/s10584-005-3485-y.

Schuiling, R.D. and P.L. de Boer, 2010: Coastal spreading of olivine to control atmospheric CO2 concentrations: A critical analysis of viability. Comment: Nature and laboratory models are different. *International Journal of Greenhouse Gas Control***, 4(5)**, 855-856, doi:10.1016/j.ijggc.2010.04.012.

Schuitema, G. and L. Steg, 2008: The role of revenue use in the acceptability of transport pricing policies. *Transportation Research Part F: Traffic Psychology and Behaviour***, 11(3)**, doi:10.1016/j.trf.2007.11.003.

Schuitema, G., L. Steg, and S. Forward, 2010a: Explaining differences in acceptability before and acceptance after the implementation of a congestion charge in Stockholm. *Transportation Research Part A: Policy and Practice***, 44(2)**, 99-109, doi:10.1016/j.tra.2009.11.005.

Schuitema, G., L. Steg, and J.A. Rothengatter, 2010b: The acceptability , personal outcome expectations , and expected effects of transport pricing policies. *Journal of Environmental Psychology***, 30**, 587-593, doi:10.1016/j.jenvp.2010.05.002.

Schuitema, G., L. Steg, and M. van Kruining, 2011: When Are Transport Pricing Policies Fair and Acceptable? *Social Justice Research***, 24(1)**, 66-84, doi:10.1007/s11211-011-0124-9.

Schuler, M.L., O. Mantegazza, and A.P.M. Weber, 2016: Engineering C4 photosynthesis into C3 chassis in the synthetic biology age. *The Plant journal: for cell and molecular biology***, 87(1)**, 51-65, doi:10.1111/tpj.13155.

Schulze, E.–D., C. Körner, B.E. Law, H. Haberl, and S. Luyssaert, 2012: Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy***, 4(6)**, 611-616, doi:10.1111/j.1757-1707.2012.01169.x.

Schwan, S. and X. Yu, 2017: Social protection as a strategy to address climate-induced migration. *International*

Journal of Climate Change Strategies and Management, IJCCSM-01-2017-0019, doi:10.1108/IJCCSM-01-2017-0019.

Schwartz, D., W. Bruine de Bruin, B. Fischhoff, and L. Lave, 2015: Advertising energy saving programs: The potential environmental cost of emphasizing monetary savings.. *Journal of Experimental Psychology: Applied***, 21(2)**, 158-166, doi:10.1037/xap0000042.

Scott, C.A., M. Kurian, and J.L. Wescoat, 2015: The Water-Energy-Food Nexus: Enhancing Adaptive Capacity to Complex Global Challenges. *Governing the Nexus*, 15-38, doi:10.1007/978-3-319-05747-7_2.

Scott, M.J. et al., 2015: Calculating impacts of energy standards on energy demand in U.S. buildings with uncertainty in an integrated assessment model. *Energy***, 90**, 1682-1694, doi:10.1016/j.energy.2015.06.127.

Scott, V. and O. Geden, 2018: The challenge of carbon dioxide removal for EU policy-making. *Nature Energy*, 1-3, doi:10.1038/s41560-018-0124-1.

Scott, V., R.S. Haszeldine, S.F.B. Tett, and A. Oschlies, 2015: Fossil fuels in a trillion tonne world. *Nature Climate Change***, 5(5)**, 419-423.

Scovronick, N., C. Dora, E. Fletcher, A. Haines, and D. Shindell, 2015: Reduce short-lived climate pollutants for multiple benefits. *The Lancet***, 386(10006)**, e28-e31, doi:10.1016/S0140-6736(15)61043-1.

Searchinger, T. et al., 2008: Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science***, 319(5867)**, 1238-1240, doi:10.1126/science.1151861.

Searchinger, T.D., T. Beringer, and A. Strong, 2017: Does the world have low-carbon bioenergy potential from the dedicated use of land? *Energy Policy***, 110**, 434-446, doi:10.1016/J.ENPOL.2017.08.016.

Seba, T., 2014: *Clean Disruption of Energy and Transportation: How Silicon Valley Will Make Oil, Nuclear, Natural Gas, Coal, Electric Utilities and Conventional Cars Obsolete by 2030*. Clean Planet Ventures, Silicon Valley, CA, USA, 290 pp.

Seidl, R. et al., 2017: Forest disturbances under climate change. *Nature Climate Change***, 7**, 395.

Seigo, S.L.O., S. Dohle, and M. Siegrist, 2014: Public perception of carbon capture and storage (CCS): A review. *Renewable and Sustainable Energy Reviews***, 38**, 848-863, doi:10.1016/j.rser.2014.07.017.

Sejersen, F., 2015: *Rethinking Greenland and the arctic in the era of climate change: New northern horizons*. 235 pp.

Semprini, G., R. Gulli, and A. Ferrante, 2017: Deep regeneration vs shallow renovation to achieve nearly Zero Energy in existing buildings. *Energy and Buildings***, 156**, 327-342, doi:10.1016/j.enbuild.2017.09.044.

Sen, B., M. Noori, and O. Tatari, 2017: Will Corporate Average Fuel Economy (CAFE) Standard help? Modeling CAFE's impact on market share of electric vehicles. *Energy Policy***, 109**, 279-287, doi:10.1016/j.enpol.2017.07.008.

Sendzimir, J., C.P. Reija, and P. Magnuszewski, 2011: Rebuilding Resilience in the Sahel. *Ecology and society***, 16(3)**, 1-29, doi:10.5751/ES-04198-160301.

Seneviratne, S.I. et al., 2018: Land radiative management as contributor to regional-scale climate adaptation and mitigation. *Nature Geoscience***, 11(2)**, 88-96, doi:10.1038/s41561-017-0057-5.

Serrao-Neumann, S., F. Crick, B. Harman, G. Schuch, and D.L. Choy, 2015: Maximising synergies between disaster risk reduction and climate change adaptation: Potential enablers for improved planning outcomes. *Environmental Science and Policy***, 50**, 46-61, doi:10.1016/j.envsci.2015.01.017.

Sewando, P.T., K.D. Mutabazi, and N.Y.S. Mdoe, 2016: Vulnerability of agro-pastoral farmers to climate risks in northern and central Tanzania. *Development Studies Research***, 3(1)**, 11-24, doi:10.1080/21665095.2016.1238311.

Seyfang, G. and A. Haxeltine, 2012: Growing grassroots innovations: Exploring the role of community-based initiatives in governing sustainable energy transitions. *Environment and Planning C: Politics and Space***, 30(3)**, 381-400, doi:https://doi.org/10.1068/c10222.

Shaffer, L.J., 2014: Making Sense of Local Climate Change in Rural Tanzania Through Knowledge Co-Production. *Journal of Ethnobiology***, 34(3)**, 315-334, doi:10.2993/0278-0771-34.3.315.

Shah, N., M. Wei, V. Letschert, A. Phadke, and E.O. Lawrence, 2015: *Benefits of Leapfrogging to Super-efficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. Lawrence Berkeley National Laboratory, Berkeley.

Shang, Y. et al., 2018: China's energy-water nexus: Assessing water conservation synergies of the total coal consumption cap strategy until 2050. *Applied Energy***, 210**, 643-660, doi:10.1016/j.apenergy.2016.11.008.

Shapiro, S., 2016: The realpolitik of building codes: overcoming practical limitations to climate resilience. *Building Research & Information***, 44(5-6)**, 490-506, doi:10.1080/09613218.2016.1156957.

Sharadin, N., 2018: Rational Coherence in Environmental Policy: Paris, Montreal, and Kigali. *Ethics, Policy & Environment***, 21(1)**, 4-8, doi:10.1080/21550085.2018.1447885.

Sharma, R., 2018: Financing Indian Urban Rail through Land Development: Case Studies and Implications for the Accelerated Reduction in Oil Associated with 1.5 °C. *Urban Planning***, 3(2)**, 21-34, doi:10.17645/up.v3i2.1158.

Shaw, C., S. Hales, P. Howden-Chapman, and R. Edwards, 2014: Health co-benefits of climate change mitigation policies in the transport sector. *Nature Climate Change***, 4(6)**, 427-433, doi:10.1038/nclimate2247.

Shayegh, S., D.L. Sanchez, and K. Caldeira, 2017: Evaluating relative benefits of different types of R&D for clean energy technologies. *Energy Policy*, doi:10.1016/j.enpol.2017.05.029.

Sheeran, K., 2006: Who Should Abate Carbon Emissions? A Note. *Environmental and Resource Economics***, 35(2)**, 89-98.

Sherman, M., J. Ford, A. Llanos-Cuentas, and M.J. Valdivia, 2016: Food system vulnerability amidst the extreme 2010--2011 flooding in the Peruvian Amazon: a case study from the Ucayali region. *Food Security***, 8(3)**, 551-570, doi:10.1007/s12571-016-0583-9.

Shi, L. et al., 2016: Roadmap towards justice in urban climate adaptation research. *Nature Climate Change***, 6(2)**, 131-137, doi:10.1038/nclimate2841.

Shindell, D., J.S. Fuglestvedt, and W.J. Collins, 2017a: The Social Cost of Methane: Theory and Applications. *Faraday Discuss.*, doi:10.1039/C7FD00009J.

Shindell, D. et al., 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science***, 335(6065)**.

Shindell, D. et al., 2017b: A climate policy pathway for near- and long-term benefits. *Science***, 356(6337)**, 493 LP - 494.

Shine, T. and G. Campillo, 2016: The Role of Development Finance in Climate Action Post-2015. .

Shleifer, A. and R.W. Vishny, 1990: Equilibrium Short Horizons of Investors and Firms. *The American Economic Review***, 80(2)**, 148-153.

Shrivastava, P. and S. Persson, 2018: Silent transformation to 1.5°C-with China's encumbered leading. *Current Opinion in Environmental Sustainability***, 31**, 130-136, doi:https://doi.org/10.1016/j.cosust.2018.02.014.

Shue, H., 2018: Mitigation gambles: uncertainty, urgency and the last gamble possible. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences***, 376(2119)**, 20170105, doi:10.1098/rsta.2017.0105.

Shukla, P.R., 2005: Aligning justice and efficiency in the global climate change regime: A developing country perspective. *Advances in the Economics of Environmental Resources***, 5**, 121-144.

Shukla, P.R., J.–C. Hourcade, E. La Rovere, E. Espagne, and B. Perrissin-Fabert, 2017: Revisiting the Carbon Pricing Challenge after COP21 and COP22. CIRED Working Paper No. 2017-59, 8 pp.

Sida, T.S., F. Baudron, H. Kim, and K.E. Giller, 2018: Climate-smart agroforestry: Faidherbia albida trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. *Agricultural and Forest Meteorology***, 248**, 339-347, doi:10.1016/j.agrformet.2017.10.013.

Siders, A.R., 2017: A role for strategies in urban climate change adaptation planning: Lessons from London. *Regional Environmental Change***, 17(6)**, 1801-1810, doi:10.1007/s10113-017-1153-1.

Siegmeier, J. et al., 2018: The fiscal benefits of stringent climate change mitigation: an overview. *Climate Policy***, 18(3)**, 352-367, doi:10.1080/14693062.2017.1400943.

SIFMA, 2017: *2017 Fact book*. 96 pp.

Sikka, A.K., A. Islam, and K.V. Rao, 2018: Climate-Smart Land and Water Management for Sustainable Agriculture. *Irrigation and Drainage***, 67(1)**, 72-81, doi:10.1002/ird.2162.

Simon, A.J., N.B. Kaahaaina, S. Julio Friedmann, and R.D. Aines, 2011: Systems analysis and cost estimates for large scale capture of carbon dioxide from air. *Energy Procedia***, 4**, 2893-2900, doi:10.1016/J.EGYPRO.2011.02.196.

Simon, D. and H. Leck, 2015: Understanding climate adaptation and transformation challenges in African cities. *Current Opinion in Environmental Sustainability***, 13**, 109-116, doi:10.1016/j.cosust.2015.03.003.

Simone, A.M. and E.A. Pieterse, 2017: *New urban worlds: inhabiting dissonant times*. 192 pp.

Sims, R. et al., 2014: Transport. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* []. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 599-670.

Singh, C., P. Dorward, and H. Osbahr, 2016a: Developing a holistic approach to the analysis of farmer decision-making: Implications for adaptation policy and practice in developing countries. *Land Use Policy***, 59**, 329-343, doi:10.1016/j.landusepol.2016.06.041.

Singh, C., P. Urquhart, and E. Kituyi, 2016b: From pilots to systems: Barriers and enablers to scaling up the use of climate information services in smallholder farming communities. CARIAA Working Paper no. 3, 56 pp.

Singh, C. et al., 2017: The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. *Climate and Development*, 1-17, doi:10.1080/17565529.2017.1318744.

Sinha, A., L.A. Darunte, C.W. Jones, M.J. Realff, and Y. Kawajiri, 2017: Systems Design and Economic Analysis of Direct Air Capture of CO 2 through Temperature Vacuum Swing Adsorption Using MIL-101(Cr)-PEI-800 and mmen-Mg 2 (dobpdc) MOF Adsorbents. *Industrial & Engineering Chemistry Research***, 56(3)**, 750-764, doi:10.1021/acs.iecr.6b03887.

Sirkis, A. et al., 2015: *Moving the trillions: a debate on positive pricing of mitigation actions*. Centro Brasil No Clima, Rio de Janeiro, Brazil, 157 pp.

Sivakumar, M.V.K., C. Collins, A. Jay, and J. Hansen, 2014: Regional prioritie s for strengthening climate services for farmers in Africa and South Asia. CCAFS Working Paper, 36 pp.

Sjöberg, L. and B.–M. Drottz-Sjöberg, 2001: Fairness, risk and risk tolerance in the siting of a nuclear waste repository. *Journal of Risk Research*, **4(1)**, 75-101, doi:10.1080/136698701456040.

Skougaard Kaspersen, P., N. Høegh Ravn, K. Arnbjerg-Nielsen, H. Madsen, and M. Drews, 2015: Influence of urban land cover changes and climate change for the exposure of European cities to flooding during high-intensity precipitation. *Proceedings of the International Association of Hydrological Sciences***, 370**, 21-27, doi:10.5194/piahs-370-21-2015.

Skuce, P.J., E.R. Morgan, J. van Dijk, and M. Mitchell, 2013: Animal health aspects of adaptation to climate change: beating the heat and parasites in a warming Europe. *animal***, 7(s2)**, 333-345.

Slade, R., A. Bauen, and R. Gross, 2014: Global bioenergy resources. *Nature Climate Change***, 4(2)**, 99-105.

Slee, B., 2015: Is there a case for community-based equity participation in Scottish on-shore wind energy production? Gaps in evidence and research needs. *Renewable and Sustainable Energy Reviews***, 41**, 540-549, doi:10.1016/j.rser.2014.08.064.

Sleenhoff, S., E. Cuppen, and P. Osseweijer, 2015: Unravelling emotional viewpoints on a bio-based economy using Q methodology. *Public Understanding of Science***, 24(7)**, 858-877, doi:10.1177/0963662513517071.

Smith, C.J. et al., 2017: Impacts of stratospheric sulfate geoengineering on global solar photovoltaic and concentrating solar power resource. *Journal of Applied Meteorology and Climatology*, JAMC-D-16-0298.1, doi:10.1175/JAMC-D-16-0298.1.

Smith, H. and P. Jenkins, 2015: Trans-disciplinary research and strategic urban expansion planning in a context of weak institutional capacity: Case study of Huambo, Angola. *Habitat International***, 46**, 244-251, doi:10.1016/j.habitatint.2014.10.006.

Smith, H., E. Kruger, J. Knot, and J. Blignaut, 2017: Conservation Agriculture in South Africa: Lessons from Case Studies. In: *Building Resilient Farming Systems in a Changing Climate* [Kassam, A.H. (ed.)].

Smith, H.A. and K. Sharp, 2012: Indigenous climate knowledges. *Wiley Interdisciplinary Reviews-Climate Change***, 3(5)**, doi:10.1002/wcc.185.

Smith, J.B., J.M. Vogel, and J.E. Cromwell III, 2009: An architecture for government action on adaptation to climate change. An editorial comment. *Climatic Change***, 95(1-2)**, 53-61, doi:10.1007/s10584-009-9623-1.

Smith, K.R. et al., 2014: Human health: Impacts, adaptation, and co-benefits. In: *Climate Change 2014 Impacts, Adaptation, and Vulnerability* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, and T.E. Bilir (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709-754.

Smith, L.J. and M.S. Torn, 2013: Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change***, 118(1)**, 89-103, doi:10.1007/s10584-012-0682-3.

Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology***, 22(3)**, 1315-1324, doi:10.1111/gcb.13178.

Smith, P., R.S. Haszeldine, and S.M. Smith, 2016a: Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK. *Environ. Sci.: Processes Impacts***, 18(11)**, 1400-1405, doi:10.1039/C6EM00386A.

Smith, P. et al., 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, Cambridge, United Kingdom and New York, NY, USA, pp. 811-922.

Smith, P. et al., 2016b: Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, **6(1)**, 42-50, doi:10.1038/nclimate2870.

Smith, S.J. and A. Mizrahi, 2013: Near-term climate mitigation by short-lived forcers. *Proceedings of the National Academy of Sciences***, 110(35)**, 14202-14206, doi:10.1073/pnas.1308470110.

Smith, S.J. and P.J. Rasch, 2013: The long-term policy context for solar radiation management. *Climatic Change***, 121(3)**, 487-497, doi:10.1007/s10584-012-0577-3.

Smithers, R., E. Holdaway, N. Rass, and N. Sanchez Ibrahim, 2017: Linking National Adaptation Plan Processes and Nationally Determined Contributions. Climate Change Policy Brief, 8 pp.

Smucker, T.A. et al., 2015: Differentiated livelihoods, local institutions, and the adaptation imperative: Assessing climate change adaptation policy in Tanzania. *Geoforum***, 59**, 39-50, doi:10.1016/J.GEOFORUM.2014.11.018.

Snow, J.T. et al., 2016: *A New Vision for Weather and Climate Services in Africa*.

Soares-Filho, B. et al., 2010: Role of Brazilian Amazon protected areas in climate change mitigation. *Proceedings of the National Academy of Sciences***, 107(24)**, 10821-10826, doi:10.1073/pnas.0913048107.

Soccol, C.R. et al., 2010: Bioethanol from lignocelluloses: Status and perspectives in Brazil. *Bioresource Technology***, 101(13)**, 4820-4825, doi:10.1016/J.BIORTECH.2009.11.067.

Socolow, R. et al., 2011: *Direct air capture of CO2 with chemicals: A technology assessment for the APS Panel on Public Affairs*. 100 pp.

Soderlund, J. and P. Newman, 2015: Biophilic architecture: a review of the rationale and outcomes. *AIMS Environmental Science*, **2(4)**, 950-969, doi:10.3934/environsci.2015.4.950.

Sohlberg, J., 2017: The effect of elite polarization: A comparative perspective on how party elites influence attitudes and behavior on climate change in the European union. *Sustainability*, **9(1)**, 1-13, doi:10.3390/su9010039.

Solecki, W., K.C. Seto, and P.J. Marcotullio, 2013: It's Time for an Urbanization Science. *Environment: Science and Policy for Sustainable Development*, **55(1)**, 12-17, doi:10.1080/00139157.2013.748387.

Solecki, W., M. Pelling, and M. Garschagen, 2017: Transitions between risk management regimes in cities. *Ecology And Society*, **22(2)**, doi:10.5751/ES-09102-220238.

Solecki, W. et al., 2018: City transformations in a 1.5 °C warmer world. *Nature Climate Change*, **8(3)**, 177-181, doi:10.1038/s41558-018-0101-5.

Somanathan, E. et al., 2014: National and Sub-national Policies and Institutions. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Sorrell, S., J. Dimitropoulos, and M. Sommerville, 2009: Empirical estimates of the direct rebound effect: A review. *Energy Policy*, **37(4)**, 1356-1371, doi:10.1016/j.enpol.2008.11.026.

Sovacool, B.K., 2016: How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research and Social Science*, **13**, 202-215, doi:10.1016/j.erss.2015.12.020.

Sovacool, B.K., B.–O. Linnér, and M.E. Goodsite, 2015: The political economy of climate adaptation. *Nature Clim. Change*, **5(7)**, 616-618, doi:10.1038/nclimate2665.

Sovacool, B.K., B.O. Linner, and R.J.T. Klein, 2017: Climate change adaptation and the Least Developed Countries Fund (LDCF): Qualitative insights from policy implementation in the Asia-Pacific. *Climatic Change*, **140(2)**, 209-226, doi:10.1007/s10584-016-1839-2.

Spence, A., W. Poortinga, C. Butler, and N.F. Pidgeon, 2011: Perceptions of climate change and willingness to save energy related to flood experience. *Nature Climate Change*, **1(1)**, 46-49, doi:10.1038/nclimate1059.

Spencer, B. et al., 2017: Case studies in co-benefits approaches to climate change mitigation and adaptation. *Journal of Environmental Planning and Management*, **60(4)**, 647-667, doi:10.1080/09640568.2016.1168287.

Spencer, T., R. Pierfederici, and others, 2015: *Beyond the numbers: understanding the transformation induced by INDCs*. N°05/15, 80 pp.

Springmann, M., H.C.J. Godfray, M. Rayner, and P. Scarborough, 2016: Analysis and valuation of the health and climate change cobenefits of dietary change. *Proceedings of the National Academy of Sciences*, **113(15)**, 4146-4151, doi:10.1073/pnas.1523119113.

Stadelmann, M., 2017: Energy Research & Social Science Mind the gap ? Critically reviewing the energy efficiency gap with empirical evidence. *Energy Research & Social Science*, **27**, 117-128, doi:10.1016/j.erss.2017.03.006.

Stavins, R.N., 1988: *Project 88 - Harnessing Market Forces to Protect Our Environment: Initiatives for the New President. A Public Policy Study sponsored by Senator Timothy E. Wirth, Colorado, and Senator John Heinz, Pennsylvania*.

Stavins, R.N. et al., 2014: International Cooperation: Agreements & Instruments. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge Unviersity Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1001 - 1081.

Steenhof, P. and E. Sparling, 2011: The role of codes, standards, and related instruments in facilitating adaptation to climate change. In: *Climate Change Adaptation in Developed Nations: From Theory to Practice* [Ford, J.D. and L. Berrang-Ford (eds.)]. Advances in Global Change Research, Springer, Dordrecht, Netherlands, pp. 243-254.

Steg, L., 2016: Values, Norms, and Intrinsic Motivation to Act Proenvironmentally. *Annual Review of Environment and Resources*, **41(1)**, 277-292, doi:10.1146/annurev-environ-110615-085947.

Steg, L. and C. Vlek, 2009: Encouraging pro-environmental behaviour: An integrative review and research agenda. *Journal of Environmental Psychology*, **29(3)**, doi:10.1016/j.jenvp.2008.10.004.

Steg, L. and J. de Groot, 2010: Explaining prosocial intentions: Testing causal relationships in the norm activation model. *British Journal of Social Psychology*, **49(4)**, doi:10.1348/014466609X477745.

Steg, L., L. Dreijerink, and W. Abrahamse, 2005: Factors influencing the acceptability of energy policies: A test of VBN theory. *Journal of Environmental Psychology*, **25(4)**, 415-425, doi:10.1016/j.jenvp.2005.08.003.

Steg, L., L. Dreijerink, and W. Abrahamse, 2006: Why are Energy Policies Acceptable and Effective? *Environment and Behavior*, **38(1)**, 92-111, doi:10.1177/0013916505278519.

Steg, L., G. Perlaviciute, and E. van der Werff, 2015: Understanding the human dimensions of a sustainable energy transition. *Frontiers in Psychology*, **6**, 1-17, doi:10.3389/fpsyg.2015.00805.

Steg, L., R. Shwom, and T. Dietz, 2017: What drives energy consumers? *IEEE Power & Energy*.

Steinhoff, D.F., A.J. Monaghan, and M.P. Clark, 2014: Projected impact of twenty-first century ENSO changes on rainfall over Central America and northwest South America from CMIP5 AOGCMs. *Climate Dynamics*, **44(5-6)**, 1329-1349, doi:10.1007/s00382-014-2196-3.

Sterling, E.J. et al., 2017: Biocultural approaches to well-being and sustainability indicators across scales. *Nature Ecology & Evolution*, **1(12)**, 1798-1806, doi:10.1038/s41559-017-0349-6.

Sterman, J.D., L. Siegel, and J.N. Rooney-Varga, 2018: Does replacing coal with wood lower CO 2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environmental Research Letters*, **13(1)**, 015007, doi:10.1088/1748-9326/aaa512.

Stern, N., 2013: The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *Journal of Economic Literature*, **51(3)**, 838-859, doi:10.1257/jel.51.3.838.

Stern, N., 2015: Economic development, climate and values: making policy. *Proceedings of the Royal Society of London B: Biological Sciences*, **282(1812)**, n/a-n/a, doi:10.1098/rspb.2015.0820.

Stern, P.C., 2011: Design principles for global commons: natural resources and emerging technologies. *International Journal of the Commons*, **5(2)**, 213-232.

Stern, P.C., 2014: Individual and household interactions with energy systems: Toward integrated understanding. *Energy Research & Social Science*, **1**, 41-48, doi:10.1016/j.erss.2014.03.003.

Stern, P.C. and G.T. Gardner, 1981: Psychological research and energy policy. *American Psychologist*, **36(4)**, 329-342, doi:10.1037/0003-066X.36.4.329.

Stern, P.C. et al., 2016a: consumption by households and organizations. *Nature Energy*, **1(May)**, 16043, doi:10.1038/NENERGY.2016.43.

Stern, P.C. et al., 2016b: Opportunities and insights for reducing fossil fuel consumption by households and organizations. *Nature Energy*, **1(May)**, 16043, doi:10.1038/NENERGY.2016.43.

Stevanović, M. et al., 2017: Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices. *Environmental Science & Technology*, **51(1)**, 365-374, doi:10.1021/acs.est.6b04291.

Stevenson, H. and J.S. Dryzek, 2014: *Democratizing Global Climate Governance*. Cambridge Univeristy Press, Cambride, UK and New York, NY, USA, 256 pp.

Stevenson, M. et al., 2016: Land use, transport, and population health: estimating the health benefits of compact cities. *The Lancet*, **388(10062)**, 2925-2935, doi:10.1016/S0140-6736(16)30067-8.

Stiglitz, J.E., 2002: *Globalization and its Discontents*. W. W. Norton & Company, New York, NY, USA, 304 pp.

Stiglitz, J.E. et al., 2017: *Report of the High-Level Commission on Carbon Prices*. Carbon Pricing Leadership Coalition, 68 pp.

Stjern, C.W. et al., 2017: Rapid Adjustments Cause Weak Surface Temperature Response to Increased Black Carbon Concentrations. *Journal of Geophysical Research: Atmospheres*, **122(21)**, 11,411-462,481, doi:10.1002/2017JD027326.

Stohl, A. et al., 2015: Evaluating the climate and air quality impacts of short-lived pollutants. *Atmospheric Chemistry and Physics*, **15(18)**, 10529-10566, doi:10.5194/acp-15-10529-2015.

Stolaroff, J.K. et al., 2012: Review of methane mitigation technologies with application to rapid release of methane from the Arctic. *Environmental Science & Technology*, **46**, 6455-6469, doi:10.1021/es204686w.

Storelvmo, T., W.R. Boos, and N. Herger, 2014: Cirrus cloud seeding: a climate engineering mechanism with reduced side effects? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **372(2031)**, 20140116-20140116, doi:10.1098/rsta.2014.0116.

Strassburg, B.B.N. et al., 2014: Biophysical suitability, economic pressure and land-cover change: a global probabilistic approach and insights for REDD+. *Sustainability Science*, **9(2)**, 129-141, doi:10.1007/s11625-013-0209-5.

Strefler, J., T. Amann, N. Bauer, E. Kriegler, and J. Hartmann, 2018: Potential and costs of carbon dioxide removal by Enhanced Weathering of rocks. *Environmental Research Letters*, **13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.

Stua, M., 2017: *From the Paris Agreement to a Low-Carbon Bretton Woods: Rationale for the Establishment of a Mitigation*. Springer.

Studart, R. and K. Gallagher, 2015: Guaranteeing Finance for Sustainable Infrastructure: A Proposal. In: *Moving the Trillions - a debate on positive pricing of mitigation actions*. pp. 92-113.

Stults, M. and S.C. Woodruff, 2017: Looking under the hood of local adaptation plans: shedding light on the actions prioritized to build local resilience to climate change. *Mitigation and Adaptation Strategies for Global Change*, **22(8)**, 1249-1279, doi:10.1007/s11027-016-9725-9.

Su, Y., P. Zhang, and Y. Su, 2015: An overview of biofuels policies and industrialization in the major biofuel producing countries. *Renewable and Sustainable Energy Reviews*, **50**, 991-1003, doi:https://doi.org/10.1016/j.rser.2015.04.032.

Suarez, P. and M. van Aalst, 2017: Geoengineering: a humanitarian concern. *Earth's Future*, **5**, 183-195, doi:10.1002/eft2.181.

Sugiyama, M., Y. Arino, T. Kosugi, A. Kurosawa, and S. Watanabe, 2017a: Next steps in geoengineering scenario research: limited deployment scenarios and beyond. *Climate Policy*, 1-9, doi:10.1080/14693062.2017.1323721.

Sugiyama, M. et al., 2017b: Transdisciplinary co-design of scientific research agendas: 40 research questions for socially relevant climate engineering research. *Sustainability Science*, **12(1)**, 31-44, doi:10.1007/s11625-016-0376-2.

Sullivan-Wiley, K.A. and A.G. Short Gianotti, 2017: Risk Perception in a Multi-Hazard Environment. *World Development*, **97**, 138-152, doi:10.1016/j.worlddev.2017.04.002.

Summers, L.H., 2016: The Age of Secular Stagnation: What It Is and What to Do About It. *Foreign Affairs*, **95**, 2.

Sun, Y., G. Huang, X. Xu, and A.C.–K. Lai, 2018: Building-group-level performance evaluations of net zero energy buildings with non-collaborative controls. *Applied Energy*, **212**, 565-576, doi:10.1016/j.apenergy.2017.11.076.

Sunderlin, W.D. et al., 2014: How are REDD+ Proponents Addressing Tenure Problems? Evidence from Brazil, Cameroon, Tanzania, Indonesia, and Vietnam. *World Development*, **55**, 37-52, doi:10.1016/j.worlddev.2013.01.013.

Sundqvist, E., P. Crill, M. Mölder, P. Vestin, and A. Lindroth, 2012: Atmospheric methane removal by boreal plants. *Geophysical Research Letters*, **39(21)**, n/a-n/a, doi:10.1029/2012GL053592.

Sunikka-Blank, M. and Y. Iwafune, 2011: Sustainable Building in Japan - Observations on a Market Transformation Policy. *Environmental Policy and Governance*, **21(5)**, 351-363, doi:10.1002/eet.580.

Surminski, S., 2013: Private-sector adaptation to climate risk. *Nature Clim. Change*, **3(11)**, 943-945, doi:10.1038/nclimate2040.

Sutherland, R.J., 1991: Market barriers to energy-efficiency investments. *Energy Journal*, **12(3)**, 15-34.

Svoboda, T., 2017: *The Ethics of Climate Engineering: Solar Radiation Management and Non-Ideal Justice*. Routledge, Abingdon, UK and New York, NY, USA, 232 pp.

Swatuk, L.A., 2015: Water conflict and cooperation in Southern Africa. *Wiley Interdisciplinary Reviews: Water*, **2(3)**, 215-230, doi:10.1002/wat2.1070.

Szabó, S., M. Moner-Girona, I. Kougias, R. Bailis, and K. Bódis, 2016: Identification of advantageous electricity generation options in sub-Saharan Africa integrating existing resources. *Nature Energy*, **1**, 16140, doi:10.1038/nenergy.2016.140.

Szerszynski, B., M. Kearnes, P. Macnaghten, R. Owen, and J. Stilgoe, 2013: Why solar radiation management geoengineering and democracy won't mix. *Environment and Planning A*, **45(12)**, 2809-2816, doi:10.1068/a45649.

Tacoli, C., B. Bukhari, and S. Fisher, 2013: *Urban poverty, food security and climate change*. IIED, Human Settlements Group.

Tait, L. and M. Euston-Brown, 2017: What role can African cities play in low-carbon development? A multilevel governance perspective of Ghana, Uganda and South Africa. *Journal of Energy in Southern Africa*, **28(3)**, 43, doi:10.17159/2413-3051/2017/v28i3a1959.

Takahashi, B., M. Burnham, C. Terracina-Hartman, A.R. Sopchak, and T. Selfa, 2016: Climate Change Perceptions of NY State Farmers : The Role of Risk Perceptions and Adaptive Capacity. *Environmental Management*, **58(6)**, 946-957, doi:10.1007/s00267-016-0742-y.

Takahashi, N. et al., 2015: Community Trial on Heat Related-Illness Prevention Behaviors and Knowledge for the Elderly. *International Journal of Environmental Research and Public Health*, **12(3)**, doi:10.3390/ijerph120303188.

Talberg, A., P. Christoff, S. Thomas, and D. Karoly, 2018: Geoengineering governance-by-default: an earth system governance perspective. *International Environmental Agreements: Politics, Law and Economics*, **18(2)**, 229-253, doi:10.1007/s10784-017-9374-9.

Tall, A. et al., 2014: Scaling up climate services for farmers: Mission possible. Learning from good practice in Africa and South Asia. CCAFS Report No. 13, 44 pp.

Tallis, M., G. Taylor, D. Sinnett, and P. Freer-Smith, 2011: Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landscape and Urban Planning*, **103(2)**, 129-138, doi:10.1016/j.landurbplan.2011.07.003.

Tassey, G., 2014: Competing in Advanced Manufacturing: The Need for Improved Growth Models and Policies. *Journal of Economic Perspectives*, **28(1)**, 27-48, doi:10.1257/jep.28.1.27.

Taub, D.R., B. Miller, and H. Allen, 2008: Effects of elevated CO 2 on the protein concentration of food crops: a meta-analysis. *Global Change Biology*, **14(3)**, 565-575, doi:10.1111/j.1365-2486.2007.01511.x.

Taufik, D., J.W. Bolderdijk, and L. Steg, 2015: Acting green elicits a literal warm glow. *Nature Climate Change*, **5(1)**, 37-40, doi:10.1038/nclimate2449.

Taufik, D., J.W. Bolderdijk, and L. Steg, 2016: Going green? The relative importance of feelings over calculation in driving environmental intent in the Netherlands and the United States. *Energy Research & Social Science*, **22**, 52-62, doi:10.1016/j.erss.2016.08.012.

Taylor, A.L., S. Dessai, and W. Bruine de Bruin, 2014: Public perception of climate risk and adaptation in the UK: A review of the literature. *Climate Risk Management***, 4-5**, 1-16, doi:10.1016/j.crm.2014.09.001.

Taylor, L.L. et al., 2016: Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nature Clim. Change***, 6(4)**, 402-406.

TEC, 2016: *Updated guidance on technology action plans*. UNFCCC, Bonn, Germany, 21 pp.

Teferi, Z. and P. Newman, 2017: Slum Regeneration and Sustainability: Applying the Extended Metabolism Model and the SDGs. *Sustainability***, 9(12)**, 2273, doi:10.3390/su9122273.

Teferi, Z.A. and P. Newman, 2018: Slum Upgrading: Can the 1.5 °C Carbon Reduction Work with SDGs in these Settlements? *Urban Planning***, 3(2)**, 52, doi:10.17645/up.v3i2.1239.

Tehranian, H. and J.F. Waegelein, 1985: Market reaction to short-term executive compensation plan adoption. *Journal of Accounting and Economics***, 7(1-3)**, 131-144, doi:10.1016/0165-4101(85)90032-1.

ten Berge, H.F.M. et al., 2012: Olivine weathering in soil, and its effects on growth and nutrient uptake in Ryegrass (Lolium perenne L.): a pot experiment. *PLoS One***, 7(8)**, e42098, doi:10.1371/journal.pone.0042098.

Termeer, C.J.A.M., A. Dewulf, and G.R. Biesbroek, 2017: Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *Journal of Environmental Planning and Management***, 60(4)**, 558-576, doi:10.1080/09640568.2016.1168288.

Tessler, Z.D. et al., 2015: Profiling risk and sustainability in coastal deltas of the world. *Science***, 349(6248)**, 638-643, doi:10.1126/science.aab3574.

Teulings, C. and R. Baldwin (eds.), 2014: *Secular stagnation: Facts, causes, and cures*. Centre for Economic Policy Research Press, London, UK, 154 pp.

The City of New York, 2013: *A Stronger, More Resilient New York*.

The City of New York, 2017: *Preliminary Climate Resiliency Design Guidelines*. NYC Mayor's Office of Recovery & Resiliency.

The World Bank Data, 2018: Market capitalization of listed domestic companies (current US$). https://data.worldbank.org/indicator/CM.MKT.LCAP.CD (Accessed: 15 May 2018).

Thi Hong Phuong, L., G.R. Biesbroek, and A.E.J. Wals, 2017: The interplay between social learning and adaptive capacity in climate change adaptation: A systematic review. *NJAS - Wageningen Journal of Life Sciences***, 82**, 1-9, doi:10.1016/j.njas.2017.05.001.

Thieme, T.A., 2017: The hustle economy. *Progress in Human Geography*, 030913251769003, doi:10.1177/0309132517690039.

Thøgersen, J., Ölander, F., 2003: Spillover of environment-friendly consumer behaviour. *Journal of Environmental Psychology***, 23**, 225-236, doi:10.1016/S0272-4944(03)00018-5.

Thomas, S., L.–A. Brischke, J. Thema, L. Leuser, and M. Kopatz, 2017: Energy sufficiency policy: how to limit energy consumption and per capita dwelling size in a decent way. In: *Proceedings of the ECEEE Summer Study*.

Thomas, S.D., 1988: The realities of nuclear power : international economic and regulatory experience.. , 289.

Thomson, G. and P. Newman, 2016: Geoengineering in the Anthropocene through Regenerative Urbanism. *Geosciences***, 6(4)**, 46, doi:10.3390/geosciences6040046.

Thornton, P.K. and M. Herrero, 2014: Climate change adaptation in mixed crop-livestock systems in developing countries. *Global Food Security***, 3(2)**, 99-107, doi:10.1016/j.gfs.2014.02.002.

Thornton, P.K. and M. Herrero, 2015: Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nature Climate Change***, 5(9)**, 830-836.

Thornton, P.K. et al., 2018: A Qualitative Evaluation of CSA Options in Mixed Crop-Livestock Systems in Developing Countries. In: *Climate Smart Agriculture : Building Resilience to Climate Change* [Lipper, L., N. McCarthy, D. Zilberman, S. Asfaw, and G. Branca (eds.)]. Springer International Publishing, Cham, pp. 385-423.

Thornton, T.F. and N. Manasfi, 2010: Adaptation-Genuine and Spurious: Demystifying Adaptation Processes in Relation to Climate Change. *Environment and Society***, 1(1)**, doi:10.3167/ares.2010.010107.

Thornton, T.F. and C. Comberti, 2017: Synergies and trade-offs between adaptation, mitigation and development. *Climatic Change***, 140(1)**, 5-18, doi:10.1007/s10584-013-0884-3.

Tiefenbeck, V. et al., 2016: Overcoming Salience Bias: How Real-Time Feedback Fosters Resource Conservation. *Management Science*, mnsc.2016.2646, doi:10.1287/mnsc.2016.2646.

Tilleard, S. and J. Ford, 2016: Adaptation readiness and adaptive capacity of transboundary river basins. *Climatic Change***, 137(3-4)**, 575-591, doi:10.1007/s10584-016-1699-9.

Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature***, 515(7528)**, 518-522, doi:10.1038/nature13959.

Tilmes, S., B.M.M. Sanderson, and B.C. O'Neill, 2016: Climate impacts of geoengineering in a delayed mitigation scenario. *Geophysical Research Letters***, 43(15)**, 8222-8229, doi:10.1002/2016GL070122.

Tilmes, S. et al., 2012: Impact of very short-lived halogens on stratospheric ozone abundance and UV radiation in a geo-engineered atmosphere. *Atmospheric Chemistry and Physics***, 12(22)**, 10945-10955, doi:10.5194/acp-12-10945-2012.

Tjiputra, J.F., A. Grini, and H. Lee, 2016: Impact of idealized future stratospheric aerosol injection on the large-scale ocean and land carbon cycles. *Journal of Geophysical Research: Biogeosciences*, **121(1)**, 2-27, doi:10.1002/2015JG003045.

Tobler, C., V.H.M. Visschers, and M. Siegrist, 2011: Organic Tomatoes Versus Canned Beans: How Do Consumers Assess the Environmental Friendliness of Vegetables? *Environment and Behavior*, **43(5)**, 591-611, doi:10.1177/0013916510372865.

Tobler, C., V.H.M. Visschers, and M. Siegrist, 2012: Consumers' knowledge about climate change. *Climatic Change*, **114(2)**, 189-209, doi:10.1007/s10584-011-0393-1.

Tokarska, K.B. and K. Zickfeld, 2015: The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. *Environmental Research Letters*, **10(9)**, 094013, doi:10.1088/1748-9326/10/9/094013.

Toleikyte, A., L. Kranzl, and A. Müller, 2018: Cost curves of energy efficiency investments in buildings - Methodologies and a case study of Lithuania. *Energy Policy*, **115**, 148-157, doi:10.1016/j.enpol.2017.12.043.

Tollefson, J., 2017: World's carbon emissions set to spike by 2% in 2017. *Nature*, **551(7680)**, 283-283, doi:10.1038/nature.2017.22995.

Torssonen, P. et al., 2016: Effects of climate change and management on net climate impacts of production and utilization of energy biomass in Norway spruce with stable age-class distribution. *GCB Bioenergy*, **8(2)**, 419-427, doi:10.1111/gcbb.12258.

Trabacchi, C. and B.K. Buchner, 2017: Adaptation Finance: Setting the Ground for Post-Paris Action. *Climate Finance*, **Volume 2**, 35-54, doi:doi:10.1142/9789814641814_0003.

Trenberth, K.E., M. Marquis, and S. Zebiak, 2016: The vital need for a climate information system. *Nature Climate Change*, **6(12)**, 1057-1059, doi:10.1038/nclimate3170.

Trisos, C.H. et al., 2018: Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination. *Nature Ecology & Evolution*, **2(3)**, 475-482, doi:10.1038/s41559-017-0431-0.

Truelove, H., A.R. Carrico, and L. Thabrew, 2015: A socio-psychological model for analyzing climate change adaptation: A case study of Sri Lankan paddy farmers. *Global Environmental Change*, **31**, 85-97, doi:10.1016/j.gloenvcha.2014.12.010.

Truelove, H.B., A.R. Carrico, E.U. Weber, K.T. Raimi, and M.P. Vandenbergh, 2014: Positive and negative spillover of pro-environmental behavior: An integrative review and theoretical framework. *Global Environmental Change*, **29**, 127-138, doi:10.1016/j.gloenvcha.2014.09.004.

Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8(5)**, doi:10.1002/wcc.476.

Tukker, A. et al., 2011: Environmental impacts of changes to healthier diets in Europe. *Ecological Economics*, **70(10)**, 1776-1788, doi:10.1016/J.ECOLECON.2011.05.001.

Tuomisto, H.L. and M.J. Teixeira de Mattos, 2011: Environmental Impacts of Cultured Meat Production. *Environmental Science & Technology*, **45(14)**, 6117-6123, doi:10.1021/es200130u.

Turner, P.A. et al., 2018: The global overlap of bioenergy and carbon sequestration potential. *Climatic Change*, **148(1-2)**, 1-10, doi:10.1007/s10584-018-2189-z.

Turnhout, E. et al., 2017: Envisioning REDD+ in a post-Paris era: between evolving expectations and current practice. *Wiley Interdisciplinary Reviews: Climate Change*, **8(1)**, e425, doi:10.1002/wcc.425.

UN, 2014: *World urbanisation prospects, 2014 revisions*. Department of Economic and Social Affairs, New York, NY, USA.

UN, 2016: *Transforming our World: The 2030 Agenda for Sustainable Development*. A/RES/70/1, United Nations (UN), New York, NY, USA, 41 pp.

UN, 2017: *World Population Prospects - 2017 Revision*. Department of Economic and Social Affairs, Population Division, United Nations, Paris, France.

Ünal, A.B., L. Steg, and M. Gorsira, 2017: Values Versus Environmental Knowledge as Triggers of a Process of Activation of Personal Norms for Eco-Driving. *Environment and Behavior*, 001391651772899, doi:10.1177/0013916517728991.

UNCBD, 2010: *Decision Adopted by the Conference of the Parties to the Convention on Biological Diversity at its Tenth Meeting*. 1-9 pp.

Underwood, B.S., Z. Guido, P. Gudipudi, and Y. Feinberg, 2017: Increased costs to US pavement infrastructure from future temperature rise. *Nature Climate Change*, **7(10)**, 704-707, doi:10.1038/nclimate3390.

UNEP, 2005: *Enhancing Capacity Building for Integrated Policy Design and Implementation for Sustainable Development*. Economics and Trade Branch, Division of Technology, Industry and Economics, United Nations Environment Programme, Geneva, Switzerland, 65 pp.

UNEP, 2011: *Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 78 pp.

UNEP, 2014: *Decoupling 2: Technologies, Opportunities and Policy Options*. United Nations Environment Programme, Nairobi, Kenya, 174 pp.

UNEP, 2015: *The financial system we need; aligning the financial system with sustainable development*. United Nations Environment Programme, 112 pp.
UNEP, 2016: *The Adaptation Finance Gap Report 2016*. United Nations Environment Programme (UNEP).
UNEP, 2017a: *The Adaptation Gap Report 2017*. United Nations Environment Programme (UNEP), Nairobi, Kenya.
UNEP, 2017b: *The Emissions Gap Report 2017*.
UNESCO, 2017: What is Local and Indigenous Knowledge? http://www.unesco.org/new/en/natural-sciences/priority-areas/links/related-information/what-is-local-and-indigenous-knowledge (Accessed: 12 May 2018).
UNFCCC, 1992: *United Nations Framework Convention on Climate Change*. UNFCCC, Bonn, Germany.
UNFCCC, 2015: Adoption of the Paris Agreement. In: *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015*. FCCC/CP/2015/10/Add.1, United Nations Framework Convention on Climate Change (UNFCCC), pp. 32.
UN-Habitat, 2011: *Cities and Climate Change: Global Report on Human Settlements 2011*. 300 pp.
UN-Habitat, 2017: Sustainable Urbanisation in the Paris Agreement. .
UNISDR, 2009: *Global Assessment Report on Disaster Risk Reduction 2009 - Risk and Poverty in a Changing Climate: Invest Today for a Safer Tomorrow*. United Nations International Strategy for Disaster Reduction, Geneva, Switzerland, 14 pp.
Upadhyay, A.P. and A. Bijalwan, 2015: Climate Change Adaptation: Services and Role of Information Communication Technology (ICT) in India. *American Journal of Environmental Protection*, **4(1)**, 70-74, doi:10.11648/j.ajep.20150401.20.
Upton, G.B. and B.F. Snyder, 2017: Funding Renewable Energy: An Analysis of Renewable Portfolio Standards. *Energy Economics*, **66(0)**, 205-216, doi:10.1016/j.eneco.2017.06.003.
Ura, K., 2015: The Experience of Gross National Happiness as Development Framework. , 38.
Ürge-Vorsatz, D., S.T. Herrero, N.K. Dubash, and F. Lecocq, 2014: Measuring the Co-Benefits of Climate Change Mitigation. *Annual Review of Environment and Resources*, **39(1)**, 549-582, doi:10.1146/annurev-environ-031312-125456.
Valdivia, C., C. Barbieri, and M.A. Gold, 2012: Between Forestry and Farming: Policy and Environmental Implications of the Barriers to Agroforestry Adoption. *Canadian Journal of Agricultural Economics*, **60(2)**, 155-175, doi:10.1111/j.1744-7976.2012.01248.x.
van Asselt, H., P. Pauw, and H. Sælen, 2015: Assessment and Review under a 2015 Climate Change Agreement. .
van der Brugge, R. and R. Roosjen, 2015: An institutional and sociocultural perspective on the adaptation pathways approach. *Journal of Water and Climate Change*, **6(4)**, 743-758, doi:10.2166/wcc.2015.001.
van der Giesen, C. et al., 2017: A Life Cycle Assessment Case Study of Coal-Fired Electricity Generation with Humidity Swing Direct Air Capture of CO2 versus MEA-Based Postcombustion Capture. *Environmental Science & Technology*, **51(2)**, 1024-1034, doi:10.1021/acs.est.6b05028.
van der Keur, P. et al., 2016: Identification and analysis of uncertainty in disaster risk reduction and climate change adaptation in South and Southeast Asia. *International Journal of Disaster Risk Reduction*, **16**, 208-214, doi:10.1016/j.ijdrr.2016.03.002.
van Der Werff, E. and L. Steg, 2015: One model to predict them all: Predicting energy behaviours with the norm activation model. *Energy Research and Social Science*, **6(July)**, 8-14, doi:10.1016/j.erss.2014.11.002.
van der Werff, E., L. Steg, and K. Keizer, 2013a: It is a moral issue: The relationship between environmental self-identity, obligation-based intrinsic motivation and pro-environmental behaviour. *Global Environmental Change*, **23(5)**, 1258-1265, doi:10.1016/j.gloenvcha.2013.07.018.
van der Werff, E., L. Steg, and K. Keizer, 2013b: The value of environmental self-identity: The relationship between biospheric values, environmental self-identity and environmental preferences, intentions and behaviour. *Journal of Environmental Psychology*, **34**, 55-63, doi:10.1016/j.jenvp.2012.12.006.
van der Werff, E., L. Steg, and K. Keizer, 2014a: Follow the signal: When past pro-environmental actions signal who you are. *Journal of Environmental Psychology*, **40**, 273-282, doi:10.1016/j.jenvp.2014.07.004.
van der Werff, E., L. Steg, and K. Keizer, 2014b: I Am What I Am, by Looking Past the Present: The Influence of Biospheric Values and Past Behavior on Environmental. *Environment and Behavior*, **46(5)**, 626-657, doi:10.1177/0013916512475209.
van Dooren, C., M. Marinussen, H. Blonk, H. Aiking, and P. Vellinga, 2014: Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns. *Food Policy*, **44**, 36-46, doi:10.1016/j.foodpol.2013.11.002.
van Kasteren, Y., 2014: How are householders talking about climate change adaptation? *Journal of Environmental Psychology*, **40**, 339-350, doi:10.1016/J.JENVP.2014.09.001.
van Oppen, M.J.H., J.K. Oliver, H.M. Putnam, and R.D. Gates, 2015: Building coral reef resilience through assisted evolution. *Proceedings of the National Academy of Sciences*, **112(8)**, 2307-2313, doi:10.1073/pnas.1422301112.
van Sluisveld, M.A.E. et al., 2015: Comparing future patterns of energy system change in 2 °C scenarios with historically observed rates of change. *Global Environmental Change*, **35**, 436-449,

doi:10.1016/j.gloenvcha.2015.09.019.
van Soest, D.P. and E.H. Bulte, 2001: Does the Energy-Efficiency Paradox Exist? Technological Progress and Uncertainty. *Environmental and Resource Economics*, **18(1)**, 101-112, doi:10.1023/A:1011112406964.
van Soest, H.L. et al., 2017: Early action on Paris Agreement allows for more time to change energy systems. *Climatic Change*, **144(2)**, 165-179, doi:10.1007/s10584-017-2027-8.
van Vliet, M.T.H., D. Wiberg, S. Leduc, and K. Riahi, 2016: Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, **6(4)**, 375-380, doi:10.1038/nclimate2903.
van Vuuren, D.P., O.Y. Edelenbosch, D.L. McCollum, and K. Riahi, 2017: A special issue on model-based long-term transport scenarios: Model comparison and new methodological developments to improve energy and climate policy analysis. *Transportation Research Part D: Transport and Environment*, **55**, 277-280, doi:10.1016/j.trd.2017.05.003.
van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391-397, doi:10.1038/s41558-018-0119-8.
Vandentorren, S. et al., 2006: Heat-related mortality August 2003 Heat Wave in France : Risk Factors for Death of Elderly People Living at Home. *Eureopean Journal of Public Health*, **16(6)**, 583-591, doi:10.1093/eurpub/ckl063.
Vandyck, T., K. Keramidas, B. Saveyn, A. Kitous, and Z. Vrontisi, 2016: A global stocktake of the Paris pledges: Implications for energy systems and economy. *Global Environmental Change*, **41**, 46-63, doi:10.1016/j.gloenvcha.2016.08.006.
Varela-Ortega, C. et al., 2016: How can irrigated agriculture adapt to climate change? Insights from the Guadiana Basin in Spain. *Regional Environmental Change*, **16(1)**, 59.
Vaughan, C. and S. Dessai, 2014: Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *WIREs Climate Change*, **5(5)**, 587-603, doi:10.1002/wcc.290.
Vaughan, C. et al., 2018: Surveying climate services: What can we learn from a bird's eye view? *Weather, Climate, and Society*, WCAS-D-17-0030.1, doi:10.1175/WCAS-D-17-0030.1.
Vaughan, N.E. and C. Gough, 2016: Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters*, **11(9)**, 095003, doi:10.1088/1748-9326/11/9/095003.
Velásquez Barrero, L.S., 1998: Agenda 21: a form of joint environmental management in Manizales, Colombia. *Environment and Urbanization*, **10(2)**, 9-36.
Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123**, 200-209, doi:10.1016/j.atmosenv.2015.10.071.
Veldman, J.W. et al., 2015: Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. *BioScience*, **65(10)**, 1011-1018, doi:10.1093/biosci/biv118.
Venables, A.J., 2016: Using Natural Resources for Development: Why Has It Proven So Difficult? *Journal of Economic Perspectives*, **30(1)**, 161-184, doi:10.1257/jep.30.1.161.
Venhoeven, L.A., J.W. Bolderdijk, and L. Steg, 2013: Explaining the paradox: How pro-environmental behaviour can both thwart and foster well-being. *Sustainability (Switzerland)*, **5(4)**, 1372-1386, doi:10.3390/su5041372.
Venhoeven, L.A., J.W. Bolderdijk, and L. Steg, 2016: Why acting environmentally-friendly feels good: Exploring the role of self-image. *Frontiers in Psychology*, **7(NOV)**, 1990-1991, doi:10.3389/fpsyg.2016.01846.
Venkataraman, C., S. Ghosh, and M. Kandlikar, 2016: Breaking out of the Box: India and Climate Action on Short-Lived Climate Pollutants. *Environmental Science & Technology*, **50(23)**, 12527-12529, doi:10.1021/acs.est.6b05246.
Vergara, W., A.R. Rios, L.M. Galindo, and J. Samaniego, 2015: Physical Damages Associated with Climate Change Impacts and the Need for Adaptation Actions in Latin America and the Caribbean. In: *Handbook of Climate Change Adaptation* [Leal Filho, W. (ed.)]. Springer-Verlag GmbH Berlin Heidelber, Berlin and Heidelberg Germany, pp. 479-491.
Verhoef, L.A., B.W. Budde, C. Chockalingam, B. García Nodar, and A.J.M. van Wijk, 2018: The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach. *Energy Policy*, **112**, 349-360, doi:10.1016/j.enpol.2017.10.034.
Verplanken, B. and D. Roy, 2013: "My Worries Are Rational, Climate Change Is Not": Habitual Ecological Worrying Is an Adaptive Response. *PLoS ONE*, **8(9)**, e74708, doi:10.1371/journal.pone.0074708.
Verplanken, B. and D. Roy, 2016: Empowering interventions to promote sustainable lifestyles: Testing the habit discontinuity hypothesis in a field experiment. *Journal of Environmental Psychology*, **45**, 127-134, doi:10.1016/j.jenvp.2015.11.008.
Verplanken, B., H. Aarts, and A. Van Knippenberg, 1997: Habit, information acquisition, and the process of making travel mode choices. *European Journal of Social Psychology*, **27(5)**, 539-560, doi:10.1002/(SICI)1099-0992(199709/10)27:5<539::AID-EJSP831>3.0.CO;2-A.
Verstegen, J. et al., 2015: What can and can't we say about indirect land-use change in Brazil using an integrated economic - land-use change model? *GCB Bioenergy*, **8(3)**, 561-578, doi:10.1111/gcbb.12270.

Veugelers, R., 2012: Which policy instruments to induce clean innovating? *Research Policy*, **41(10)**, 1770-1778, doi:https://doi.org/10.1016/j.respol.2012.06.012.

Vicente-Vicente, J.L., R. García-Ruiz, R. Francaviglia, E. Aguilera, and P. Smith, 2016: Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: A meta-analysis. *Agriculture, Ecosystems & Environment*, **235**, 204-214, doi:https://doi.org/10.1016/j.agee.2016.10.024.

Viegas, J., L. Martinez, P. Crist, and S. Masterson, 2016: Shared Mobility: Inovation for Liveable Cities. *International Transport Forum's Corporate Partnership Board*, 1-56, doi:10.1787/5jlwvz8bd4mx-en.

Villarroel Walker, R., M.B. Beck, J.W. Hall, R.J. Dawson, and O. Heidrich, 2014: The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. *Journal of Environmental Management*, **141**, 104-115, doi:10.1016/j.jenvman.2014.01.054.

Vinke-de Kruijf, J. and C. Pahl-Wostl, 2016: A multi-level perspective on learning about climate change adaptation through international cooperation. *Environmental Science & Policy*, **66**, 242-249, doi:10.1016/j.envsci.2016.07.004.

Vision 2020 Project Team, 2011: *Vision 2020: New York City Comprehensive Waterfront Plan*. 192 pp.

Visioni, D., G. Pitari, and V. Aquila, 2017a: Sulfate geoengineering: a review of the factors controlling the needed injection of sulfur dioxide. *Atmospheric Chemistry and Physics*, **17(6)**, 3879-3889, doi:10.5194/acp-2016-985, 2016.

Visioni, D. et al., 2017b: Sulfate Geoengineering Impact on Methane Transport and Lifetime : Results from the Geoengineering Model Intercomparison Project (GeoMIP). *Atmos. Chem. Phys.*, **15(July)**, 1-35, doi:10.5194/acp-17-11209-2017.

Visschers, V.H.M., J. Shi, M. Siegrist, and J. Arvai, 2017: Beliefs and values explain international differences in perception of solar radiation management: insights from a cross-country survey. *Climatic Change*, **142(3-4)**, 531-544, doi:10.1007/s10584-017-1970-8.

Vlek, C.A.J. and L. Steg, 2007: Human behavior and environmental sustainability: Problems, driving forces, and research topics. *Journal of Social Issues*, **63(1)**, 1-19, doi:10.1111/j.1540-4560.2007.00493.x.

Vogel, C., S.C. Moser, R.E. Kasperson, and G.D. Dabelko, 2007: Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. *Global Environmental Change*, **17(3-4)**, 349-364, doi:doi: 10.1016/j.gloenvcha.2007.05.002.

von der Assen, N., J. Jung, and A. Bardow, 2013: Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls. *Energy & Environmental Science*, **6(9)**, 2721-2734, doi:10.1039/C3EE41151F.

Voskamp, I.M. and F.H.M. Van de Ven, 2015: Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events. *Building and Environment*, **83**, 159-167, doi:10.1016/j.buildenv.2014.07.018.

Vrontisi, Z. et al., 2018: Enhancing global climate policy ambition towards a 1.5 °C stabilization: a short-term multi-model assessment. *Environmental Research Letters*, **13(4)**, 044039, doi:10.1088/1748-9326/aab53e.

Wachsmuth, D., D.A. Cohen, and H. Angelo, 2016: Expand the frontiers of urban sustainability. *Nature*, **536(7617)**, 391-393, doi:10.1038/536391a.

Wadud, Z., D. MacKenzie, and P. Leiby, 2016: Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transportation Research Part A: Policy and Practice*, **86**, 1-18, doi:10.1016/j.tra.2015.12.001.

Waisman, H., J. Rozenberg, and J.C. Hourcade, 2013: Monetary compensations in climate policy through the lens of a general equilibrium assessment: The case of oil-exporting countries. *Energy Policy*, **63**, 951-961.

Waisman, H., C. Guivarch, F. Grazi, and J.C. Hourcade, 2012: The Imaclim-R model: infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Climatic Change*, **114(1)**, 101-120, doi:10.1007/s10584-011-0387-z.

Walker, W. and M. Lönnroth, 1983: Nuclear power struggles : industrial competition and proliferation control. , 204.

Wallace, B., 2017: A framework for adapting to climate change risk in coastal cities. *Environmental Hazards*, **16(2)**, 149-164, doi:10.1080/17477891.2017.1298511.

Walsh, J.E., 2014: Intensified warming of the Arctic: Causes and impacts on middle latitudes. *Global and Planetary Change*, **117(Supplement C)**, 52-63, doi:10.1016/j.gloplacha.2014.03.003.

Wamsler, C., 2007: Bridging the gaps : stakeholder-based strategies for risk reduction and financing for the urban poor. *Environment & Urbanization*, **19(1)**, 115-152, doi:10.1177/0956247807077029.

Wamsler, C., 2017: Stakeholder involvement in strategic adaptation planning: Transdisciplinarity and co-production at stake? *Environmental Science & Policy*, **75(March)**, 148-157, doi:10.1016/j.envsci.2017.03.016.

Wamsler, C. and E. Brink, 2014a: Interfacing citizens' and institutions' practice and responsibilities for climate change adaptation. *Urban Climate*, **7**, 64-91, doi:10.1016/j.uclim.2013.10.009.

Wamsler, C. and E. Brink, 2014b: Moving beyond short-term coping and adaptation. *Environment & Urbanization*, **26(6)**, 86-111, doi:10.1177/0956247813516061.

Wang, G. et al., 2017: Continued increase of extreme El Nino frequency long after 1.5°C warming stabilization. *Nature Clim. Change*, **7(8)**, 568-572, doi:10.1038/nclimate3351.

Wang, Q., F. Xiao, F. Zhang, and S. Wang, 2013: Labile soil organic carbon and microbial activity in three subtropical plantations. *Forestry*, **86(5)**, 569-574, doi:10.1093/forestry/cpt024.

Wang, Q., X. Chen, A.N. Jha, and H. Rogers, 2014: Natural gas from shale formation - The evolution, evidences and challenges of shale gas revolution in United States. *Renewable and Sustainable Energy Reviews*, **30**, 1-28, doi:https://doi.org/10.1016/j.rser.2013.08.065.

Wang, Q. et al., 2015: Structural Evolution of Household Energy Consumption: A China Study. *Sustainability*, **7**, 3919-3932, doi:10.3390/su7043919.

Wang, X. et al., 2016: Taking account of governance: Implications for land-use dynamics, food prices, and trade patterns. *Ecological Economics*, **122(Supplement C)**, 12-24, doi:https://doi.org/10.1016/j.ecolecon.2015.11.018.

Wangui, E.E. and T.A. Smucker, 2017: Gendered opportunities and constraints to scaling up: a case study of spontaneous adaptation in a pastoralist community in Mwanga District, Tanzania. *Climate and Development*, 1-8, doi:10.1080/17565529.2017.1301867.

Ward, J., S. Fankhauser, C. Hepburn, H. Jackson, and R. Rajan, 2009: *Catalysing low-carbon growth in developing economies: Public Finance Mechanisms to scale up private sector investment in climate solution*. 28 pp.

Ward, P.J., W.P. Pauw, M.W. van Buuren, and M.A. Marfai, 2013: Governance of flood risk management in a time of climate change: the cases of Jakarta and Rotterdam. *Environmental Politics*, **22(3)**, 518-536, doi:10.1080/09644016.2012.683155.

Warren, C.R. et al., 2005: Green On Green': Public perceptions of wind power in Scotland and Ireland. *Journal of Environmental Planning and Management*, **48(6)**, 853-875, doi:10.1080/09640560500294376.

Waters, J. and W.N. Adger, 2017: Spatial, network and temporal dimensions of the determinants of adaptive capacity in poor urban areas. *Global Environmental Change*, **46**, 42-49, doi:10.1016/j.gloenvcha.2017.06.011.

Watkins, K., 2015: Power, people, planet: seizing Africa's energy and climate opportunities. .

Weber, E.U., 2015: Climate change demands behavioral change: What are the challenges. *Social Research: An International Quarterly*, **82(3)**.

Wee, B., 2015: Peak car: The first signs of a shift towards ICT-based activities replacing travel? A discussion paper. *Transport Policy*, **42**, 1-3, doi:10.1016/j.tranpol.2015.04.002.

Weenig, M.W.H. and C.J.H. Midden, 1991: Communication Network Influences on Information Diffusion and Persuasion. *Journal of Per*, **61(5)**, 734-742.

Wehkamp, J., N. Koch, S. Lübbers, and S. Fuss, 2018a: Governance and deforestation - a meta-analysis in economics. *Ecological Economics*, **144**, 214-227, doi:10.1016/j.ecolecon.2017.07.030.

Wehkamp, J. et al., 2018b: Accounting for institutional capacity in global forest modeling. *Environmental Modelling & Software* (in press), doi:10.1016/j.envsoft.2018.01.020.

Wehner, M.F., K.A. Reed, B. Loring, D. Stone, and H. Krishnan, 2018: Changes in tropical cyclones under stabilized 1.5 and 2.0°C global warming scenarios as simulated by the Community Atmospheric Model under the HAPPI protocols. *Earth System Dynamics*, **9(1)**, 187-195, doi:10.5194/esd-9-187-2018.

Wei, M., S.J. Smith, and M.D. Sohn, 2017: Experience curve development and cost reduction disaggregation for fuel cell markets in Japan and the US. *Applied Energy*, **191**, 346-357, doi:https://doi.org/10.1016/j.apenergy.2017.01.056.

Wei, Y., D. Tang, Y. Ding, and G. Agoramoorthy, 2016: Incorporating water consumption into crop water footprint: A case study of China's South-North Water Diversion Project. *Science of The Total Environment*, **545-546**, 601-608, doi:10.1016/J.SCITOTENV.2015.12.062.

Weindl, I. et al., 2015: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environmental Research Letters*, **10(9)**, 94021.

Weitzman, M.L., 2015: A Voting Architecture for the Governance of Free-Driver Externalities, with Application to Geoengineering. *Scandinavian Journal of Economics*, **117(4)**, 1049-1068, doi:10.1111/sjoe.12120.

Wejs, A., K. Harvold, S.V. Larsen, and I.–L. Saglie, 2014: Legitimacy building in weak institutional settings: climate change adaptation at local level in Denmark and Norway. *Environmental Politics*, **23(3)**, 490-508, doi:10.1080/09644016.2013.854967.

Weldegebriel, Z.B. and M. Prowse, 2013: Climate-Change Adaptation in Ethiopia: To What Extent Does Social Protection Influence Livelihood Diversification? *Development Policy Review*, **31**, o35-o56, doi:10.1111/dpr.12038.

Well, M. and A. Carrapatoso, 2017: REDD+ finance: policy making in the context of fragmented institutions. *Climate Policy*, **17(6)**, 687-707, doi:10.1080/14693062.2016.1202096.

Wells, L., B. Rismanchi, and L. Aye, 2018: A review of Net Zero Energy Buildings with reflections on the Australian context. *Energy and Buildings*, **158**, 616-628, doi:10.1016/j.enbuild.2017.10.055.

Wenzel, G.W., 2009: Canadian Inuit subsistence and ecological instability - If the climate changes, must the Inuit? *Polar Research*, **28(1)**, 89-99, doi:10.1111/j.1751-8369.2009.00098.x.

Wesseling, J.H. et al., 2017: The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews*,

79(Supplement C), 1303-1313, doi:10.1016/j.rser.2017.05.156.
West, S.E. and R.C. Williams, 2004: Estimates from a consumer demand system: implications for the incidence of environmental taxes. *Journal of Environmental Economics and Management***, 47(3)**, 535-558, doi:10.1016/j.jeem.2003.11.004.
Westphal, M.I., S. Martin, L. Zhou, and D. Satterthwaite, 2017: Powering Cities in the Global South: How Energy Access for All Benefits the Economy and the Environment. , 55.
White, C.J. et al., 2017: Potential applications of subseasonal-to-seasonal (S2S) predictions. *Meteorological Applications*, doi:10.1002/met.1654.
White, R., J. Turpie, and G. Letley, 2017: *Greening Africa's Cities: Enhancing the Relationship between Urbanization, Environmental Assets, and Ecosystem Services*. 56 pp.
Whitmarsh, L., G. Seyfang, and S.O.N. Workspace., 2011: Public engagement with carbon and climate change: To what extent is the public 'carbon capable'? *Global Environmental Change***, 21(1)**, 56-65, doi:10.1016/j.gloenvcha.2010.07.011.
WHO, 2015: Lessons learned on health adaptation to climate variability and change: experiences across low- and middle-income countries. *WHO*.
Whyte, K.P., 2012: Now This! Indigenous Sovereignty, Political Obliviousness and Governance Models for SRM Research. *Ethics, Policy & Environment***, 15(2)**, 172-187, doi:10.1080/21550085.2012.685570.
Wibeck, V. et al., 2017: Making sense of climate engineering: a focus group study of lay publics in four countries. *Climatic Change***, 145(1-2)**, 1-14, doi:10.1007/s10584-017-2067-0.
Wigand, C. et al., 2017: A Climate Change Adaptation Strategy for Management of Coastal Marsh Systems. *Estuaries and Coasts***, 40(3)**, 682-693, doi:10.1007/s12237-015-0003-y.
Wilcox, J., P.C. Psarras, and S. Liguori, 2017: Assessment of reasonable opportunities for direct air capture. *Environmental Research Letters***, 12(6)**, 65001.
Williams, M. et al., 2011: Options for policy responses and their impacts. In: *Integrated Assessment of Black Carbon and Tropospheric Ozone*. United Nations Environment Programme (UNEP), Nairobi, Kenya, pp. 171-250.
Williams, P. et al., 2017: Community-based observing networks and systems in the Arctic: Human perceptions of environmental change and instrument-derived data. *Regional Environmental Change*, doi:10.1007/s10113-017-1220-7.
Williams, P.M. and E.R.M. Druffel, 1987: Radiocarbon in dissolved organic matter in the central North Pacific Ocean. *Nature***, 330(6145)**, 246-248, doi:10.1038/330246a0.
Williamson, P. and R. Bodle, 2016: Update on Climate Geoengineering in Relation to the Convention on Biological Diversity: Potential Impacts and Regulatory Framework. , 158.
Williamson, P. et al., 2012: Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging governance. *Process Safety and Environmental Protection***, 90(6)**, 475-488, doi:10.1016/J.PSEP.2012.10.007.
Willis, R., 2017: How Members of Parliament understand and respond to climate change. *The Sociological Review*, 1-17, doi:10.1177/0038026117731658.
Wilson, C., 2012: Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. *Energy Policy***, 50**, 81-94, doi:10.1016/j.enpol.2012.04.077.
Wilson, C. and H. Dowlatabadi, 2007: Models of Decision Making and Residential Energy Use. *Annual Review of Environment and Resources***, 32(1)**, 169-203, doi:10.1146/annurev.energy.32.053006.141137.
Wilson, C., A. Grubler, N. Bauer, V. Krey, and K. Riahi, 2013: Future capacity growth of energy technologies: Are scenarios consistent with historical evidence? *Climatic Change***, 118(2)**, 381-395, doi:10.1007/s10584-012-0618-y.
Wilson, S.A. et al., 2009: Carbon Dioxide Fixation within Mine Wastes of Ultramafic-Hosted Ore Deposits: Examples from the Clinton Creek and Cassiar Chrysotile Deposits, Canada. *Economic Geology***, 104(1)**, 95-112.
Windeatt, J.H. et al., 2014: Characteristics of biochars from crop residues: Potential for carbon sequestration and soil amendment. *Journal of Environmental Management***, 146**, 189-197, doi:https://doi.org/10.1016/j.jenvman.2014.08.003.
Winkler, H., 2017: Reducing energy poverty through carbon tax revenues in South Africa. *Journal of Energy in Southern Africa***, 28(3)**, 12, doi:10.17159/2413-3051/2017/v28i3a2332.
Winkler, H. and N.K. Dubash, 2015: Who determines transformational change in development and climate finance? *Climate Policy*, 783-791, doi:DOI: 10.1080/14693062.2015.1033674.
Winkler, H., T. Letete, and A. Marquard, 2013: Equitable access to sustainable development: operationalizing key criteria. *Climate Policy***, 13(4)**, 411-432, doi:10.1080/14693062.2013.777610.
Winkler, H. et al., 2011: Equitable access to sustainable development: Contribution to the body of scientific knowledge. *Beijing, Brasilia, Cape Town, and Mumbai: BASIC Experts*.
Winkler, H. et al., 2017: Countries start to explain how their climate contributions are fair: more rigour needed. *International Environmental Agreements: Politics, Law and Economics*, doi:10.1007/s10784-017-9381-x.
Wise, M., M. Muratori, and P. Kyle, 2017: Biojet fuels and emissions mitigation in aviation: An integrated assessment

modeling analysis. *Transportation Research Part D: Transport and Environment*, **52**, 244-253, doi:10.1016/j.trd.2017.03.006.

WMO, 2015: Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services. , 308.

Wolak, F.A., 2011: Do residential customers respond to hourly prices? Evidence from a dynamic pricing experiment. *American Economic Review*, **101(3)**, 83-87, doi:10.1257/aer.101.3.83.

Wolfrom, L. and M. Yokoi-Arai, 2015: Financial instruments for managing disaster risks related to climate change. *OECD Journal: Financial Market Trends*, **2015(1)**, 25-47.

Wollenberg, E. et al., 2016: Reducing emissions from agriculture to meet the 2C target. *Global Change Biology*, **22(12)**, 3859-3864, doi:10.1111/gcb.13340.

Wolske, K.S., P.C. Stern, and T. Dietz, 2017: Explaining interest in adopting residential solar photovoltaic systems in the United States: Toward an integration of behavioral theories. *Energy Research & Social Science*, **25**, 134-151, doi:10.1016/j.erss.2016.12.023.

Wong, P.–H., 2014: Maintenance Required: The Ethics of Geoengineering and Post-Implementation Scenarios. *Ethics, Policy & Environment*, **17(2)**, 186-191, doi:10.1080/21550085.2014.926090.

Wong, S., 2012: Overcoming obstacles against effective solar lighting interventions in South Asia. *Energy Policy*, **40**, 110-120, doi:https://doi.org/10.1016/j.enpol.2010.09.030.

Wood, B.T., C.H. Quinn, L.C. Stringer, and A.J. Dougill, 2017: Investigating Climate Compatible Development Outcomes and their Implications for Distributive Justice: Evidence from Malawi. *Environmental Management*, **1**, 1-18, doi:10.1007/s00267-017-0890-8.

Wood, P. and F. Jotzo, 2011: Price floors for emissions trading. *Energy Policy*, **39(3)**, 1746-1753.

Wood, S.A., A.S. Jina, M. Jain, P. Kristjanson, and R.S. DeFries, 2014: Smallholder farmer cropping decisions related to climate variability across multiple regions. *Global Environmental Change*, **25**, 163-172, doi:10.1016/j.gloenvcha.2013.12.011.

Woodcock, J. et al., 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *The Lancet*, **374(9705)**, 1930-1943, doi:10.1016/S0140-6736(09)61714-1.

Woodruff, S.C. and M. Stults, 2016: Numerous strategies but limited implementation guidance in US local adaptation plans. *Nature Climate Change*, **6(8)**, 796-802, doi:10.1038/nclimate3012.

Woods, B.A., H. Nielsen, A.B. Pedersen, and D. Kristofersson, 2017: Farmers' perceptions of climate change and their likely responses in Danish agriculture. *Land Use Policy*, **65(May 2015)**, 109-120, doi:10.1016/j.landusepol.2017.04.007.

Woolf, D., J.E. Amonette, A. Street-Perrott, J. Lehmann, and S. Joseph, 2010: Sustainable bio-char to mitigate global climate change. *Nature Communications*, **1(56)**, doi:doi:10.1038/ncomms1053.

World Bank, 2016: *World Bank Group Climate Action Plan*. World Bank, Washington DC, USA, 59 pp.

World Bank, 2017a: Pacific Possible: Long-term Economic Opportunities and Challenges for Pacific Island Countries. .

World Bank, 2017b: Understanding Poverty: Safety Nets. http://www.worldbank.org/en/topic/safetynets (Accessed: 4 December 2017).

World Bank, 2018a: Global Financial Development Report - Bankers without borders. , 01 - 137, doi:10.1596/978-1-4648-1148-7.

World Bank, 2018b: Groundswell: Preparing for Internal Climate Migration. .

World Economic Forum, 2013: *The Green Investment Report: ways and means to unlock private finance for green growth*. 40 pp.

World Economic Forum, 2015: Industrial Internet of Things. .

Wright, H. et al., 2014: Farmers, food and climate change: ensuring community-based adaptation is mainstreamed into agricultural programmes. *Climate and Development*, **6(4)**, 318-328, doi:10.1080/17565529.2014.965654.

Wu, P., J. Ridley, A. Pardaens, R. Levine, and J. Lowe, 2015: The reversibility of CO2 induced climate change. *Climate Dynamics*, **45(3)**, 745-754, doi:10.1007/s00382-014-2302-6.

Xia, L., A. Robock, S. Tilmes, and R.R. Neely, 2016: Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate. *Atmospheric Chemistry and Physics*, **16(3)**, 1479-1489, doi:10.5194/acp-16-1479-2016.

Xiao, J.J., H. Li, J. Jian, and X. Haifeng, 2011: Sustainable Consumption and Life Satisfaction. *Social Indicators Research*, **104(2)**, 323-329, doi:10.1007/s11205-010-9746-9.

Xie, J. et al., 2017: An integrated assessment of urban flooding mitigation strategies for robust decision making. *Environmental Modelling & Software*, **95(Supplement C)**, 143-155, doi:10.1016/j.envsoft.2017.06.027.

Xu, Y. and V. Ramanathan, 2017: Well below 2°C: Mitigation strategies for avoiding dangerous to catastrophic climate changes. *Proceedings of the National Academy of Sciences*, **114(39)**, 10315-10323, doi:10.1073/pnas.1618481114.

Xue, X. et al., 2015: Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches. *Water Research*, **77**, 155-169, doi:10.1016/j.watres.2015.03.017.

Yamamoto, L., D.A. Serraglio, and F.S. Cavedon-Capdeville, 2017: Human mobility in the context of climate change and disasters: a South American approach. *International Journal of Climate Change Strategies and*

Management, IJCCSM-03-2017-0069, doi:10.1108/IJCCSM-03-2017-0069.

Yang, Y.C.E., S. Wi, P.A. Ray, C.M. Brown, and A.F. Khalil, 2016: The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories. *Global Environmental Change***, 37**, 16-30, doi:10.1016/j.gloenvcha.2016.01.002.

Yangka, D. and M. Diesendorf, 2016: Modeling the benefits of electric cooking in Bhutan: A long term perspective. *Renewable and Sustainable Energy Reviews***, 59**, 494-503, doi:10.1016/j.rser.2015.12.265.

Yangka, D. and P. Newman, 2018: Bhutan: Can the 1.5 °C Agenda Be Integrated with Growth in Wealth and Happiness? *Urban Planning***, 3(2)**, 94, doi:10.17645/up.v3i2.1250.

Yax L., P. and S. Álvarez, 2016: Bioindicadores y conocimiento ancestral/tradicional para el pronóstico meteorológico en comunicades indígenas Maya - K'iche' de Nahualá, Sololá. Poster Presentation pp.

Yenneti, K. and R. Day, 2016: Distributional justice in solar energy implementation in India: The case of Charanka solar park. *Journal of Rural Studies***, 46**, 35-46, doi:10.1016/j.jrurstud.2016.05.009.

Young, O.R., 2016: *Governing Complex Systems: Social Capital for the Anthropocene*. The MIT Press, Cambridge, MA, USA and London, UK, 296 pp.

Young, W. et al., 2015: Changing Behaviour: Successful Environmental Programmes in the Workplace. *Business Strategy and the Environment***, 24(8)**, 689-703, doi:10.1002/bse.1836.

Yuan, X., J. Zuo, R. Ma, and Y. Wang, 2017: How would social acceptance affect nuclear power development? A study from China. *Journal of Cleaner Production***, 163(Supplement C)**, 179-186, doi:https://doi.org/10.1016/j.jclepro.2015.04.049.

Zahariev, K., J.R. Christian, and K.L. Denman, 2008: Preindustrial, historical, and fertilization simulations using a global ocean carbon model with new parameterizations of iron limitation, calcification, and N2 fixation. *Progress in Oceanography***, 77(1)**, 56-82, doi:10.1016/j.pocean.2008.01.007.

Zanchi, G., N. Pena, and N. Bird, 2012: Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy***, 4(6)**, 761-772, doi:10.1111/j.1757-1707.2011.01149.x.

Zangheri, P., R. Armani, M. Pietrobon, and L. Pagliano, 2018: Identification of cost-optimal and NZEB refurbishment levels for representative climates and building typologies across Europe. *Energy Efficiency***, 11(2)**, 337-369, doi:10.1007/s12053-017-9566-8.

Zaval, L., E.M. Markowitz, and E.U. Weber, 2015: How Will I Be Remembered? Conserving the Environment for the Sake of One's Legacy. *Psychological Science***, 26(2)**, 231-236, doi:10.1177/0956797614561266.

Zeebe, R.E., 2005: Feasibility of ocean fertilization and its impact on future atmospheric CO2 levels. *Geophysical Research Letters***, 32(9)**, doi:10.1029/2005gl022449.

Zelli, F., 2011: The fragmentation of the global climate governance architecture. *Wiley Interdisciplinary Reviews: Climate Change***, 2(1)**, 255-270.

Zeman, F., 2014: Reducing the Cost of Ca-Based Direct Air Capture of CO 2. *Environmental Science & Technology***, 48(19)**, 11730-11735, doi:10.1021/es502887y.

Zeng, S. and Z. Chen, 2016: Impact of fossil fuel subsidy reform in China: Estimations of household welfare effects based on 2007-2012 data. *Economic and Political Studies***, 4(3)**, 299-318, doi:10.1080/20954816.2016.1218669.

Zhang, H., 2016: Towards global green shipping: the development of international regulations on reduction of GHG emissions from ships. *International Environmental Agreements: Politics, Law and Economics***, 16(4)**, 561-577, doi:10.1007/s10784-014-9270-5.

Zhang, H., W. Chen, and W. Huang, 2016: TIMES modelling of transport sector in China and USA: Comparisons from a decarbonization perspective. *Applied Energy***, 162**, 1505-1514, doi:10.1016/j.apenergy.2015.08.124.

Zhang, W. et al., 2017: Perception, knowledge and behaviors related to typhoon: A cross sectional study among rural residents in Zhejiang, China. *International Journal of Environmental Research and Public Health***, 14(5)**, 1-12, doi:10.3390/ijerph14050492.

Ziervogel, G., A. Cowen, and J. Ziniades, 2016a: Moving from Adaptive to Transformative Capacity: Building Foundations for Inclusive, Thriving, and Regenerative Urban Settlements. *Sustainability***, 8(9)**, 955, doi:10.3390/su8090955.

Ziervogel, G., J. Waddell, W. Smit, and A. Taylor, 2016b: Flooding in Cape Town's informal settlements: barriers to collaborative urban risk governance. *South African Geographical Journal***, 98(1)**, 1-20, doi:10.1080/03736245.2014.924867.

Ziervogel, G. et al., 2017: Inserting rights and justice into urban resilience: a focus on everyday risk. *Environment and Urbanization***, 29(1)**, 123-138, doi:10.1177/0956247816686905.

Zomer, R.J. et al., 2016: Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets. *Scientific Reports***, 6(April)**, 29987, doi:10.1038/srep29987.

Zusman, E., A. Miyatsuka, J. Romero, and M. Arif, 2015: Aligning Interests around Mitigating Short Lived Climate Pollutants (SLCP) in Asia: A Stepwise Approach. , 14.

Contents

Supplementary Material 4.A Benchmark indicators for sectoral changes in emissions as presented in Table 4.1 (Section 4.2.1)

Integrated Assessment Models (IAMs) and other sector scenarios provide sectoral detail underpinning the declines in Greenhouse Gas (GHG) emissions by the middle of the century (Section 2.3 and Section 2.4). Supplementary Material 4.A, Table 1 indicates the pace of the transitions that are deemed necessary in 2020, 2030 and 2050 at the sector level for 1.5°C-consistent pathways, and complements this with bottom-up studies from literature that give actionable policy targets (the lines in white). A summary of this table is presented in Section 4.2.1.

Supplementary Material 4.A, Table 1: Benchmark indicators indicating the sectoral changes in emissions, fuels and technologies that would need to take place in 1.5°C-consistent pathways, based on selected IAM 1.5°C pathways assessed in Chapter 2 (with high and low overshoot (OS)) (dark grey rows), four archetype scenarios (light grey rows), and bottom-up studies (white rows).

		Energy			Buildings		Transport			Industry
		Share of renewable in primary energy [%]	Share of renewable in electricity [%]	Share of Fossil fuels in electricity generation [%]	Reduction of energy demand in buildings [% rel. to 2010]	Direct emissions reductions from buildings [% rel. to 2010]	Share of low carbon fuels (electricity, hydrogen and biofuel) in transport [%]	Share of electricity in transport [%]	Share of biofuels in transport [%]	Industrial emission reductions [% rel. to 2010]
2020	1.5°C low OS	15.31 (16.23, 14.03)	26.26 (28.83, 23.58)	61.08 (63.17, 58.74)	-10.86 (-7.53, -14.83)	-0.83 (6.62, -9.69)	4.39 (4.51, 3.59)	1.24 (1.79, 1.09)	1.97 (3.17, 1.55)	-11.81 (-1.66, -17.80)
	1.5°C high OS	15.08 (15.84, 14.44)	28.37 (29.24, 25.08)	61.58 (63.83, 59.70)	-12.49 (-10.75, -19.44)	-3.52 (6.62, -15.22)	3.59 (4.45, 3.27)	1.40 (1.53, 1.09)	2.18 (2.98, 1.72)	-15.50 (-12.70, -23.70)
	S1	12.46	23.24	63.72	-9.20	-0.83		0.95	1.69	4.46
	S2	16.61	27.00	60.11	-16.20	-0.25	2.18	0.97	1.22	-20.61
	S5	13.46	17.38	71.03			3.16	0.95	2.20	
	LED	15.63	24.61	54.11	-8.78	15.11		2.51		-32.87
	(Figueres et al., 2017)		30							
	(Kuramochi et al., 2017)					20-35				10
	(IEA, 2017a)	15	31	58	5	12	8	2	5	-9
2030	1.5°C low OS	28.75 (35.31, 25.45)	52.63 (58.90, 44.48)	31.54 (38.14, 23.14)	-2.61 (5.41, -7.73)	30.11 (43.16, 20.58)	9.71 (15.24, 8.44)	4.99 (6.84, 3.18)	5.06 (9.60, 2.12)	39.81 (49.58, 30.13)
	1.5°C high OS	23.65 (27.45, 20.03)	42.73 (53.78, 36.91)	42.02 (47.27, 32.61)	-16.64 (-12.07, -20.01)	8.15 (23.54, -0.61)	6.65 (8.32, 5.55)	3.46 (4.68, 2.54)	3.54 (3.85, 1.38)	17.67 (27.65, -12.81)
	S1	28.79	57.89	27.84	-7.68	35.32		3.92	5.06	49.09

	S2	28.72	47.89	35.37	-14.12	47.92	5.17	4.46	0.71	19.11
	S5	13.78	25.11	57.38			3.43	1.32	1.93	
	LED	37.42	59.64	17.14	30.42	59.81		20.93		42.10
	(Löffler et al., 2017)	50	78							
	(Rockström et al., 2017)	20								
	(Kuramochi et al., 2017)					60-70				20
	(IEA, 2017a)	20	47	38	7	43	16.4	6	11	22
	(WBCSD, 2017)				-11				10	
2050	1.5°C low OS	58.37 (66.65, 49.97)	75.98 (85.32, 68.54)	8.69 (13.59, 4.80)	-19.43 (2.17, -37.44)	68.30 (89.48, 54.32)	52.95 (65.14, 34.10)	22.63 (30.20, 16.74)	14.71 (21.73, 10.11)	78.69 (89.17, 70.60)
	1.5°C high OS	62.16 (67.51, 47.48)	82.39 (88.34, 63.65)	6.33 (16.06, 2.26)	-37.41 (-13.37, -51.04)	48.64 (59.49, 40.82)	38.38 (43.62, 27.01)	18.49 (22.88, 13.67)	14.96 (17.78, 5.10)	68.12 (80.61, 53.62)
	S1	58.37	81.26	10.15	-20.54	79.74		33.68	12.95	73.70
	S2	52.90	63.08	11.42	-24.59	89.65	25.65	22.67	2.98	72.81
	S5	67.04	70.27	6.69			53.36	9.54	35.46	
	LED	72.51	77.40	0.19	44.67	95.00		59.21		91.38
	(Löffler et al., 2017)	100	100	0			98			
	(Rockström et al., 2017)		100	0						
	(Figueres et al., 2017)					100				50
	(Kuramochi et al., 2017)		100			80 - 90				
	(IEA, 2017a)	29	74	10	11	81	59	31	27	57
	(WBCSD, 2017)								27	

Notes: Values for '1.5C low OS' and '1.5C high OS' indicate the median and the interquartile ranges for indicators for 1.5°C-consistent pathways distinguishing high and low overshoot, collected in the scenario database established for the assessment of this Special Report (see Section 2.1 and Annex 2.3). Four illustrative pathway archetypes were selected for comparison: S1 (AIM 2.0, SSP1-19), S2 (MESSAGE-GLOBIOM 1.0, SSP2-19), S5 (REMIND-MAgPIE 1.5, SSP5-19) and LED (MESSAGEix-GLOBIOM 1.0, LowEnergyDemand) (see Section 2.1) The selected studies indicate mitigation transitions in key sectors consistent with limiting warming to 1.5°C (Figueres et al., 2017; Kuramochi et al., 2017; Löffler et al., 2017; Rockström et al., 2017) or below 2°C (IEA, 2017a; WBCSD, 2017), grounded in published scenarios combined with expert judgment.

Supplementary Material 4.B Enabling conditions and constraints of overarching adaptation options as discussed in Section 4.3.5

Supplementary Material 4.B, Table 1: Overarching adaptation options: enabling conditions and constraints. This table is underpinning Section 4.3.5.

Adaptation option	Feasibility	Enabling conditions	Constraints	Examples
Disaster risk management (DRM)	*Medium evidence (high agreement)*	Pools resources and expertise for risk reduction (Howes et al., 2015; Kelman et al., 2015; Wallace, 2017) Integrates adaptation into existing management (Howes et al., 2015) Supports post-disaster recovery and reconstruction (Kelman et al., 2015; Kull et al., 2016) Engagement of local and Indigenous knowledge can improve preparedness and response (McNamara and Prasad, 2014; Mawere and Mubaya, 2015; Kaya et al., 2016; Chambers et al., 2017; Granderson, 2017)	Uncertainty over projected climate impacts, absence of downscaled climate projections (van der Keur et al., 2016; de Leon and Pittock, 2017; Wallace, 2017) Limited institutional, technical, and financial capacity in frontline agencies (de Leon and Pittock, 2017; Kita, 2017; Wallace, 2017) Adaptation and DRM communities operate separately (Kelman et al., 2015; Serrao-Neumann et al., 2015; de Leon and Pittock, 2017)	*Glacial lake outburst floods (GLOFs)* 1.5°C will increase risk of GLOFs (Cogley, 2017; Kraaijenbrink et al., 2017). Infrastructural measures technically and economically unfeasible in many regions (Muñoz et al., 2016; Schwanghart et al., 2016; Watanabe et al., 2016; Haeberli et al., 2017) Early warning systems (Anacona et al., 2015), and monitoring of dangerous lakes and surrounding slopes (including using remote sensing) offer DRM opportunities (Emmer et al., 2016; Milner et al., 2017) Institutional leadership and community engagement essential for effectiveness (Anacona et al., 2015; Watanabe et al., 2016)
Risk sharing and spreading: insurance	*Medium evidence (medium agreement)*	Buffers climate risk (Wolfrom and Yokoi-Arai, 2015; O'Hare et al., 2016; Glaas et al., 2017; Jenkins et al., 2017; Patel et al., 2017). Shifts the mobilization of financial resources towards strategic approaches (Surminski et al., 2016) Incentivises investments and behavior that reduce exposure (Linnerooth-Bayer and Hochrainer-Stigler, 2015; Shapiro, 2016; Jenkins et al., 2017).	Can provide disincentives for reducing risk and can distort incentives for adaptation strategies (Annan and Schlenker, 2015; Nicola, 2015) Underwrites a return to the 'status-quo' rather than enabling adaptive behavior (O'Hare et al., 2016) Financial, social, and institutional barriers to implementation and uptake, especially in low income nations (García Romero and Molina, 2015; Joyette et al., 2015; Lashley and Warner, 2015; Jin et al., 2016)	*Crop insurance* In Kenya during the 2011 drought, index-based insurance pay-outs for livestock reduced distress sales by 64% among better-off pastoralist households and reduced the likelihood of rationing food intake by 43% among poorer households (Hansen et al., 2017) In USA, (Annan and Schlenker, 2015) found insured crops were significantly more sensitive to extreme heat because insured farmers were disincentivised from investing in costly adaptation strategies since their insurance compensated for potential losses

				In Bangladesh low institutional trust and financial literacy means that fewer women enrol in weather-based crop insurance (Akter et al., 2016) *World Bank Cat bond issuance in Caribbean* In 2007, the Caribbean Catastrophe Risk Insurance Facility was formed to pool risk from tropical cyclones, earthquakes, and excess rainfalls (Murphy et al., 2012; CCRIF, 2017) 36 payouts have been made to 13 governments, totalling 130.5 million USD and partially funded by CCRIF, within 14 days of the event (CCRIF, 2017). Speed of payment allows countries to finance immediate needs (Murphy et al., 2012) Though widely perceived to be successful, evidence of success remains limited (Teh, 2015)
Risk sharing and spreading: social protection programmes	*Medium evidence (medium agreement)*	Builds generic adaptive capacity and reduces social vulnerability (Weldegebriel and Prowse, 2013; Eakin et al., 2014; Lemos et al., 2016; Schwan and Yu, 2017). Must be complemented with a comprehensive climate risk management approach (Schwan and Yu, 2017) that also takes into account disaster risk management, adaptation, and vulnerability reduction goals (Davies et al., 2013).	Inadequate targeting, leakages, and lack of institutional architecture, especially in LDCs (Ravi and Engler, 2015; Schwan and Yu, 2017) Uncertainties about effectiveness of processes of delivering social protection (e.g. cash or "in-kind"). Necessary but insufficient to decrease households' vulnerability if standalone (Lemos et al., 2016) When delivered without emphasis on vulnerability reduction, investments may be maladaptive in long run (Nelson et al., 2016)	*Cash transfer programmes* In sub-Saharan Africa, cash transfer programmes targeting poor communities have proven successful in smoothing household welfare and food security during droughts, strengthening community ties, and reducing debt levels (del Ninno et al., 2016; Asfaw et al., 2017; Asfaw and Davis, 2018). In Brazil, higher levels of income due to cash transfer programs have been linked to food security, as households are able to invest in irrigation, but there have been limited long-term investments in reducing vulnerability among the poorest households (Lemos et al., 2016; Mesquita and Bursztyn, 2016; Nelson et al., 2016).
Education and learning	*Medium evidence (high agreement)*	Co-production of solutions strengthens adaptation implementation (Butler et al., 2016a; Thi Hong Phuong et al., 2017; Ford et al., 2018)	Not appropriate in all circumstances (e.g., highly marginalized locations) (Ford et al., 2016, 2018)	*Participatory scenario planning (PSP)* PSP is a process by which multiple stakeholders work together to envision future scenarios under a range of climatic conditions (Flynn et al., 2018).

		Social learning strengthens adaptation and affects longer-term change (Clemens et al., 2015; Ensor and Harvey, 2015; Henly-Shepard et al., 2015). International learning and cooperation mechanisms, supranational organizations (Vinke-de Kruijf and Pahl-Wostl, 2016), and international, collaborative projects (Cochrane et al., 2017; Harvey et al., 2017) can build adaptive capacity.	Education and learning on their own may not provide "enough adaptive capacity to respond to climate change" (Thi Hong Phuong et al., 2017) Participation in and of itself does not necessarily build capacity (Ford et al., 2016)	PSP has been observed to facilitate the interaction of multiple knowledge systems, resulting in learning and the co-production of knowledge on adaptation (Tschakert et al., 2014; Oteros-Rozas et al., 2015; Star et al., 2016; Flynn et al., 2018).
Population health and health system	*Medium evidence (high agreement)*	1.5°C will primarily exacerbate existing health challenges (Smith et al., 2014a), which can be targeted by enhancing health services. Age, pre-existing medical conditions and social deprivation are found to be the key (but not the only) factors that make people vulnerable and lead to more adverse health outcomes related to climate change impacts. This can be mainstreamed through existing health programing and service delivery (WHO, 2015; Paavola, 2017) Needs to be combined with iterative management involving regular monitoring of effectiveness in the light of climate impacts (Hess and Ebi, 2016; Ebi and del Barrio, 2017) Collaboration with local stakeholders, public education campaigns, and the tailoring of communication to local needs are essential (Berry and Richardson, 2016; van Loenhout et al., 2016).	Governance challenges: e.g. absence of coordination across scales, lack of mandate for action on adaptation (Austin et al., 2016; Ebi and del Barrio, 2017; Shimamoto and McCormick, 2017) Absence of information and understanding on climate impacts (Nigatu et al., 2014; Xiao et al., 2016; Sheehan et al., 2017) Many health services currently don't consider climate change (Hess and Ebi, 2016). Adaptation strategies based on individual preparedness, action and behaviour change may aggravate health and social inequalities due to their selective uptake, unless they are coupled with broad public information campaigns and financial support for undertaking adaptive measures (Paavola, 2017)	*Heat-wave early warning and response systems* Heat wave early warning and response systems coordinate the implementation of multiple measures in response to predicted extreme temperatures (e.g. public announcements, opening public cooling shelters, distributing information on heat stress symptoms) and have been shown to be effective in a wide variety of contexts (Knowlton et al., 2014; Takahashi et al., 2015; Nitschke et al., 2016, 2017).
Indigenous knowledge	*Medium evidence*	Indigenous knowledge underpins the adaptive capacity of Indigenous		*Cultural programming*

	(high agreement)	communities through the diversity and flexibility of Indigenous agro-ecological systems, collective social memory, repository of accumulated experience, and from social networks that are essential for disaster response and recovery (Hiwasaki et al., 2015; Pearce et al., 2015; Mapfumo et al., 2016; Sherman et al., 2016; Ingty, 2017; Ruiz-Mallén et al., 2017) Knowledge of environmental conditions helps communities detect and monitor change (Johnson et al., 2015; Mistry and Berardi, 2016; Williams et al., 2017) .	Acculturation, dispossession of land rights and land grabbing, colonization, and social change are challenging Indigenous knowledge systems (Ford, 2012; Nakashima et al., 2012; McNamara and Prasad, 2014; Pearce et al., 2015). Broader structural challenges, systemic inequality, and dominant governance systems prevent Indigenous epistemologies and worldviews from meaningfully being integrated into adaptation (Thornton and Manasfi, 2010; Mistry et al., 2016; Russell-Smith et al., 2017). Can promote conservative attitudes, limit uptake of new information and practices, and may not be sustainable in all circumstances given socio-cultural changes experienced (Granderson, 2017; Kihila, 2017; Mccubbin et al., 2017)	Options such as integration of Indigenous knowledge into resource management systems and school curricula, digital storytelling and filmmaking, cultural events, web-based knowledge banks, radio dramas, documentation of knowledge, are identified as potential adaptations (Cunsolo Willox et al., 2013; McNamara and Prasad, 2014; MacDonald et al., 2015b; Pearce et al., 2015; Chambers et al., 2017; Inamara and Thomas, 2017) but need to be carefully analysed for their potential to reduce vulnerability, including potential trade-offs (Granderson, 2017).
Human migration	*Low evidence* (but rapidly growing, *low agreement)*	Revising and adopting migration issues in national DRR policies, NAPs, and INDCs/NDCs (Kuruppu and Willie, 2015; Yamamoto et al., 2017), Utilizing existing social protection programmes to manage climate-induced migration (Schwan and Yu, 2017), Moving away from ad hoc approaches to migration and displacement (Thomas and Benjamin, 2018). Migration can serve as an important risk management strategy, leading to increased incomes (Cattaneo and Peri, 2016).	Research conducted on a “case by case” approach fails to provide the effective scaling of policy to national or international levels (Gemenne and Blocher, 2017; Grecequet et al., 2017). Few policies on migration exist at the national or sub-national scales (Yamamoto et al., 2017) Financial, social and ecological costs (Grecequet et al., 2017) Stress on urban system resources and services (Bhagat, 2017)	*Autonomous and planned relocation in SIDS and semi-arid regions* Migration is improving access to financial and social capital and reducing risk exposure in some locations (e.g., in the Solomon Islands (Birk and Rasmussen, 2014)). The ad hoc nature of migration and displacement can be overcome by integrating disaster risk reduction and climate change adaptation into national sustainable development plans (Thomas and Benjamin, 2018). In dryland India, populations in rural regions already experiencing 1.5°C warming are migrating to cities (Gajjar et al., 2018) but are inadequately covered by existing policies (Bhagat, 2017).

		Migration might become the only feasible adaptation option in highly vulnerable areas (Betzold, 2015; Wilkinson et al., 2016)	Migrants at risk of insecure tenure, unsafe living conditions, and exclusion in their destinations (Bettini et al., 2016; Gioli et al., 2016; Bhagat, 2017; Schwan and Yu, 2017)	
Climate services	*Medium evidence (high agreement)*	Rapid technical development, due to increased financial inputs and growing demand is enabling improved quality of climate information (Rogers and Tsirkunov, 2010; Clements et al., 2013; Perrels et al., 2013; Gasc et al., 2014; WMO, 2015; Roudier et al., 2016). Multiple stakeholder engagement and participatory processes to interpret climate information are effective to improve uptake and use (Mantilla et al., 2014; Sivakumar et al., 2014; Coulibaly et al., 2015; Gebru et al., 2015; Brasseur and Gallardo, 2016; Lourenço et al., 2016; Singh et al., 2016; Vaughan et al., 2016; Kihila, 2017; Lobo et al., 2017). Scaling climate services may occur through leveraging capacities of project champions, knowledge brokers, and intermediaries (Mantilla et al., 2014; Coulibaly et al., 2015), co-production of knowledge (Kirchhoff et al., 2013) that enables users to actively participate with valid expertise of the particularities of their decision-making context (Vaughan and Dessai, 2014), developing clear financial models to ensure sustainability (Webber and Donner, 2017), which includes multi-stakeholder engagement through iterative participatory processes (Girvetz et al., 2014; Dorward et al., 2015), and leveraging appropriate	Issues of timing of information provision and scale of information remain barriers (Dinku et al., 2014; Jancloes et al., 2014; Gebru et al., 2015; Weisse et al., 2015; Brasseur and Gallardo, 2016; Cortekar et al., 2016; Singh et al., 2016; Snow et al., 2016; Vaughan et al., 2016; Kihila, 2017) Lower uptake by women, remote communities, those without technical support (Carr and Onzere, 2017; Singh et al., 2017) Issues of trust and usability of information provided (Jones et al., 2016b; Singh et al., 2017; White et al., 2017a). Continued focus on supply-driven provision of climate in- formation rather than specific needs of end users (Lourenço et al., 2016)	Semi-arid regions in India and sub-Saharan Africa facing 1.5°C warming are seeing benefits of climate services in the agriculture planning, drought management, and flood warning (Vincent et al., 2015; Lobo et al., 2017; Singh et al., 2017; Vaughan et al., 2018a) Climate services are seeing wide application in sectors such as agriculture, health, disaster management, insurance (Lourenço et al., 2016; Vaughan et al., 2018a) with implications for adaptation decision-making. Several programmes aimed at using climate services for better decision making are showing signs of success: from various actors, at various scales, and using different forms of information delivery and uptake. These involve participatory analysis of seasonal forecasts in East Africa (Dorward et al., 2015), NGO-driven weather advisories in India (Lobo et al., 2017), innovations in government-led agriculture extension in various countries across sub-Saharan Africa and South Asia (Singh et al., 2016), and broadening the scope of climate services to directly inform spatial planning and adaptation interventions in the Netherlands (Goosen et al., 2013).

		communication channels such as mobile technology (Hampson et al., 2014; Gebru et al., 2015).		

Supplementary Material 4.C Carbon dioxide removal costs, deployment and side-effects: literature basis for Figure 4.2 (Section 4.3.7)

Supplementary Material 4.C, Table 1: References supporting Figure 4.2 in Section 4.3.7: Evidence on Carbon Dioxide Removal (CDR) abatement costs, 2050 deployment potentials, and side effects.Based on systematic review (Fuss et al., 2018b).

Technology	Costs	Potentials
Afforestation and reforestation (AR)	(Myers and Goreau, 1991; van Kooten et al., 1992; Winjum et al., 1992; Dixon et al., 1993; Winjum et al., 1993; Swisher, 1994; Brown et al., 1995; Chang, 1999; Plantinga et al., 1999; van Kooten et al., 1999; Kooten, 2000; Sohngen and Alig, 2000; Plantinga and Mauldin, 2001; Ravindranath et al., 2001; Sohngen and Mendelsohn, 2003; van Vliet et al., 2003; Baral and Guha, 2004; Richards and Stokes, 2004; Koning et al., 2005; Lakyda et al., 2005; Lee et al., 2005; Olschewski and Benítez, 2005; Richards and Stavins, 2005; Yemshanov et al., 2005; Benítez and Obersteiner, 2006; Han et al., 2007; Ahn, 2008; Hedenus and Azar, 2009; Dominy et al., 2010; Rootzén et al., 2010; Ryan et al., 2010; Torres et al., 2010; Winsten et al., 2011; Paterson and Bryan, 2012; Townsend et al., 2012; Nijnik et al., 2013; Paul et al., 2013; Polglase et al., 2013; Carwardine et al., 2015; Evans et al., 2015; Maraseni and Cockfield, 2015; Haim et al., 2016)	(Dixon et al., 1994; Nilsson and Schopfhauser, 1995; Cannell, 2003; Richards and Stokes, 2004; Houghton et al., 2015)
Bioenergy with carbon dioxide capture and storage (BECCS)	(Möllersten et al., 2003, 2004, 2006; Keith et al., 2006; Azar et al., 2006; Luckow et al., 2010; Abanades et al., 2011; Gough and Upham, 2011; Laude and Ricci, 2011; Laude et al., 2011; Ranjan and Herzog, 2011; Carbo et al., 2011; De Visser et al., 2011; Fabbri et al., 2011; Koornneef et al., 2012b; Kärki et al., 2013; Fornell et al., 2013; Akgul et al., 2014; Johnson et al., 2014b; Arasto et al., 2014; Al-Qayim et al., 2015; Onarheim et al., 2015; Creutzig et al., 2015; Moreira et al., 2016; Rochedo et al., 2016; Sanchez and Callaway, 2016)	(Fischer and Schrattenholzer, 2001; Yamamoto et al., 2001; Hoogwijk et al., 2005; Moreira, 2006; Obersteiner et al., 2006; Smeets et al., 2007; Smeets and Faaij, 2007; Hakala et al., 2008; Hoogwijk et al., 2009; van Vuuren et al., 2009; Dornburg et al., 2010; Gregg and Smith, 2010; Thrän et al., 2010; Beringer et al., 2011; Haberl et al., 2011; Cornelissen et al., 2012; Erb et al., 2012; Rogner et al., 2012; Smith et al., 2012b; Lauri et al., 2014; Kraxner and Nordström, 2015; Searle and Malins, 2015; Buchholz et al., 2016; Calvin et al., 2016; Tokimatsu et al., 2017)
Biochar	(McCarl et al., 2009; Smith, 2016)	(Lehmann et al., 2006; Laird et al., 2009; Lee et al., 2010; Moore et al., 2010; Pratt and Moran, 2010; Woolf et al., 2010; Powell and Lenton, 2012; Hamilton et al., 2015; Lomax et al., 2015; Smith, 2016)
Soil carbon sequestration	(Smith et al., 2008)	(Batjes, 1998; Metting et al., 2001; Lal, 2003a, 2003b, 2004a, 2004c; Lal et al., 2007; Smith et al., 2008; Lal, 2010; Salati et al., 2010; Conant, 2011; Lal, 2011; Smith, 2012; Benbi, 2013; Lal, 2013; Lorenz

		and Lal, 2014; Powlson et al., 2014; Sommer and Bossio, 2014; Henderson et al., 2015; Lassaletta and Aguilera, 2015; Smith, 2016; Minasny et al., 2017; Zomer et al., 2017)
Direct air carbon dioxide capture and storage (DACCS)	(Zeman, 2003, 2014; Keith et al., 2006; Nikulshina et al., 2006; Stolaroff et al., 2008; Lackner, 2009; Simon et al., 2011; Socolow et al., 2011; House et al., 2011; Holmes and Keith, 2012a; Kulkarni and Sholl, 2012; Mazzotti et al., 2013; Zhang et al., 2014b; Geng et al., 2016; Sakwa-Novak et al., 2016; SEAB, 2016; Sinha et al., 2017; van der Giesen et al., 2017)	
Enhanced weathering (EW)	(Schuiling and Krijgsman, 2006; Hartmann and Kempe, 2008; Köhler et al., 2010; Renforth, 2012; Taylor et al., 2016; Strefler et al., 2018a)	(Hartmann and Kempe, 2008; Köhler et al., 2010, 2013; Renforth et al., 2011; Hauck et al., 2016; Taylor et al., 2016; Strefler et al., 2018a)
Ocean alkalinisation (OA)	(Rau and Caldeira, 1999; Rau et al., 2007; Harvey, 2008; Rau, 2008; Paquay and Zeebe, 2013; Renforth et al., 2013; Renforth and Kruger, 2013; Renforth and Henderson, 2017)	(Harvey, 2008; Paquay and Zeebe, 2013; González and Ilyina, 2016)
Reviews	(Lenton, 2010; McGlashan et al., 2012; McLaren, 2012; Lenton, 2014; Caldecott et al., 2015; NRC, 2015; UNEP, 2017b)	

Supplementary Material 4.D Guidance and assessment for feasibility assessment

Supplementary Material 4.D.1 Guidance for feasibility assessment in Section 4.5.1

Supplementary Material 4.D.1, Table 1: Guidance for conducting the feasibility assessment of mitigation and adaptation options. See Supplementary Material 4.D.2 for the assessment and literature basis of the assessment of mitigation options and Supplementary Material 4.D.3 for the assessment and literature basis of adaptation options.

Entry for indicator-option combination	**Guidance for conducting the feasibility assessment of mitigation and adaptation options**	
NA (not applicable)	The indicator is not relevant to the option	
NE (no evidence)	• No peer-reviewed literature could be located supporting an assessment of whether this indicator would limit the option's feasibility • The peer-reviewed literature that mentions the issue is not robust enough	
LE (limited evidence)	• One or two papers make statements/present research that could be a basis for the assessment, but this evidence is considered too limited • Two or more papers provide a basis for the assessment as a side-issue in the paper, not as a core issue	
A	A feasibility assessment can be made: • If there are one or two robust papers (or more) that contain references which also support the assessment • If literature is plentiful • If one or a number of meta-studies and reviews provide extensive treatment of the option/indicator combination	A = The indicator could block the feasibility of this option
B		B = The indicator does not have a positive, nor a negative effect on the feasibility of the option
C		C = The indicator does not pose any barrier to the feasibility of this option

Supplementary Material 4.D.1, Table 2: Parameters used for the calculation of the overall feasibility of the dimension-option combinations

$\#indicators$	Number of indicators used to assess the overall feasibility of a dimension, typically two to five.
$\#NA$	Number of indicators that are not applicable (NA) to the option
$\#NE\&LE$	Total number of indicators for which there is no evidence (NE) or limited evidence (LE)
$\#A$	Number of indicators assessed as A
$\#B$	Number of indicators assessed as B
$\#C$	Number of indicators assessed as C
$\#effective\ indicators$	$\#effective\ indicators = \#indicators - \#NA$

AVG	$AVG = (1 * \#A + 2 * \#B + 3 * \#C)/\#effective\ indicators$

Supplementary Material 4.D.1, Table 3: Legend criteria for the overall feasibility of the dimension-option combinations as shown in Table 4.11 for mitigation options and Table 4.12 or adaptation options.

Legend of Table 4.11 and Table 4.12	**Legend criteria for the overall feasibility of each of the dimension-option combinations**
▨	$\#indicators = \#NA$
⬜	$\#NE\&LE > 0.5 * \#effective\ indicators$
░	$AVG \leq 1.5$ $\#NE\&LE \leq 0.5 * \#effective\ indicators$
🟧	$1.5 < AVG \leq 2.5$ $\#NE\&LE \leq 0.5 * \#effective\ indicators$
🟫	$AVG > 2.5$ $\#NE\&LE \leq 0.5 * \#effective\ indicators$

Supplementary Material 4.D.2 Feasibility assessment of mitigation options as presented in Section 4.5.2

Supplementary Material 4.D.2.i Feasibility assessment of mitigation options in energy system transitions

Supplementary Material 4.D.2.i, Table 1: Feasibility assessment of energy system transition mitigation options: Wind (on-shore & off-shore); Solar PV; and Bioenergy. For methodology, see Supplementary Material 4.D.1.

		Wind (on-shore & off-shore)		Solar PV		Bioenergy	
	Evidence	Robust		Robust		Robust	
	Agreement	Medium		High		Medium	
Economic	Cost-effectiveness	🟧	(Silva Herran et al., 2016); (IRENA 2015); (IRENA, 2016); (WEC), 2016); (Shafiee et al., 2016); (Voormolen et al., 2016)	🟫	(Climate Council 2017b); (IRENA 2015); (IRENA, 2016); (Cengiz and Mamiş, 2015)	🟧	(Brown, 2015; Creutzig et al., 2015; Patel et al., 2016)
	Absence of distributional effects	🟧	(Greene and Geisken, 2013); (Corfee-Morlot et al., 2012)	🟫	(Toovey and Malin, 2016); (Corfee-Morlot et al., 2012)	🟧	(Arndt et al., 2011b; German and Schoneveld, 2012; Creutzig et al., 2013; Hunsberger et al., 2014; Buck, 2016; Robledo-Abad et al., 2017; Stevanović et al., 2017) (Popp et al., 2014; Persson, 2015; Kline et al., 2017; Searchinger et al., 2017), (German and Schoneveld, 2012) (Schoneveld et al., 2011)(Bernesson et al., 2004)(Grau et al., 2010) (Agoramoorthy et al., 2009)(Ewing and Msangi, 2009)
	Employment & productivity enhancement potential	🟫	(IEA 2017d); (IRENA 2017b); (Council, 2016); (Council, 2012)	🟫	(IEA) 2017d); (IRENA 2017b); (Council 2017b); (Council, 2016)	🟫	(Parcell and Westhoff, 2006; Gohin, 2008; Wicke et al., 2009; Arndt et al., 2011a)

		🟫		🟫		🟫	(Rathmann et al., 2012; Silalertruksa et al., 2012; Augusto Horta Nogueira and Silva Capaz, 2013; Ribeiro, 2013)
Technological	Technical scalability	🟫	(IRENA 2017b); (Al-Maghalseh and Maharmeh, 2016); (Silva Herran et al., 2016);(IRENA 2017a)	🟫	(IRENA 2017a)	🟫	(Soccol et al., 2009; Fiorese et al., 2014; Vimmerstedt et al., 2015; Humpenöder et al., 2017)
	Maturity	🟫	(UNEP 2017b); (IRENA 2017a)	🟫	(Despotou, 2012)	🟫	(Soccol et al., 2009; Corsatea, 2014; Fiorese et al., 2014; Creutzig et al., 2015; Strzalka et al., 2017)
	Simplicity	🟧	(IRENA, 2016)	🟫	(IRENA, 2016)	🟫	(Demirbas and Demirbas, 2007; Surendra et al., 2014)
	Absence of risk	🟫	(UNEP 2017b)	🟫	(UNEP 2017b); (Bahill and Chaves, 2013)	🟫	Carbon Neutrality - debate (Buchholz et al., 2016; Liu et al., 2018)
Institutional	Political acceptability	🟧	(UNEP 2017b); (WEC) 2016); (Borch et al., 2014); (Bistline, 2017); (Kar and Sharma, 2015) (Baker, 2015) (Furtado and Perrot, 2015)	🟧	(UNEP 2017b); (Shukla et al., 2018)(Baker, 2015)	🟧	(Longstaff et al., 2015; Favretto et al., 2017; Goetz et al., 2017) Suggestions for more focus on implementation challenges to avoid indirect Land Use Change, food price increases, land tenure conflicts (Timilsina et al., 2012; Broch et al., 2013; Montefrio and Sonnenfeld, 2013; Stattman et al., 2013; Aha and Ayitey, 2017)
	Legal & administrative acceptability	🟫	(UNEP 2017b); (Bistline, 2017); (Kar and Sharma, 2015); (Comello et al., 2017)	🟫	(UNEP 2017b); (Comello et al., 2017); (Shukla et al., 2018); (Shrimali and Rohra, 2012)	⬜	(Gamborg et al., 2014; Amos, 2016; Naiki, 2016)
	Institutional capacity	🟧	(UNEP 2017b); (Corfee-Morlot et al., 2012); (Goodale and Milman, 2016); (Bistline, 2017); (Kar and Sharma, 2015); (Comello et al., 2017)	🟧	(UNEP 2017b); (Corfee-Morlot et al., 2012); (Comello et al., 2017); (Shukla et al., 2018); (Shrimali and Rohra, 2012)	LE	(Gamborg et al., 2014) (Favretto et al., 2017)
	Transparency & accountability potential	🟫	(UNEP 2017b); (Bistline, 2017) (Eberhard et al., 2014) (Furtado and Perrot, 2015)(Swilling et al., 2016)	🟫	(UNEP 2017b) (Eberhard et al., 2014) (Swilling et al., 2016)	⬜	(Plevin et al., 2010; Creutzig et al., 2015)

		🟫		🟫		⬜	management (Pyörälä et al., 2014; Torssonen et al., 2016; Baul et al., 2017; Kilpeläinen et al., 2017) Carbon neutrality –feedstock and time frame (Zanchi et al., 2012; Hammar et al., 2015; Daioglou et al., 2017; Booth, 2018; Sterman et al., 2018) dLUC and iLUC challenges emissions (Schulze et al., 2012; Harris et al., 2015; Repo et al., 2015; DeCicco et al., 2016; Qin et al., 2016) (Buchholz et al., 2014; Röder et al., 2015; Röder and Thornley, 2016; Robledo-Abad et al., 2017)
Socio-cultural	Social co-benefits (health, education)	🟫	(Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b); (Silva Herran et al., 2016); (Geels et al., 2017)	🟫	(Geels et al., 2017); (IEA) 2017d); (UNEP) 2017a); (UNEP 2017b)	🟧	(Kar et al., 2012; Anenberg et al., 2013; Knoblauch et al., 2014; Porter et al., 2015; Weldu et al., 2017)
	Public acceptance	🟧	(Geels et al., 2017); (IEA, 2017d); (UNEP 2017a); (UNEP 2017b); (Geraint and Gianluca, 2016); (Borch et al., 2014); (Kondili and Kaldellis, 2012); (Sütterlin and Siegrist, 2017); (Brennan et al., 2017); (Heidenreich, 2015)	🟫	(Geels et al. 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b); (Sütterlin and Siegrist, 2017); (Brennan et al., 2017)	⬜	(Khanal et al., 2010; Delshad and Raymond, 2013; Dragojlovic and Einsiedel, 2015; Moula et al., 2017) (Fytili and Zabaniotou, 2017; Goetz et al., 2017)
	Social & regional inclusiveness	🟫	(Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b)	🟧	(Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b)	🟧	(Creutzig et al., 2013, 2015; Favretto et al., 2017; Robledo-Abad et al., 2017)
	Intergenerational equity	🟫	(Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b)	🟫	(Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b)	NE	
	Human capabilities	🟫	(Geels et al., 2017); (IEA) 2017d); (UNEP) 2017a); (UNEP 2017b); (Bistline, 2017)	🟧	(Geels et al., 2017); (IEA) 2017d); (UNEP 2017a); (UNEP 2017b); (Shrimali and Rohra, 2012); (Shukla et al., 2018)	NE	
Environmental/ecological	Reduction of air pollution	🟫	(UNEP 2017a); (UNEP 2017b); (Council, 2012); (Kondili and Kaldellis, 2012)	🟫	(UNEP 2017a); (UNEP 2017b)	LE	(Kar et al., 2012; Anenberg et al., 2013; Knoblauch et al., 2014; Porter et al., 2015; Weldu et al., 2017)

	Reduction of toxic waste	🟫	(UNEP 2017a); (UNEP 2017b)	🟧	(UNEP 2017a); (UNEP 2017b)	NE	
	Reduction of water use	🟫	(UNEP 2017a); (UNEP 2017b); (Kondili and Kaldellis, 2012)	🟫	(UNEP 2017a); (UNEP 2017b)	⬜	(Smith et al., 2016) (Bonsch et al., 2016) (Gerbens-Leenes et al., 2009; Gheewala et al., 2011; Smith and Torn, 2013; Bonsch et al., 2016; Lampert et al., 2016; Mouratiadou et al., 2016; Wei et al., 2016; Mathioudakis et al., 2017)
	Improved biodiversity	🟫	(UNEP 2017a); (UNEP 2017b)	🟫	(UNEP, 2017a); (UNEP 2017b)	🟧	(Immerzeel et al., 2014; Dale et al., 2015; Holland et al., 2015; Kline et al., 2015; Santangeli et al., 2016; Tarr et al., 2017) (Holland et al., 2015; Santangeli et al., 2016) Mixed evidence pointing more to negative impacts for first-generation and sometimes even positive for second-generation.
Geophysical	Physical feasibility (physical potentials)	🟧	(UNEP 2017a); (UNEP 2017b); (Al-Maghalseh and Maharmeh, 2016)	🟫	(UNEP 2017a); (UNEP 2017b)	🟧	(Slade et al., 2014) (Beringer et al., 2011; Klein et al., 2014; Creutzig et al., 2015; Kraxner and Nordström, 2015; Searle and Malins, 2015; Smith et al., 2016; Boysen et al., 2017b; Tokimatsu et al., 2017; Heck et al., 2018)
	Limited use of land	🟧	(UNEP 2017a); (UNEP 2017b); (Silva Herran et al., 2016); (Mohan, 2017)	🟧	(UNEP 2017a); (UNEP 2017b); (Mohan, 2017)	⬜	(Popp et al., 2014; Creutzig et al., 2015; Williamson, 2016; Robledo-Abad et al., 2017) (Bonsch et al., 2016; Hammond and Li, 2016)

	Limited use of scarce (geo)physical resources	🟧	(UNEP 2017a); (UNEP 2017b)	🟧	(UNEP 2017a); (UNEP 2017b)	NA	
	Global spread	🟫	(UNEP 2017a); (UNEP 2017b)	🟧	(UNEP 2017a); (UNEP 2017b)	🟧	(Deng et al., 2015; Daioglou et al., 2017; Robledo-Abad et al., 2017)

Supplementary Material 4.D.2.i, Table 2: Feasibility assessment of energy system transition mitigation options: Electricity storage; Power sector CCS; and Nuclear energy. For methodology, see Supplementary Material 4.D.1.

		Electricity storage		Power sector CCS		Nuclear energy	
	Evidence	Robust		Robust		Robust	
	Agreement	Medium		High		High	
Economic	Cost-effectiveness	🟧	(ACOLA, 2017); (Schmidt et al., 2017); (Quann, 2017); (IRENA 2015)	🟧	Studies indicate that CCS in the power sector is somewhere in the middle range of mitigation options. It's a significant additional cost but the scale is usually large so much CO_2 is reduced (Global CCS Institute, 2017) (Rubin et al., 2015) (IEA, 2017a)(Castrejón et al., 2018)	🟧	(Bruckner et al., 2014) (Lovering et al., 2016; Koomey et al., 2017) (Finon and Roques, 2013)
	Absence of distributional effects	🟧	(Corfee-Morlot et al., 2012; ACOLA, 2017)	NE		NE	
	Employment & productivity enhancement potential	🟧	(ACOLA, 2017); (Climate Council, 2017); (IEA 2017); (IRENA, 2017b)	🟧	Higher than coal/gas without CCS, on par with wind, geothermal, nuclear (IEA, 2017a)(Wei et al., 2010)(Koelbl et al., 2016)	🟧	(Wei et al., 2010) (Kenley et al., 2009)
Technological	Technical scalability	🟫	(ACOLA, 2017); (IRENA, 2017a)	🟫	(IPCC, 2005) (de Coninck and Benson, 2014)(Aminu et al., 2017)	🟫	(IAEA, 2018) (Bruckner et al., 2014) (for current-generation plants)
	Maturity	🟧	(ACOLA, 2017); (IRENA, 2017a)	🟧	(Zheng and Xu, 2014; Abanades et al., 2015; Bui et al., 2018; Qiu and Yang, 2018)	🟫	(Bruckner et al., 2014)
	Simplicity	🟧	(ACOLA, 2017); (IRENA, 2016)	LE	(Wei et al., 2010) (IEA GHG, 2012)	⬜	(Esteban and Portugal-Pereira, 2014)
	Absence of risk	🟫	(ACOLA, 2017); (UNEP, 2017a)	🟧	(IPCC, 2005) (de Coninck and Benson, 2014)(Boot-Handford et al., 2014)(Aminu et al., 2017)	🟧	(Wheatley et al., 2016) (Rose and Sweeting, 2016) (Hirschberg et al., 2016)

Institutional	Political acceptability	🟧	(ACOLA, 2017); (Nguyen et al., 2017); (UNEP, 2017a)	🟧	(de Coninck and Benson, 2014)(Boot-Handford et al., 2014)(Aminu et al., 2017)	🟧	(Bruckner et al., 2014) (IAEA, 2017)
	Legal & administrative acceptability	🟧	(ACOLA, 2017); (Nguyen et al., 2017); (UNEP, 2017a)	🟧	(Boot-Handford et al., 2014; de Coninck and Benson, 2014; Dixon et al., 2015)	NE	
	Institutional capacity	🟧	(ACOLA, 2017); (IEA 2017a); (Nguyen et al., 2017); (UNEP 2017b); (Corfee-Morlot et al., 2012)	LE	(Ashworth et al., 2015)	░	(Figueroa, 2016) (Juraku, 2016) (Tosa, 2015) (Vivoda and Graetz, 2015) (Taebi and Mayer, 2017) (Kim and Chung, 2018)
	Transparency & accountability potential	🟧	(ACOLA, 2017); (Nguyen et al., 2017); (UNEP, 2017a)	NE		░	(Figueroa, 2016)
Socio-cultural	Social co-benefits (health, education)	░	(ACOLA, 2017); (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b)	NE		🟧	(Bruckner et al., 2014) (Oe et al., 2016) (Suzuki et al., 2016) (WHO, 2011) (Ishikawa, 2014) (Nagataki et al., 2013) (Endo et al., 2012) (Kawaguchi and Yukutake, 2017) (Nakayachi et al., 2015) (Fridman et al., 2016) (Beresford et al., 2016) (Hirschberg et al., 2016)
	Public acceptance	🟧	(ACOLA, 2017); (Climate Council 2017a); (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b)	░	(Ashworth et al., 2015) (Aminu et al., 2017) (Seigo et al., 2014)	░	(Huhtala and Remes, 2017) (Diaz-Maurin and Kovacic, 2015) (Wu, 2017) (Kim et al., 2014) (Murakami et al., 2015) (Ho et al., 2018) (Tsujikawa et al., 2016) (Nishikawa et al., 2016) (Bruckner et al., 2014) (IAEA, 2017)
	Social & regional inclusiveness	🟫	(ACOLA, 2017); (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b)	NA		NE	
	Intergenerational equity	🟫	(ACOLA, 2017); (Geels et al., 2017); (IEA 2017d); (UNEP 2017a); (UNEP 2017b)	░	(Alcalde et al., 2018)	░	(Bruckner et al., 2014)
	Human capabilities	🟧	(ACOLA, 2017; Geels et al., 2017; (IEA 2017d); (UNEP 2017a);	░	(Shackley et al., 2009; IEA GHG, 2012)	NE	

		🟧	(UNEP 2017b) (Newman et al., 2017)	▫			
Environmental/ecological	Reduction of air pollution	🟧	(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)	🟫	(Koornneef et al., 2008; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009; Korre et al., 2010; Nie et al., 2011; Modahl et al., 2012; Corsten et al., 2013; Cuéllar-Franca and Azapagic, 2015; Gibon et al., 2017)	🟫	(Cheng and Hammond, 2017)
	Reduction of toxic waste	▫	(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)	▫	(Koornneef et al., 2008; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009; Korre et al., 2010; Nie et al., 2011; Modahl et al., 2012; Corsten et al., 2013; Cuéllar-Franca and Azapagic, 2015; Gibon et al., 2017)	▫	(Bruckner et al., 2014)
	Reduction of water use	🟧	(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)	▫	, (Cooney et al., 2015) (Koornneef et al., 2012a) (Koornneef et al., 2008; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009; Korre et al., 2010; Nie et al., 2011; Modahl et al., 2012; Corsten et al., 2013; Cuéllar-Franca and Azapagic, 2015; Gibon et al., 2017)	🟧	(Kato et al., 2012) (Ueda et al., 2013) (Tsumune et al., 2012) (Sakaguchi et al., 2012) (Bailly du Bois et al., 2012) (Bruckner et al., 2014)
	Improved biodiversity	NA		🟫	(Koornneef et al., 2012a) (Koornneef et al., 2008; Odeh and Cockerill, 2008; Pehnt and Henkel, 2009; Korre et al., 2010; Nie et al., 2011; Modahl et al., 2012; Corsten et al., 2013; Cuéllar-Franca and Azapagic, 2015; Gibon et al., 2017)	🟫	(Cheng and Hammond, 2017)
Geophysical	Physical feasibility (physical potentials)	🟫	(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)	🟫	(IPCC, 2005) (de Coninck and Benson, 2014) (Scott et al., 2015)	🟫	(Bruckner et al., 2014)
	Limited use of land	🟫	(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)	🟫	Non-controversial so not investigated.	🟫	(Cheng and Hammond, 2017)

	Limited use of scarce (geo)physical resources	░	(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b) (Newman et al., 2017)	▒	(Scott et al., 2015) (IPCC, 2005) (de Coninck and Benson, 2014) (on storage capacity, otherwise no issues)	█	(NEA, 2016) (Bruckner et al., 2014)
	Global spread	█	(ACOLA, 2017); (UNEP 2017a); (UNEP 2017b)	█	(IPCC, 2005) (de Coninck and Benson, 2014)	█	(IAEA, 2017)

Supplementary Material 4.D.2.ii Feasibility assessment of mitigation options in land & ecosystem transitions

Supplementary Material 4.D.2.ii, Table 1: Feasibility assessment of the land and ecosystem transition mitigation options: Reduced food wastage and efficient food production; Dietary shifts; Sustainable intensification of agriculture; and Ecosystems restoration. For methodology, see Supplementary Material 4.D.1.

		Reduced food wastage and efficient food production		Dietary shifts		Sustainable intensification of agriculture		Ecosystems restoration	
	Evidence	Robust		Medium		Medium		Medium	
	Agreement	High		High		High		High	
Economic	Cost-effectiveness	🟫	(FAO, 2013a; Thyberg and Tonjes, 2016; Hebrok and Boks, 2017)	LE	(FAO, 2013b)	LE	(Havlik et al., 2014)	🟫	(Griscom et al., 2017; Phan et al., 2017) AD - (Kindermann et al., 2008) (Overmars et al., 2014)(Dang Phan et al., 2014) REDD+ (Rakatama et al., 2017) (Ickowitz et al., 2017)
	Absence of distributional effects	🟧	(Porpino et al., 2015; Thyberg and Tonjes, 2016; Alexander et al., 2017; Hebrok and Boks, 2017)	LE	(Żukiewicz-Sobczak et al., 2014)	LE	(Smith et al., 2017a)	🟧	Biofuels certification (German and Schoneveld, 2012) (Caplow et al., 2011) REDD+ tenure (Sunderlin et al., 2014)(Poudyal et al., 2016) (Howson and Kindon, 2015) AD - Food sec (Erb et al., 2016) (Atela et al., 2014)
	Employment & productivity enhancement potential	🟧	(Thyberg and Tonjes, 2016; Alexander et al., 2017; Popp et al., 2017) (Shepon et al., 2016)	🟫	(Haggblade et al., 2015; Tschirley et al., 2015; Berti and Mulligan, 2016; Blay-Palmer et al., 2016; Alexander et al., 2017;	🟧	(Foley et al., 2011; Harvey et al., 2014; Clark and Tilman, 2017; Griscom et al., 2017)	🟧	Wetlands - (Brander et al., 2013) Forest carbon (Neimark et al., 2016) Yields, income and capital (Fenger et al., 2017; Jena et

		🟧		🟫	Clark and Tilman, 2017)(Shepon et al., 2016)	🟧		🟧	al., 2017) but are not uncontested (Blackman and Rivera, 2011; Hidayat et al., 2015; Oya et al., 2017).
Technological	Technical scalability	🟧	(Högy et al., 2009; DaMatta et al., 2010; Lin et al., 2013; Challinor et al., 2014; Papargyropoulou et al., 2014; De Souza et al., 2015; Hebrok and Boks, 2017)	🟧	(Hallström et al., 2015; Alexander et al., 2017; Clark and Tilman, 2017)	🟧	(Harvey et al., 2014; Clark and Tilman, 2017; Griscom et al., 2017; Waldron et al., 2017; Ramankutty et al., 2018) (Pretty and Bharucha, 2014; Petersen and Snapp, 2015; Adhikari et al., 2018a)	🟫	(Smith et al., 2014b) – Table 11.2; (Houghton et al., 2015; Griscom et al., 2017; Houghton and Nassikas, 2018)
	Maturity	NE		NE		LE	(Pretty and Bharucha, 2014; Petersen and Snapp, 2015)	🟫	(McLaren, 2012; Smith et al., 2012a; Goetz et al., 2015)
	Simplicity	NE		NE		NE		🟫	Ecosystem restoration – (Smith et al., 2014b; Erb et al., 2017; Griscom et al., 2017)
	Absence of risk	🟫	(Lin et al., 2013; Papargyropoulou et al., 2014; Hebrok and Boks, 2017)	🟫	(Hallström et al., 2015; Alexander et al., 2017; Clark and Tilman, 2017; Röös et al., 2017)	🟧	(Harvey et al., 2014; Clark and Tilman, 2017; Griscom et al., 2017; Waldron et al., 2017; Ramankutty et al., 2018; Sparovek et al., 2018) (Adhikari et al., 2018a)	🟫	(Smith et al., 2014b) Table 11.9 *No major breakthroughs since AR5
Institutional	Political acceptability	🟫	(Refsgaard and Magnussen, 2009; Lin et al., 2013; Thornton and Herrero, 2014; Jones et al., 2016b; Thyberg and Tonjes, 2016; Singh et al., 2017; White et al., 2017a)	NE		🟧	(Smith and Gregory, 2013; Harvey et al., 2014; Sparovek et al., 2018) (Godfray and Garnett, 2014)	🟫	Legitimacy (Nantongo, 2017) REDD+ (Cronin et al., 2016) (Di Gregorio et al., 2017a)

	Legal & administrative acceptability	NE		NE		🟧	(Smith and Gregory, 2013; Harvey et al., 2014)	🟧	(Creutzig et al., 2013; Sunderlin et al., 2014)
	Institutional capacity	🟫	(Refsgaard and Magnussen, 2009; Thornton and Herrero, 2014; Briley et al., 2015; Jones et al., 2016b; Thyberg and Tonjes, 2016; Singh et al., 2017; White et al., 2017a)	NE		🟧	(Smith and Gregory, 2013; Harvey et al., 2014; Sparovek et al., 2018) (Lu et al., 2015; Petersen and Snapp, 2015; Mungai et al., 2016; Adhikari et al., 2018a)	🟧	(Unruh, 2011; Marion Suiseeya and Caplow, 2013) (Wylie et al., 2016)
	Transparency & accountability potential	🟫	(Briley et al., 2015; Jones et al., 2016b; Thyberg and Tonjes, 2016; Singh et al., 2017; White et al., 2017a)	NE		NE		🟧	(Neimark et al., 2016) (Strassburg et al., 2014)
Socio-cultural	Social co-benefits (health, education)	🟫	(Lin et al., 2013; Tilman and Clark, 2014; Wellesley et al., 2015; Thyberg and Tonjes, 2016; Hebrok and Boks, 2017; Popp et al., 2017)	🟧	(Alexander et al., 2016, 2017; Stoll-Kleemann and Schmidt, 2017; Ritchie et al., 2018)	🟫	(Smith and Gregory, 2013; Harvey et al., 2014; Ramankutty et al., 2018; Sparovek et al., 2018) (Pretty et al., 2011; Jones et al., 2012; Falconnier et al., 2018)	🟫	(Caplow et al., 2011; Spencer et al., 2017)
	Public acceptance	🟧	(Lin et al., 2013; Popp et al., 2017)	🟧	(Alexander et al., 2016, 2017; Stoll-Kleemann and Schmidt, 2017)	🟫	(Smith and Gregory, 2013; Harvey et al., 2014; Ramankutty et al., 2018; Sparovek et al., 2018) (Godfray and Garnett, 2014; Adhikari et al., 2018a)	🟫	AR, (Braun et al., 2017) Wetlands – (Scholte et al., 2016) Ecosystem services –(Lin et al., 2012; Kragt et al., 2016; Thompson et al., 2016)
	Social & regional inclusiveness	🟧	(Lin et al., 2013; Tilman and Clark, 2014; Hebrok and Boks, 2017; Popp et al., 2017)	🟧	(Khoury et al., 2014; Tilman and Clark, 2014; Alexander et al., 2016, 2017; Stoll-Kleemann and Schmidt, 2017; Ritchie et al., 2018)	🟧	(Smith and Gregory, 2013; Harvey et al., 2014; Ramankutty et al., 2018; Sparovek et al., 2018) (Pretty et al., 2011; Franke et al., 2014; Petersen and Snapp, 2015)(Pretty and	🟧	(Lyons and Westoby, 2014) (Ribot and Larson, 2012; Jagger et al., 2014; Brimont et al., 2015; Howson and Kindon, 2015)

		🟧		🟧		🟧	Bharucha, 2014; Struik and Kuyper, 2017)	🟧	
	Intergenerational equity	NE		LE	(Bajželj et al., 2014)	NE		🟫	(Unruh, 2011) (Pascuala et al., 2010) *No major breakthroughs since AR5
	Human capabilities	🟫	(Tilman and Clark, 2014; Thyberg and Tonjes, 2016; Hebrok and Boks, 2017)	🟧	(Tilman and Clark, 2014; Ritchie et al., 2018)	LE	(Pretty and Bharucha, 2014; Mungai et al., 2016)(Baltenweck et al., 2003)	LE	Social and human assets (Smith et al., 2014b) Table 11.5 *No major breakthroughs since AR5
Environmental/ ecological	Reduction of air pollution	LE	(Thyberg and Tonjes, 2016)	🟫	(Tilman and Clark, 2014; Hallström et al., 2015; Ritchie et al., 2018)	NE		NE	
	Reduction of toxic waste	NE		NE		🟧	(Pretty and Bharucha, 2014; Ramankutty et al., 2018) (Stevens and Quinton, 2009; Soussana and Lemaire, 2014; Lu et al., 2015) (Tilman et al., 2011a)	NE	
	Reduction of water use	🟫	(Bajželj et al., 2014; West et al., 2014; Westhoek et al., 2014)(Thyberg and Tonjes, 2016)	🟫	(Bajželj et al., 2014; West et al., 2014; Westhoek et al., 2014)	LE	(Pretty and Bharucha, 2014)	🟫	(van Noordwijk et al., 2016) AD - (Ellison et al., 2017) (Devaraju, Bala, & Modak, 2015) (Brander et al., 2013)
	Improved biodiversity	🟫	(Ramankutty et al., 2018)(Johnson et al., 2014a)	🟫	(Tilman and Clark, 2014; Hallström et al., 2015) (Ramankutty et al., 2018)(Clark and Tilman, 2017)	🟫	(Pretty and Bharucha, 2014; Waldron et al., 2017)	🟫	AD- (Jantz et al., 2014; Jantke et al., 2016) ES – pollination Kaiser Bunbury 2017; (Rey Benayas et al., 2009; Bullock et al., 2011; Veldman et al., 2015)
Geophysical	Physical feasibility (physical potentials)	🟫	(Cherubin et al., 2015; Ivy et al., 2017)	NE		NE		🟫	(Erb et al., 2017; Griscom et al., 2017) AD - (Canadell and Schulze, 2014; Erb et al., 2016)

		🟫		LE				🟫	Ecosystem restoration secondary forests – (Houghton et al., 2015; Houghton and Nassikas, 2018) REDD+ (Strassburg et al., 2014) Increased risk from climate change – (Canadell et al 2008)
	Limited use of land	🟫	(Ramankutty et al., 2018; Sparovek et al., 2018) (Thyberg and Tonjes, 2016)	LE	(Benton et al., 2018) (Ramankutty et al., 2018) (Shepon et al., 2016)	🟧	(Harvey et al., 2014; Clark and Tilman, 2017)	🟧	(Humpenöder et al., 2015) REDD+ (Strassburg et al., 2014) AD - restricts land onto which agriculture, grazing and bioenergy plantations can be deployed, which may lead to GHG emissions, increase food prices (Kreidenweis et al., 2016) (Erb et al., 2016)
	Limited use of scarce (geo)physical resources	NE		NE		🟫	(Foley et al., 2011)	NE	
	Global spread	LE	(Thyberg and Tonjes, 2016)	NE		LE	(Petersen and Snapp, 2015; Mungai et al., 2016) (Havlik et al., 2014) (Tilman et al., 2011b)	🟫	REDD+ (Strassburg et al., 2014); (Erb et al., 2017)

Supplementary Material 4.D.2.iii Feasibility assessment of mitigation options in urban & infrastructure system transitions

Supplementary Material 4.D.2.iii, Table 1: Feasibility assessment of urban and infrastructure system transition mitigation options: Land-use & urban planning; Electric cars and buses; and Sharing schemes. For methodology, see Supplementary Material 4.D.1.

		Land-use & urban planning		Electric cars and buses		Sharing schemes	
	Evidence	Robust		Medium		Limited	
	Agreement	Medium		High		Medium	
Economic	Cost-effectiveness	🟫	(Trubka et al., 2010); (Nahlika and Chester, 2014); (Lee and Erickson, 2017); (Sharma, 2018); (Ahlfeldt and Pietrostefani, 2017); (Ahlfeldt and Pietrostefani, 2017) ;	🟧	(Peterson and Micha lek, 2013); (IEA, 2017b)	🟫	(Ambrosino et al., 2016); (Cheyne and Imran, 2016); (Kent and Dowling, 2016)
	Absence of distributional effects	🟧	(Wiktorowicz et al., 2018); (Teferi and Newman, 2018); (Broekhoff et al., 2018); (Lwasa, 2017) (Colenbrander et al., 2015)	░	(Glazebrook and Newman, 2018); (Sivak and Schoettle, 2018)	🟫	(Gomez et al., 2015); (Ambrosino et al., 2016); (Kent and Dowling, 2016)
	Employment & productivity enhancement potential	🟧	(Han et al., 2018); (Ambrosino et al., 2016); (Ambrosino et al., 2016) ; (Gao and Newman, 2018); (Ahlfeldt and Pietrostefani, 2017) ; (Broto, 2017)	🟧	(Whitelegg, 2016); (IEA, 2017b)	🟧	((Cheyne and Imran, 2016) ; (Sweet, 2014)
Technological	Technical scalability	🟫	(Zhang et al., 2018a) (Sharma, 2018) (Broekhoff et al., 2018)	🟫	(Brown et al., 2010) (IEA, 2017b)	🟫	(Reis et al., 2016); (Ambrosino et al., 2016); (Broch et al., 2013); (Kent and Dowling, 2016)
	Maturity	🟧	(Newman et al., 2017); (Parnell, 2015)	🟧	(Whitelegg, 2016); (IEA, 2017b)	🟧	(Kent and Dowling, 2016); (Le Vine et al., 2014) ;
	Simplicity	░	(Newman et al., 2017); (Lilford et al., 2017) ;	🟧	(Glazebrook and Newman, 2018); (IEA, 2017b)	🟧	(Ambrosino et al., 2016); (Giuliano and Hanson, 2017)
	Absence of risk	LE	(Newman et al., 2017)	🟫	(Whitelegg, 2016); (IEA, 2017b)	🟧	(Ambrosino et al., 2016); (Kent and Dowling, 2016)
Institutional	Political acceptability	🟧	(Grandin et al., 2018) ; (Broekhoff et al., 2018)	🟧	(Bakker and Trip, 2013) ; (IEA, 2017b)	🟧	(Ambrosino et al., 2016) ; (Le Vine et al., 2014)

	Legal & administrative acceptability	🟧	(Grandin et al., 2018) ; (Broekhoff et al., 2018)	🟫	(Wirasingha et al., 2008) ; (IEA, 2017b)	░	(Le Vine et al., 2014) ; (Cannon and Summers, 2014)
	Institutional capacity	🟧	(Chau et al., 2018) ; (Geneletti et al., 2017)	🟧	(Wirasingha et al., 2008) ; (IEA, 2017b)	🟧	(Kent and Dowling, 2016); (Glazebrook and Newman, 2018)
	Transparency & accountability potential	🟫	(Moglia et al., 2018)	🟫	(Wirasingha et al., 2008); (IEA, 2017b)	🟫	(Newman et al., 2017) ; (Glazebrook and Newman, 2018)
Socio-cultural	Social co-benefits (health, education)	🟫	(Su et al., 2016); (Nahlika and Chester, 2014); (Chava et al., 2018a); (Chava et al., 2018b); (Chava and Newman, 2016); (Jillella et al., 2015)	🟫	(IEA, 2017b); (Newman et al., 2017)	🟫	(Rojas-Rueda et al., 2012); (Kent and Dowling, 2016); (Cheyne and Imran, 2016); (de Groot and Steg, 2007)
	Public acceptance	🟧	(Moglia et al., 2018) ; (Chava et al., 2018a); (Chava et al., 2018b); (Chava and Newman, 2016); (Jillella et al., 2015)	🟧	(Zhang et al., 2011) ; (Bockarjova and Steg, 2014) ; (Liao et al., 2017)	🟧	(Reis et al., 2016) ; (Ambrosino et al., 2016) ; (Le Vine et al., 2014) ; (Kent and Dowling, 2016) ; (de Groot and Steg, 2007)
	Social & regional inclusiveness	🟧	(Endo et al., 2017) ; (Teferi and Newman, 2018); (Broekhoff et al., 2018); (Chava et al., 2018a) ; (Chava et al., 2018b); (Chava and Newman, 2016) ; (Jillella et al., 2015); (Lwasa, 2017); (Colenbrander et al., 2017)	LE	(Newman et al., 2017)	🟧	(Kent and Dowling, 2016); (Cheyne and Imran, 2016)
	Intergenerational equity	LE	(Newman et al., 2017)	🟫	(Newman et al., 2017) ; (Kenworthy and Schiller, 2018)	🟫	(Le Vine et al., 2014); (Cheyne and Imran, 2016) ; (Glazebrook and Newman, 2018)
	Human capabilities	🟧	(Moglia et al., 2018)	🟧	(Newman et al., 2017); (Wirasingha et al., 2008)	🟧	(Reis et al., 2016) ; (Newman et al., 2017)
Environmental/ecological	Reduction of air pollution	🟫	(Zhang et al., 2018a) ; (Zubelzu et al., 2015) ; (Thomson and Newman, 2018) ; (Glazebrook and Newman, 2018); (Sharma, 2018)	🟫	(Sioshansi and Denholm, 2009) ; (Kenworthy and Schiller, 2018)	🟫	(Le Vine et al., 2014) ; (Nijland and van Meerkerk, 2017) ; (Newman and Kenworthy, 2015) ; (Glazebrook and Newman, 2018)
	Reduction of toxic waste	LE	(Thomson and Newman, 2018)	LE	(Hawkins et al., 2013)	🟫	(Newman et al., 2017) ; (Newman and Kenworthy, 2015) ; (Glazebrook and Newman, 2018)

	Reduction of water use	🟫	(Serrao-Neumann et al., 2017)	LE	(Glazebrook and Newman, 2018)	🟧	(Stephan and Crawford, 2016) (Newman et al., 2017)
	Improved biodiversity	🟫	(Huang et al., 2018)	LE	(Glazebrook and Newman, 2018)	🟫	(Newman et al., 2017) ; (Newman and Kenworthy, 2015) ; (Glazebrook and Newman, 2018)
Geophysical	Physical feasibility (physical potentials)	🟫	(Hsieh et al., 2017) ; (Wiktorowicz et al., 2018)	🟫	(Glazebrook and Newman, 2018) ; (Kenworthy and Schiller, 2018)	🟫	(Kent and Dowling, 2016) ; (Newman et al., 2017)
	Limited use of land	🟫	(Hsieh et al., 2017)	░	(Glazebrook and Newman, 2018); (Kenworthy and Schiller, 2018)	🟫	(Hamilton and Wichman, 2018) ; (Kent and Dowling, 2016) ; (Newman et al., 2017)
	Limited use of scarce (geo)physical resources	LE	(Thomson and Newman, 2018)	░	(Newman et al., 2017) ; (Kenworthy and Schiller, 2018)	🟫	(Newman et al., 2017) ; (Newman and Kenworthy, 2015) ; (Glazebrook and Newman, 2018)
	Global spread	🟫	(Pacheco-Torres et al., 2017) ; (Glazebrook and Newman, 2018)	🟫	(Newman et al., 2017); (Dhar et al., 2017); (Dhar et al., 2018)	🟧	(Kent and Dowling, 2016); (Le Vine et al., 2014)

Supplementary Material 4.D.2.iii, Table 2: Feasibility assessment of urban and infrastructure system transition mitigation options: Public transport; Non-motorised transport; and Aviation & shipping. For methodology, see Supplementary Material 4.D.1.

		Public transport		Non-motorised transport		Aviation & shipping	
	Evidence	Robust		Robust		Medium	
	Agreement	Medium		High		Medium	
Economic	Cost-effectiveness	🟫	(Nahlika and Chester, 2014; Bouf and Faivre D'arcier, 2015; Lee and Erickson, 2017; Lin and Du, 2017; Glazebrook and Newman, 2018; Kenworthy and Schiller, 2018)	🟫	(Deenihan and Caulfield, 2014; Gössling and Choi, 2015; MacDonald Gibson et al., 2015; Brown et al., 2016b; Matan and Newman, 2016; Rajé and Saffrey, 2016; Litman, 2017, 2018)	░	(Corbett et al., 2009; Dessens et al., 2014; Cames et al., 2015b, 2015a)
	Absence of distributional effects	🟫	(Kenworthy and Schiller, 2018; Linovski et al., 2018; Yangka and Newman, 2018)	🟫	(Jensen et al., 2017); (Litman, 2018); (Lohmann and Gasparini, 2017); (Newman and Kenworthy, 2015); (Matan and Newman, 2016)	LE	(Cames et al., 2015a)
	Employment & productivity enhancement potential	🟫	(Hazledine et al., 2017; Gao and Newman, 2018; Kenworthy and Schiller, 2018)	🟧	(Rohani and Lawrence, 2017); (Litman, 2017); (Litman, 2018); (Matan and Newman, 2016)	🟧	(Cames et al., 2015a; Gencsü and Hino, 2015)
Technological	Technical scalability	🟫	(Kenworthy and Schiller, 2018; Yangka and Newman, 2018; Zhang et al., 2018a)	🟫	(Newman and Kenworthy, 2015; Matan and Newman, 2016; Reis et al., 2016; Stevenson et al., 2016)	🟫	(Dessens et al., 2014; Gencsü and Hino, 2015)
	Maturity	🟫	(Kenworthy and Schiller, 2018); (Newman et al., 2017)	🟫	(Newman et al., 2015; Matan and Newman, 2016; Stevenson et al., 2016; Jensen et al., 2017; Newman et al., 2017)	░	(Corbett et al., 2009; Cames et al., 2015b)
	Simplicity	🟧	(Kenworthy and Schiller, 2018); (Newman et al., 2017)	🟫	(Matan and Newman, 2016; Rajé and Saffrey, 2016; Stevenson et al., 2016; Litman, 2017, 2018)	LE	(Dessens et al., 2014)
	Absence of risk	🟫	(Kenworthy and Schiller, 2018); (Mohamed et al., 2017)	🟫	(Stevenson et al., 2016); (Lohmann and Gasparini, 2017); (Matan and Newman, 2016)	LE	(Dessens et al., 2014)

Institutional	Political acceptability	🟫	(Wijaya et al., 2017); (Yangka and Newman, 2018); (Sharma, 2018), (Gao and Newman, 2018); (Glazebrook and Newman, 2018); (Kenworthy and Schiller, 2018) (Mohamed et al., 2017)	🟫	(Giles-Corti et al., 2016); (Jensen et al., 2017); (Litman, 2017); (Litman, 2018); (McCosker et al., 2018); (Matan and Newman, 2016); (Newman and Kenworthy, 2015)	🟧	(Zhang, 2016); (Shi, 2016). (Smale et al., 2012); (Bows-Larkin, 2015); (Sikorska, 2015).
	Legal & administrative acceptability	🟫	(Kenworthy and Schiller, 2018); (Yangka and Newman, 2018)	🟫	(Litman, 2018); (Lohmann and Gasparini, 2017)	░	(Zhang, 2016); (Shi, 2016). (Smale et al., 2012); (Bows-Larkin, 2015); (Sikorska, 2015).
	Institutional capacity	🟫	(Sharma, 2018); (Newman et al., 2017) (Kenworthy and Schiller, 2018)	🟧	(Reis et al., 2016); (Litman, 2018)	░	(Zhang, 2016); (Shi, 2016). (Smale et al., 2012); (Bows-Larkin, 2015); (Sikorska, 2015).
	Transparency & accountability potential	LE	(Bouf and Faivre D'arcier, 2015); (Kenworthy and Schiller, 2018)	🟫	(Lah, 2017); (Matan and Newman, 2016); (Newman and Kenworthy, 2015)	🟫	(Zhang, 2016); (Shi, 2016). (Smale et al., 2012); (Bows-Larkin, 2015); (Sikorska, 2015)
Socio-cultural	Social co-benefits (health, education)	🟫	(Steg, 2003; Gatersleben and Uzzell, 2007; Nahlika and Chester, 2014; Lin and Du, 2017; Yangka and Newman, 2018);	🟫	(Maibach et al., 2009; Woodcock et al., 2009; Deenihan and Caulfield, 2014; Gilderbloom et al., 2015; MacDonald Gibson et al., 2015; Mansfield and Gibson, 2015; Matan et al., 2015; Brown et al., 2016b; Giles-Corti et al., 2016; Matan and Newman, 2016; Rajé and Saffrey, 2016; Stevenson et al., 2016; Jensen et al., 2017; Lah, 2017; Lohmann and Gasparini, 2017; Maizlish et al., 2017; Litman, 2018)	LE	(EEA, 2017)
	Public acceptance	🟧	(Steg, 2003; Wijaya et al., 2017)	🟧	(Jensen et al., 2017); (Lohmann and Gasparini, 2017); (Matan and Newman, 2016); (Newman et al., 2017); (Gatersleben and Uzzell, 2007)	🟧	(EEA, 2017); (Bows-Larkin, 2015); (Sikorska, 2015)

	Social & regional inclusiveness	🟫	(Nahlika and Chester, 2014); (Yangka and Newman, 2018)	🟫	(Stevenson et al., 2016); (Gilderbloom et al., 2015); (Jensen et al., 2017)	LE	(EEA, 2017)
	Intergenerational equity	🟫	(Kenworthy and Schiller, 2018); (Yangka and Newman, 2018); (Newman et al., 2017)	🟫	(Litman, 2018); (Rajé and Saffrey, 2016)	LE	(Gencsü and Hino, 2015)
	Human capabilities	🟫	(Kenworthy and Schiller, 2018); (Newman et al., 2017)	🟫	(Reis et al., 2016); (Newman et al., 2017)	🟫	European Environment Agency. (2017); (Bows-Larkin, 2015); (Sikorska, 2015)
Environmental/ecological	Reduction of air pollution	🟫	(Zhang et al., 2018a); (Glazebrook and Newman, 2018); (Yangka and Newman, 2018); (Kenworthy and Schiller, 2018)	🟫	(Stevenson et al., 2016); (Maizlish et al., 2017); (Woodcock et al., 2009)	🟫	(EEA, 2017); (Bouman et al., 2017); (Cames et al., 2015a) (Dessens et al., 2014)
	Reduction of toxic waste	LE	(Newman et al., 2017)	LE	(Newman et al., 2017)	🟫	(EEA, 2017); (Maragkogianni et al., 2016)
	Reduction of water use	LE	(Newman et al., 2017)	LE	(Newman et al., 2017)	🟧	(EEA, 2017); (Maragkogianni et al., 2016)
	Improved biodiversity	🟫	(Newman et al., 2017; Kenworthy and Schiller, 2018)	LE	(Newman et al., 2017)	🟧	(EEA, 2017); (Maragkogianni et al., 2016)
Geophysical	Physical feasibility (physical potentials)	🟫	(Kenworthy and Schiller, 2018; Yangka and Newman, 2018)	🟫	(Lah, 2017); (Panter et al., 2016)	🟫	(EEA, 2017); (Bows-Larkin, 2015); (Sikorska, 2015)
	Limited use of land	🟫	(Ahmad et al., 2016; Kenworthy and Schiller, 2018)	🟫	(Stevenson et al., 2016); (McCormack and Shiell, 2011); (Litman, 2017); (Ye et al., 2018); (Newman et al., 2017)	LE	(EEA, 2017)
	Limited use of scarce (geo)physical resources	🟫	(Lin and Du, 2017; Kenworthy and Schiller, 2018)	🟫	(Newman et al., 2017; Ye et al., 2018)	🟧	(de Jong et al., 2017; EEA, 2017)
	Global spread	🟫	(Bouf and Faivre D’arcier, 2015; Glazebrook and Newman, 2018; Kenworthy and Schiller, 2018)	🟫	(Stevenson et al., 2016; Litman, 2017; Lohmann and Gasparini, 2017)	🟫	(Maragkogianni et al., 2016; EEA, 2017)

Supplementary Material 4.D.2.iii, Table 3: Feasibility assessment of urban and infrastructure system transition mitigation options: Smart grids; Efficient appliances; and Low/zero-energy buildings. For methodology, see Supplementary Material 4.D.1.

		Smart grids		Efficient appliances		Low/zero-energy buildings	
	Evidence	Medium		Medium		Medium	
	Agreement	Medium		High		High	
Economic	Cost-effectiveness	🟧	(Crispim et al., 2014; Hall and Foxon, 2014; Marques et al., 2014; Muench et al., 2014; Foxon et al., 2015; Bigerna et al., 2016; Ramos et al., 2016; Schachter and Mancarella, 2016)	🟫	(McNeil and Bojda, 2012; Garg et al., 2017; Gerke et al., 2017)	🟫	(Neroutsou and Croxford, 2016; Balaban and Puppim de Oliveira, 2017; Ballarini et al., 2017; Stocker and Koch, 2017; Carlson and Pressnail, 2018)
	Absence of distributional effects	🟧	(Green and Newman, 2017), (Wiktorowicz et al., 2018) (Neureiter, 2017)	🟧	(Rao, 2013; Rao et al., 2016; McInnes, 2017; Rao and Ummel, 2017)	🟫	(Figus et al., 2017); (McInnes, 2017)
	Employment & productivity enhancement potential	🟫	(Naus et al., 2014); (Foxon et al., 2015); (Shomali and Pinkse, 2016).	🟧	(Ryan and Campbell, 2012; Cambridge Econometrics, 2015; Garrett-Peltier, 2017; Hartwig et al., 2017)	🟫	(Scott et al., 2008; Ryan and Campbell, 2012; Urge-Vorsatz et al., 2012; Mirasgedis et al., 2014; Cambridge Econometrics, 2015; Hartwig et al., 2017; Krarti and Dubey, 2018)
Technological	Technical scalability	🟫	(Crispim et al., 2014); (Zheng et al., 2014); (Connor et al., 2014); (Ramos et al., 2016); (Derakhshan et al., 2016).	🟫	(Roland and Wood, 2009); (Parikh and Parikh, 2016); (Rao et al., 2016); (Rao and Ummel, 2017); (Salleh et al., 2018)	🟫	(Hartwig et al., 2017); (Krarti et al., 2017)
	Maturity	🟧	(Crispim et al., 2014); (Clerici et al., 2015); (Abi Ghanem and Mander, 2014); (Zheng et al., 2014); (Ramos et al., 2016); (Otuoze et al., 2018); (Derakhshan et al., 2016).	🟫	(Zogg et al., 2009); (Diczfalusy and Taylor, 2011); (Rao and Ummel, 2017); (Rao et al., 2016)	🟧	(González et al., 2017); (Diczfalusy and Taylor, 2011); (Jain et al., 2017b)

		🟧		🟫		🟧	
	Simplicity	░	(Crispim et al., 2014); (Clerici et al., 2015); (Abi Ghanem and Mander, 2014); (Zheng et al., 2014); (Ramos et al., 2016); (Otuoze et al., 2018); (Derakhshan et al., 2016); (Giannantoni, 2014).	🟫	(Reyna and Chester, 2017)	LE	(Salvalai et al., 2017)
	Absence of risk	🟧	(Naus et al., 2014); (Crispim et al., 2014); (Clerici et al., 2015); (Ramos et al., 2016); (Bigerna et al., 2016); (Otuoze et al., 2018);	NE		NE	
Institutional	Political acceptability	🟧	(Naus et al., 2014); (Crispim et al., 2014); (Meadowcroft et al., 2018); (Shomali and Pinkse, 2016); (Marques et al., 2014); (Hall and Foxon, 2014); (Vesnic-Alujevic et al., 2016); (Bulkeley et al., 2016).	🟫	(Pereira and da Silva, 2017); (Ringel, 2017)	🟫	(Pereira and da Silva, 2017); (Ringel, 2017)
	Legal & administrative acceptability	🟧	(Crispim et al., 2014); (Bigerna et al., 2016); (Marques et al., 2014); (Foxon et al., 2015);	🟫	(Pereira and da Silva, 2017)	🟧	(Pereira and da Silva, 2017); (Chandel et al., 2016); (Jain et al. 2017)
	Institutional capacity	░	(Crispim et al., 2014); (Clerici et al., 2015); (Ramos et al., 2016); (Otuoze et al., 2018); (Meadowcroft et al., 2018); (Marques et al., 2014); (Muench et al., 2014). (Foxon et al., 2015);	🟧	(Pereira and da Silva, 2017); (Shah et al., 2015)	🟧	(Pereira and da Silva, 2017); (Yu et al., 2017)
	Transparency & accountability potential	░	(Naus et al., 2014); (Bigerna et al., 2016); (Otuoze et al., 2018); (Naus et al., 2014); (Hall and Foxon, 2014); (Hansen and Hauge, 2017).	LE	(Gentile et al., 2015);	LE	(Meyers and Kromer, 2008)
Socio -	Social co-benefits (health, education)	🟫	(Naus et al., 2014; Foxon et al., 2015; Shomali and Pinkse, 2016;	🟫	(Payne et al., 2015);	🟧	(Payne et al., 2015); (Ryan and Campbell, 2012);

		🟫	Hansen and Hauge, 2017; Meadowcroft et al., 2018; Otuoze et al., 2018);	🟫	(Ryan and Campbell, 2012)	🟧	(Balaban and Puppim de Oliveira, 2017); (Xiong et al., 2015)
	Public acceptance	🟧	(Hall and Foxon, 2014; Naus et al., 2014; Bigerna et al., 2016; Hansen and Hauge, 2017) (Green and Newman, 2017)	🟫	(Jain et al., 2018); (Swim et al., 2014); (Winward et al., 1998); (Boardman, 2004); (Reyna and Chester, 2017)	NE	
	Social & regional inclusiveness	🟫	(Wiktorowicz et al., 2018); (Green and Newman, 2017); (Neureiter, 2017)	🟧	(Rao and Pachauri, 2017); (Rao et al., 2016); (Rao and Ummel, 2017)	NE	
	Intergenerational equity	🟫	(Schlör et al., 2015); (Green and Newman, 2017)	NA	energy efficiency saves natural resources and therefore it is fair for future generations	NA	N/A energy efficiency saves natural resources and therefore it is fair for future generations
	Human capabilities	⬜	(Naus et al., 2014; Hansen and Hauge, 2017)	NA		NE	
Environmental/ecological	Reduction of air pollution	🟫	(Clerici et al., 2015); (Newman et al., 2017)	🟫	(Zhou et al., 2018); (Ryan and Campbell, 2012)	🟧	(Zhou et al., 2018); (Ryan and Campbell, 2012); (Balaban and Puppim de Oliveira, 2017); (Xiong et al., 2015)
	Reduction of toxic waste	🟧	(Newman et al., 2017); (Foxon et al., 2015);	🟫	(Ryan and Campbell, 2012)	🟫	(Ryan and Campbell, 2012)
	Reduction of water use	🟫	(Newman et al., 2017); (Wiktorowicz et al., 2018)	🟫	(Zhou et al., 2018)	🟫	(Loiola et al., 2018)
	Improved biodiversity	🟫	(Newman et al., 2017); (Wiktorowicz et al., 2018)	NA		NA	
Geop hysic	Physical feasibility (physical potentials)	🟫	(Foxon et al., 2015);	🟫	(Heidari et al., 2018);	🟫	(Laitner, 2013)

		🟫	(Wiktorowicz et al., 2018); (Green and Newman, 2017)	🟫	(Laitner, 2013)	🟫	
	Limited use of land	NA		NA	N/A energy efficient appliances do not take up more land than inefficient appliances	NA	Existing buildings refurbishment do not use additional land New buildings use more land if not rebuilt over demolished buildings
	Limited use of scarce (geo)physical resources	🟧	(Newman et al., 2017); (Wiktorowicz et al., 2018)	LE	(Needhidasan et al., 2014) possible that upgrades lead to landfill contamination	NA	N/A limited impact and limited use of scarce resources
	Global spread	🟧	(Crispim et al., 2014; Foxon et al., 2015; Ramos et al., 2016)	NA	N/A efficient appliances available everywhere where access to electricity or energy is available	NA	

Supplementary Material 4.D.2.iv Feasibility assessment of mitigation options in industrial system transitions

Supplementary Material 4.D.2.iv Table 1: Feasibility assessment of industrial system transition mitigation options: Energy efficiency; Bio-based & circularity; Electrification & hydrogen; and Industrial CCUS. For methodology, see Supplementary Material 4.D.1.

		Energy efficiency		Bio-based & circularity		Electrification & hydrogen		Industrial CCUS	
	Evidence	Robust		Medium		Medium		Robust	
	Agreement	High		Medium		High		High	
Economic	Cost-effectiveness	🟫	(Hasanbeigi et al., 2014; Napp et al., 2014; Forman et al., 2016; Wesseling et al., 2017)	🟧	(Taibi et al., 2012; Ali et al., 2017; Wesseling et al., 2017)	⬜	(Åhman et al., 2016; Philibert, 2017; Wesseling et al., 2017; Bataille et al., 2018)	🟧	(Mikunda et al., 2014)(Rubin et al., 2015)(Irlam, 2017)
	Absence of distributional effects	LE	(Zha and Ding, 2015)	NE		LE	(Nabernegg et al., 2017)	NE	
	Employment & productivity enhancement potential	🟧	(He et al., 2013; Zhang et al., 2015; Henriques and Catarino, 2016; Färe et al., 2018)	🟧	(Nabernegg et al., 2017)(Fuentes-Saguar et al., 2017)	LE	(Nabernegg et al., 2017)	🟧	(Koelbl et al., 2016)
Technological	Technical scalability	🟫	(Fischedick et al., 2014; Bataille et al., 2018)	🟫	(de Besi and McCormick, 2015; Wesseling et al., 2017)	🟫	(Fischedick et al., 2014; Bataille et al., 2018)(Wang et al., 2017b)	🟫	(Boot-Handford et al., 2014; Global CCS Institute, 2017; Bui et al., 2018)
	Maturity	🟫	(Hasanbeigi et al., 2014; Napp et al., 2014; Forman et al., 2016; Wesseling et al., 2017)	🟧	(Quader et al., 2016)(Wesseling et al., 2017)	⬜	(Quader et al., 2016; Philibert, 2017)	🟧	(Boot-Handford et al., 2014; Mikunda et al., 2014; Abanades et al., 2015; Global CCS Institute, 2017; Bui et al., 2018)
	Simplicity	🟧	(Fernández-Viñé et al., 2010; Wakabayashi, 2013)	⬜	(Wesseling et al., 2017)(Henry et al., 2006)	NE		⬜	(IEA GHG, 2012)

	Absence of risk	NA		LE	(Ali et al., 2017)	NE		🟧	(IPCC, 2005) (de Coninck and Benson, 2014)(Boot-Handford et al., 2014)(Aminu et al., 2017)
Institutional	Political acceptability	🟫	(Zhang et al., 2015; Åhman et al., 2016; Henriques and Catarino, 2016)	LE	(Sleenhoff and Osseweijer, 2016)(Goetz et al., 2017)(Longstaff et al., 2015)	🟫	(Åhman et al., 2016; Philibert, 2017; Wesseling et al., 2017; Bataille et al., 2018)	🟧	(Mikunda et al., 2014)(Aminu et al., 2017)
	Legal & administrative acceptability	🟫	(Zhang et al., 2015; Åhman et al., 2016; Henriques and Catarino, 2016)	░	(Wesseling et al., 2017)	NE		🟧	(de Coninck and Benson, 2014; Dixon et al., 2015; Bui et al., 2018)
	Institutional capacity	🟧	(Fernández-Viñé et al., 2010; Wakabayashi, 2013; Henriques and Catarino, 2016)	░	(Lewandowski, 2016)(Henry et al., 2006)	NE		🟧	(Boot-Handford et al., 2014; de Coninck and Benson, 2014; Dixon et al., 2015; Bui et al., 2018)
	Transparency & accountability potential	NA		LE	(Schulze et al., 2012; Harris et al., 2015; Lewandowski, 2015; Repo et al., 2015; DeCicco et al., 2016; Qin et al., 2016)	NA		NE	
Socio-cultural	Social co-benefits (health, education)	NA		NE		NA		NA	
	Public acceptance	🟫	(Fischedick et al., 2014)	░	(Khanal et al., 2010; Delshad and Raymond, 2013; Pfau et al., 2014; Dragojlovic and Einsiedel, 2015; Lewandowski, 2015; Sleenhoff and Osseweijer, 2016; Moula et al., 2017)	LE	(Åhman et al., 2016; Wesseling et al., 2017)	░	(Wallquist et al., 2012; Seigo et al., 2014; Ashworth et al., 2015)(Aminu et al., 2017)

	Social & regional inclusiveness	NA		🟧	(Creutzig et al., 2013, 2015; Robledo-Abad et al., 2017)(Knoblauch et al., 2014; Porter et al., 2015)	NA		NE	
	Intergenerational equity	NA		NE		NA		NE	
	Human capabilities	🟧	(Cagno et al., 2013; Brunke et al., 2014; Wesseling et al., 2017)	LE	(Henry et al., 2006)	NE		LE	(IEA GHG, 2012)
Environmental/ ecological	Reduction of air pollution	🟫	(Brunke et al., 2014; Rasmussen, 2017; Zhang et al., 2018b)	NE		NE		🟫	(IPCC, 2005) (Koornneef et al., 2012a)
	Reduction of toxic waste	NE		NE		NE		NE	
	Reduction of water use	🟧	(Gu et al., 2014)(Kubule et al., 2016)(Walker et al., 2013)	NE		NE		░	(Hylkema and Rand, 2014) (Koornneef et al., 2012a)
	Improved biodiversity	NE		NE		NE		LE	(Koornneef et al., 2012a)
Geophysical	Physical feasibility (physical potentials)	🟧	(Napp et al., 2014; Åhman et al., 2016; Wesseling et al., 2017)	░	(Slade et al., 2014) (Beringer et al., 2011; Klein et al., 2014; Creutzig et al., 2015; Kraxner and Nordström, 2015; Searle and Malins, 2015; Smith et al., 2016; Boysen et al., 2017b; Tokimatsu et al., 2017; Heck et al., 2018)	🟧	(Philibert, 2017)	░	(IPCC, 2005; de Coninck and Benson, 2014; Scott et al., 2015)
	Limited use of land	NA		░	(Popp et al., 2014; Creutzig et al., 2015; Williamson, 2016;	NE		NE	

		▒		░	Robledo-Abad et al., 2017) (Bonsch et al., 2016; Hammond and Li, 2016)(Henry et al., 2018)				
	Limited use of scarce (geo)physical resources	🟫	(Zhang et al., 2014a; Rasmussen, 2017)	NE		NE		NE	
	Global spread	🟫	(Worrell et al., 2008; Fischedick et al., 2014; Åhman et al., 2016; Bataille et al., 2018)	🟫	(Taibi et al., 2012)(Fischedick et al., 2014; Wesseling et al., 2017)	🟫	(Taibi et al., 2012) (Fischedick et al., 2014; Wesseling et al., 2017)	🟫	(Kuramochi et al., 2012; Mikunda et al., 2014; Bui et al., 2018)

Supplementary Material 4.D.2.v Feasibility assessment of carbon dioxide removal mitigation options

Supplementary Material 4.D.2.v, Table 1: Feasibility assessment of carbon dioxide removal mitigation options: Bioenergy with carbon dioxide capture and storage (BECCS); and Direct air carbon dioxide capture and storage (DACCS). For methodology, see Supplementary Material 4.D.1.

		BECCS		DACCS	
	Evidence	Robust		Medium	
	Agreement	Medium		Medium	
Economic	Cost-effectiveness	░	Reviews - (McLaren, 2012; Caldecott et al., 2015; NRC, 2015) (Honegger and Reiner, 2018) (Luckow et al., 2010; Koornneef et al., 2012b; Arasto et al., 2014) Ethanol – (De Visser et al., 2011; Fabbri et al., 2011; Fornell et al., 2013; Johnson et al., 2014b; Rochedo et al., 2016) Combustion – (Kärki et al., 2013; Akgul et al., 2014; Al-Qayim et al., 2015; Onarheim et al., 2015; Sanchez and Callaway, 2016) (Fuss et al., 2018b) (Bhave et al. 2017)	░	(Keith et al., 2006; Pielke, 2009; House et al., 2011; Ranjan and Herzog, 2011; Simon et al., 2011; Holmes and Keith, 2012b; Zeman, 2014; Sanz-Pérez et al., 2016; Sinha et al., 2017)
	Absence of distributional effects	▓	Bioenergy - (Creutzig et al., 2013, 2015; Hunsberger et al., 2014; Buck, 2016; Robledo-Abad et al., 2017) (Arndt et al., 2011b; German and Schoneveld, 2012; Creutzig et al., 2013; Hunsberger et al., 2014; Buck,	NA	

		🟧	2016; Robledo-Abad et al., 2017; Stevanović et al., 2017) (Popp et al., 2014; Persson, 2015; Kline et al., 2017; Searchinger et al., 2017)	▒	
	Employment & productivity enhancement potential	NE		NA	
Technological	Technical scalability	🟧	(Azar et al., 2010, 2013; Gough and Upham, 2011) (Nemet et al., 2018)	🟧	(Lackner, 2009; Pielke, 2009; Lackner et al., 2012; Nemet and Brandt, 2012; Pritchard et al., 2015) (Nemet et al., 2018)
	Maturity	🟧	(McGlashan et al., 2012; McLaren, 2012; Kemper, 2015; Pang et al., 2017) (Boucher et al., 2014; Fuss et al., 2014; Anderson and Peters, 2016; Vaughan and Gough, 2016; Minx et al., 2017; Strefler et al., 2018c; Vaughan et al., 2018b) (Nemet et al., 2018)	▫	(McLaren, 2012; Boot-Handford et al., 2014; NRC, 2015; Nemet et al., 2018) Demos – (Holmes et al., 2013; Rau et al., 2013; Agee et al., 2016) (Nemet et al., 2018)
	Simplicity	▫	Niche markets – (Möllersten et al., 2003; Sanna et al., 2012)	▫	Niche markets – (Lackner et al., 2012; Hou et al., 2017; Ishimoto et al., 2017)
	Absence of risk	🟧	(Boysen et al., 2017b) (Anderson and Peters, 2016; Vaughan and Gough, 2016) (IPCC, 2005) (de Coninck and Benson, 2014)(Boot-Handford et al., 2014)(Aminu et al., 2017)	🟧	(IPCC, 2005) (de Coninck and Benson, 2014)(Boot-Handford et al., 2014)(Aminu et al., 2017)
Institutional	Political acceptability	▫	BECCS features rarely in policy debates (Fridahl, 2017) (Boysen et al., 2017a)	NE	

	Legal & administrative acceptability	LE	(Honegger and Reiner, 2018)(Kemper, 2015)	🟧	(Boot-Handford et al., 2014; de Coninck and Benson, 2014; Dixon et al., 2015)
	Institutional capacity	🟧	(McLaren, 2012) (Frank et al., 2013) (Burns and Nicholson, 2017) (Kemper, 2015)	NE	(McLaren, 2012)
	Transparency & accountability potential	LE	(McLaren, 2012; NRC, 2015; Nemet et al., 2018)	LE	(McGlashan et al., 2012; McLaren, 2012; Nemet et al., 2018)
Socio-cultural	Social co-benefits (health, education)	🟧	(Knoblauch et al., 2014; Porter et al., 2015; Weldu et al., 2017)	NA	
	Public acceptance	▒	(Thornley et al., 2009; Gough and Upham, 2011; Wallquist et al., 2012; Mabon et al., 2013; Boot-Handford et al., 2014; Gough et al., 2014; Dowd et al., 2015; Lomax et al., 2015; Boysen et al., 2017b; Fridahl, 2017; Robledo-Abad et al., 2017)	▒	(Lackner and Brennan, 2009; Mabon et al., 2013; Boot-Handford et al., 2014; Gough et al., 2014; Lomax et al., 2015)
	Social & regional inclusiveness	LE	(Creutzig et al., 2013, 2015; Robledo-Abad et al., 2017)	NE	
	Intergenerational equity	NE		NE	
	Human capabilities	LE	(IEA GHG, 2012)	LE	(IEA GHG, 2012)
	Impact on landscapes	NE		NE	
Environmental/ecological	Reduction of air pollution	🟧	(Knoblauch et al., 2014; Porter et al., 2015; Weldu et al., 2017)	NA	
	Reduction of toxic waste	NA		NA	

	Reduction of water use		(Smith and Torn 2013, Smith 2016, Fajardy and MacDowell 2017). (Gerbens-Leenes et al., 2009; Gheewala et al., 2011; Smith and Torn, 2013; Bonsch et al., 2016; Lampert et al., 2016; Mouratiadou et al., 2016; Wei et al., 2016; Mathioudakis et al., 2017) (Hylkema and Rand, 2014) (Koornneef et al., 2012a)	NE	
	Improved biodiversity		(Lindenmayer and Hobbs, 2004; Barlow et al., 2007; Immerzeel et al., 2014; Creutzig et al., 2015) (Holland et al., 2015; Santangeli et al., 2016) (Dale et al., 2015; Kline et al., 2015; Tarr et al., 2017)	NA	
Geophysical	Physical feasibility (physical potentials)		Bioenergy - (Beringer et al., 2011; Klein et al., 2014; Creutzig et al., 2015; Kraxner and Nordström, 2015; Searle and Malins, 2015; Smith et al., 2016; Boysen et al., 2017b; Tokimatsu et al., 2017; Heck et al., 2018) CCS – (Dooley, 2013; Selosse and Ricci, 2017)		CCS – (Dooley, 2013; Selosse and Ricci, 2017) (McLaren, 2012; NRC, 2015; Smith et al., 2016; Fuss et al., 2018a)
	Limited use of land		(Beringer et al., 2011; Creutzig et al., 2015; NRC, 2015; Smith et al., 2016; Heck et al., 2018)		(Keith, 2009; Holmes and Keith, 2012b; Lackner et al., 2012; NRC, 2015)
	Limited use of scarce (geo)physical resources	NE		NE	

	Global spread	🟧	(Bright et al., 2015; Robledo-Abad et al., 2017)	🟫	(Clarke et al., 2014)

Supplementary Material 4.D.2.v, Table 2: Feasibility assessment of carbon dioxide removal mitigation options: Afforestation & reforestation; Soil carbon sequestration & biochar; and Enhanced weathering. For methodology, see Supplementary Material 4.D.1.

		Afforestation & reforestation		Soil carbon sequestration & biochar		Enhanced weathering	
	Evidence	Robust		Robust		Medium	
	Agreement	High		High		Low	
Economic	Cost-effectiveness	▓	(Sohngen and Mendelsohn, 2003; Richards and Stokes, 2004; Richards and Stavins, 2005; Nijnik and Halder, 2013; Humpenöder et al., 2014) Reviews - (McLaren, 2012; Caldecott et al., 2015; NRC, 2015)	▓	Reviews - (McGlashan et al., 2012; McLaren, 2012; Caldecott et al., 2015; Smith et al., 2016; Fuss et al., 2018a) BC – (Roberts et al., 2010; Shackley et al., 2011) SCS – (Smith, 2016)	░	Reviews - (McLaren, 2012; NRC, 2015) (Schuiling and Krijgsman, 2006; Hartmann and Kempe, 2008; Köhler et al., 2010; Renforth, 2012; Hartmann et al., 2013; Taylor et al., 2016; Strefler et al., 2018a) OA – (Renforth and Henderson, 2017)
	Absence of distributional effects	▒	Locatelli et al 2015, Renner et al 2008 (Lyons and Westoby, 2014)	▓	world poor stand to benefit (Stringer et al., 2012)	NE	
	Employment & productivity enhancement potential	▒	(Smith et al., 2014b)	▓	(Lal, 2004c; Van Straaten, 2006; Pan et al., 2009; Jeffery et al., 2011) (Jeffery et al., 2011)	NE	
Technological	Technical scalability	▓	(Shvidenko et al., 1997; Polglase et al., 2013; Cunningham et al., 2015; Zhang and Yan, 2015) (Nemet et al., 2018)	▒	(Jiang et al., 2014; Novak et al., 2016; Kammann et al., 2017) (Nemet et al., 2018) BC – (Roberts et al., 2010; Shackley et al., 2011)	▒	(Hangx and Spiers, 2009; Taylor et al., 2016) (Nemet et al., 2018)

	Maturity	🟫	(McLaren, 2012; NRC, 2015; Nemet et al., 2018) Demons – (Gong et al., 2013; Zinda et al., 2017) (Nemet et al., 2018)	🟫	(McLaren, 2012; Olson, 2013; Olson et al., 2014; Piccoli et al., 2016; Triberti et al., 2016; Vochozka et al., 2016) (Nemet et al., 2018)	▨	(McLaren, 2012; Hartmann et al., 2013; NRC, 2015) (Nemet et al., 2018)
	Simplicity	NE		NE		NE	
	Absence of risk	NE		NE		NE	
Institutional	Political acceptability	NE		NE		NE	
	Legal & administrative acceptability	NE		NE		NA	
	Institutional capacity	🟧	(McLaren, 2012) (Wang et al., 2016; Wehkamp et al., 2018b) (Wehkamp et al., 2018a) – Meta analysis until Feb 2016	LE	(Whitman and Lehmann, 2009; Dilling and Failey, 2013; Stavi and Lal, 2013)	LE	(McLaren, 2012; Moosdorf et al., 2014; Buck, 2016)
	Transparency & accountability potential	LE	(McLaren, 2012)	🟧	Accounting -(Sanderman and Baldock, 2010; McLaren, 2012; Downie et al., 2014; Nemet et al., 2018) (Smith et al., 2012a; Jandl et al., 2014)	NE	(McLaren, 2012)
Socio-cultural	Social co-benefits (health, education)	🟫	(Genesio et al., 2016; Ravi et al., 2016)	NE		NE	(Schuiling and Krijgsman, 2006; Taylor et al., 2016)
	Public acceptance	🟧	Private landholders – (Nijnik and Halder, 2013; Schirmer and Bull, 2014; Trevisan et al., 2016)	🟫	(Glenk and Colombo, 2011; Lomax et al., 2015; Jørgensen and Termansen, 2016)	LE	(Wright et al., 2014b)
	Social & regional inclusiveness	🟧	(Atela et al., 2014; Sunderlin et al., 2014; Brugnach et al., 2017; Ngendakumana et al., 2017; Turnhout et al., 2017)	NE		NE	

	Intergenerational equity	LE	(Smith et al., 2014b)	NE		NE	
	Human capabilities	NE		NE		NE	
Environmental/ecological	Reduction of air pollution	NA		NA		🟧	(Schuiling and Krijgsman, 2006; Taylor et al., 2016)
	Reduction of toxic waste	NA		NE		LE	(Schuiling and Krijgsman, 2006; Hartmann et al., 2013)
	Reduction of water use	🟧	(Jackson et al., 2005; Smith and Torn, 2013; Deng et al., 2017)	🟫	(Lal, 2004b; Bamminger et al., 2016; Smith, 2016)	LE	(Kheshgi, 1995; Rau and Caldeira, 1999; Harvey, 2008; Köhler et al., 2013; NRC, 2015)
	Improved biodiversity	🟧	(Díaz et al., 2009; McKinley et al., 2011; Hall et al., 2012; Venter et al., 2012; Greve et al., 2013; Cunningham et al., 2015; Locatelli et al., 2015a; Paul et al., 2016)	NE		NA	
Geophysical	Physical feasibility (physical potentials)	🟧	(Sohngen and Mendelsohn, 2003; Canadell and Raupach, 2008; Strengers et al., 2008; Thomson et al., 2008; van Minnen et al., 2008; Houghton et al., 2015; Sonntag et al., 2016; Griscom et al., 2017)	🟧	BC –(Lehmann et al., 2006; Laird et al., 2009; Lee et al., 2010; Woolf et al., 2010; Lenton, 2010; Moore et al., 2010; Pratt and Moran, 2010; McLaren, 2012; Powell and Lenton, 2012; Lomax et al., 2015; Smith, 2016; Paustian et al., 2016) SCS – (Batjes, 1998; Metting et al., 2001; Lal, 2013, 2003a, 2003b, 2004a, 2004c, 2010, 2011; Lal et al., 2007; Smith et al., 2008; Salati et al., 2010; Conant, 2011; Smith, 2012, 2016; Benbi, 2013; Lorenz and Lal,	🟫	(House et al., 2007; Hartmann and Kempe, 2008; Hangx and Spiers, 2009; Wilson et al., 2009; Köhler et al., 2010, 2013; Morales-Florez et al., 2011; Renforth et al., 2011; Manning and Renforth, 2013; Taylor et al., 2016; Hauck et al., 2016; Strefler et al., 2018a)

		🟧		🟧	2014; Powlson et al., 2014; Sommer and Bossio, 2014; Lassaletta and Aguilera, 2015; Henderson et al., 2015; Minasny et al., 2017; Zomer et al., 2017)	🟫	
	Limited use of land	⬜	(Smith and Torn, 2013; Houghton et al., 2015)	🟫	(Smith, 2016; Fuss et al., 2018a)	🟫	(Hartmann et al., 2013; Strefler et al., 2018b) Could enhance yields reducing land competition pressure – (Edwards et al., 2017; Kantola et al., 2017)
	Limited use of scarce (geo)physical resources	LE	(Smith and Torn, 2013)	NA		LE	(NRC, 2015)
	Global spread	🟧	(Anderson et al., 2011; Arora and Montenegro, 2011; Wang et al., 2014)	🟧	Permanence diff areas – BC - (Zimmermann et al., 2012; Sheng et al., 2016)	🟫	(Garcia et al., 2018; Strefler et al., 2018a)

Supplementary Material 4.D.3 Feasibility assessment of adaptation options as presented in Section 4.5.3

Supplementary Material 4.D.3.i Feasbility assessment of adaptation options in energy system transitions

Supplementary Material 4.D.3.i, Table 1: Feasibility assessment of energy system transition adaptation option: Power infrastructure, including water. For methodology, see Supplementary Material 4.D.1.

		Power infrastructure, including water	
	Evidence	Medium	
	Agreement	High	
Economic	Micro-economic viability	🟧	(Kopytko and Perkins, 2011; Inderberg and Løchen, 2012; Brouwer et al., 2015)
	Macro-economic viability	🟫	(Koch and Vögele, 2009; Kopytko and Perkins, 2011; Soito and Freitas, 2011; Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Brouwer et al., 2015; Cortekar and Groth, 2015; Panteli and Mancarella, 2015; van Vliet et al., 2016)
	Socio-economic vulnerability reduction potential	🟧	(Koch and Vögele, 2009; Soito and Freitas, 2011; Cortekar and Groth, 2015; van Vliet et al., 2016)
	Employment & productivity enhancement potential	🟧	(Inderberg and Løchen, 2012; Cortekar and Groth, 2015; Panteli and Mancarella, 2015; van Vliet et al., 2016)
Technological	Technical resource availability	🟫	(Koch and Vögele, 2009; Soito and Freitas, 2011; Inderberg and Løchen, 2012; Jahandideh-Tehrani et al., 2014; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)
	Risks mitigation potential (stranded Assets, unforeseen Impacts)	🟫	(Koch and Vögele, 2009; Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)
Institutional	Political acceptability	🟧	(Soito and Freitas, 2011; Inderberg and Løchen, 2012; Cortekar and Groth, 2015; Murrant et al., 2015)
	Legal & regulatory acceptability	🟧	(Soito and Freitas, 2011; Inderberg and Løchen, 2012; Cortekar and Groth, 2015; Benson, 2018)
	Institutional capacity & Administrative feasibility	🟧	(Eisenack and Stecker, 2012; Inderberg and Løchen, 2012; Cortekar and Groth, 2015; Murrant et al., 2015)
	Transparency & accountability potential	LE	(Inderberg and Løchen, 2012; Cortekar and Groth, 2015)

Socio-cultural	Social co-benefits (health, education)	NA	(Soito and Freitas, 2011)
	Socio-cultural acceptability	NE	(Soito and Freitas, 2011; Inderberg and Løchen, 2012)
	Social & regional inclusiveness	LE	(Soito and Freitas, 2011)
	Intergenerational equity	LE	(Soito and Freitas, 2011)
Environmental/ecolog	Ecological capacity	🟧	(Koch and Vögele, 2009; Soito and Freitas, 2011; Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)
	Adaptive capacity/resilience	🟫	(Koch and Vögele, 2009; Soito and Freitas, 2011; Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Cortekar and Groth, 2015; Murrant et al., 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)
Geophysical	Physical feasibility	🟧	(Koch and Vögele, 2009; Eisenack and Stecker, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Brouwer et al., 2015; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)
	Land use change enhancement potential	⬜	(Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Parkinson and Djilali, 2015)
	Hazard risk reduction potential	🟧	(Inderberg and Løchen, 2012; Schaeffer et al., 2012; Jahandideh-Tehrani et al., 2014; Brouwer et al., 2015; Cortekar and Groth, 2015; Murrant et al., 2015; Panteli and Mancarella, 2015; Parkinson and Djilali, 2015; van Vliet et al., 2016)

Supplementary Material 4.D.3.ii Feasbility assessment of adaptation options in land & ecosystem transitions

Supplementary Material 4.D.3.ii, Table 1: Feasibility assessment of land and ecosystem transition adaptation options: Conservation agriculture; Efficient irrigation; Efficient livestock; Agroforestry; and Community-based adaptation. For methodology, see Supplementary Material 4.D.1.

		Conservation agriculture		Efficient irrigation		Efficient livestock		Agroforestry		Community-based adaptation	
	Evidence	Medium		Medium		Limited		Medium		Medium	
	Agreement	Medium		Medium		High		High		High	
Economic	Micro-economic viability	🟧	(Grabowski and Kerr, 2014; Jat et al., 2014; Pittelkow et al., 2014; Thierfelder et al., 2015, 2017; Smith et al., 2017b)	🟧	(Olmstead, 2014; Roco et al., 2014; Venot et al., 2014; Varela-Ortega et al., 2016; Bjornlund et al., 2017; Herwehe and Scott, 2017; Mdemu et al., 2017)	🟧	(Thornton and Herrero, 2014; Herrero et al., 2015; Weindl et al., 2015; Ghahramani and Bowran, 2018)	🟧	(Valdivia et al., 2012; K Murthy, 2013; Lasco et al., 2014; Mbow et al., 2014a, 2014b; Brockington et al., 2016; Iiyama et al., 2017; Jacobi et al., 2017; Hernández-Morcillo et al., 2018)	🟧	(Mannke, 2011; Archer et al., 2014; Wright et al., 2014a; Fernández-Giménez et al., 2015; Dodman et al., 2017a)
	Macro-economic viability	🟧	(Ndah et al., 2015; Thierfelder et al., 2015; Smith et al., 2017b)	▨	(Elliott et al., 2014; Kirby et al., 2014; Olmstead, 2014; Girard et al., 2015; Kahil et al., 2015; Varela-Ortega et al., 2016; Bjornlund et al., 2017; Herwehe and Scott, 2017)	🟧	(Herrero et al., 2015; Weindl et al., 2015; García de Jalón et al., 2017)	🟧	(Valdivia et al., 2012; Lasco et al., 2014; Jacobi et al., 2017; Hernández-Morcillo et al., 2018)	NE	
	Socio-economic vulnerability reduction potential	🟧	(Bhan and Behera, 2014; Pittelkow et al., 2014; Stevenson et al., 2014; Prosdocimi et al., 2016; Smith et al., 2017b)	🟧	(Burney and Naylor, 2012; Levidow et al., 2014; Roco et al., 2014; Venot et al., 2014; Ashofteh et al., 2017; Bjornlund et al., 2017)	🟧	(Herrero et al., 2015; García de Jalón et al., 2017; Thornton et al., 2018)	🟧	(Valdivia et al., 2012; Brockington et al., 2016; Coq-Huelva et al., 2017; Coulibaly et al., 2017; Iiyama et al., 2017; Jacobi et al., 2017; Quandt et al., 2017)	🟧	(Mannke, 2011; Archer et al., 2014; Reid and Huq, 2014; Wright et al., 2014a; Fernández-Giménez et al., 2015; Ensor et al., 2016, 2018; Ford et al., 2018)

	Employment & productivity enhancement potential	▨	(Bhan and Behera, 2014; Grabowski and Kerr, 2014; Kirkegaard et al., 2014; Pittelkow et al., 2014; Stevenson et al., 2014)	🟫	(Burney and Naylor, 2012; Burney et al., 2014; Kirby et al., 2014; Levidow et al., 2014)	🟧	(Briske et al., 2015; García de Jalón et al., 2017)	LE	(Verchot et al., 2007; Buckeridge et al., 2012)	▨	(Mannke, 2011; Reid and Huq, 2014; Fernández-Giménez et al., 2015)
Technological	Technical resource availability	🟧	(Palm et al., 2014; Stevenson et al., 2014; Adenle et al., 2015; Smith et al., 2017b)	🟧	(Venot et al., 2014; Esteve et al., 2015; Fishman et al., 2015; Azhoni et al., 2017; Mdemu et al., 2017)	▨	(Descheemaeker et al., 2016; Thornton et al., 2018)	🟧	(Verchot et al., 2007; Valdivia et al., 2012; Mbow et al., 2014a; Iiyama et al., 2017; Jacobi et al., 2017; Hernández-Morcillo et al., 2018)	LE	(Wright et al., 2014a; Fernández-Giménez et al., 2015)
	Risks mitigation potential	🟧	(Bhan and Behera, 2014; Palm et al., 2014; Pittelkow et al., 2014)	🟧	(Burney et al., 2014; Fishman et al., 2015; Jägermeyr et al., 2015; Blanc et al., 2017)	🟧	(Briske et al., 2015; Thornton and Herrero, 2015; Thornton et al., 2018)	🟧	(Verchot et al., 2007; Jacobi et al., 2017; Abdulai et al., 2018; Hernández-Morcillo et al., 2018; Sida et al., 2018)	NA	
Institutional	Political acceptability	🟧	(Adenle et al., 2015; Dougill et al., 2017; Westengen et al., 2018)	🟧	(Burney and Naylor, 2012; Esteve et al., 2015)	NE		🟧	(Buckeridge et al., 2012; Mbow et al., 2014b; Jacobi et al., 2017)	NA	
	Legal & regulatory acceptability	NE		NA		NE		🟧	(Place et al., 2012; Mbow et al., 2014a, 2014b; Jacobi et al., 2017; Hernández-Morcillo et al., 2018)	NA	
	Institutional capacity & Administrative feasibility	🟧	(Bhan and Behera, 2014; Harvey et al., 2014; Kassam et al., 2014; Adenle et al., 2015; Baudron et al., 2015; Ndah et al., 2015; Li et al., 2016; Dougill et al., 2017; Smith et al., 2017b)	🟧	(Burney and Naylor, 2012; Burney et al., 2014; Levidow et al., 2014; Venot et al., 2014; Kahil et al., 2015; Azhoni et al., 2017; Mdemu et al., 2017)	▨	(Herrero et al., 2015; Descheemaeker et al., 2016)	🟧	(Buckeridge et al., 2012; Place et al., 2012; Jacobi et al., 2017; Hernández-Morcillo et al., 2018)	🟧	(Mannke, 2011; Archer et al., 2014; Ayers et al., 2014; Wright et al., 2014a; Reid and Huq, 2014; Sovacool et al., 2015; Fernández-Giménez et al., 2015; Scolobig et al., 2015; Ensor et al., 2016,

		🟧		🟧		░		🟧		🟧	2018; Reid, 2016; Ford et al., 2018)
	Transparency & accountability potential	LE	(Brouder and Gomez-Macpherson, 2014; Palm et al., 2014; Challinor et al., 2018)	🟧	(Levidow et al., 2014; Azhoni et al., 2017)	NA		NE		🟧	(Archer et al., 2014; Reid and Huq, 2014; Fernández-Giménez et al., 2015; Sovacool et al., 2015)
Socio-cultural	Social co-benefits (health, education)	🟧	(Pittelkow et al., 2014; Smith et al., 2017b; Pradhan et al., 2018)	LE	(Venot et al., 2014; Mdemu et al., 2017)	🟧	(Herrero et al., 2015; Thornton and Herrero, 2015; Thornton et al., 2018)	🟧	(Clark and Tilman 2017b; Thierfelder et al. 2017; Varela-Ortega et al. 2016; Hernández-Morcillo et al. 2018; Coq-Huelva et al. 2017; Coulibaly et al. 2017; Quandt et al. 2017; Jacobi et al. 2017; Brockington et al. 2016)	🟧	(Mannke, 2011; Archer et al., 2014; Ayers et al., 2014; Wise et al., 2014; Wright et al., 2014a; Fernández-Giménez et al., 2015; Sovacool et al., 2015; Ensor et al., 2016, 2018; Ford et al., 2018)
	Socio-cultural acceptability	🟧	(Giller et al., 2015; Ndah et al., 2015; Thierfelder et al., 2015)	🟧	(Roco et al., 2014; Venot et al., 2014; Girard et al., 2015; Mdemu et al., 2017)	🟧	(Herrero et al., 2015; Ghahramani and Bowran, 2018; Thornton et al., 2018)	🟧	(Jarvis et al., 2008; Valdivia et al., 2012; Coq-Huelva et al., 2017; Iiyama et al., 2017; Jacobi et al., 2017; Hernández-Morcillo et al., 2018)	🟫	(Mannke, 2011; Green et al., 2014; Reid and Huq, 2014; Wise et al., 2014; Wright et al., 2014a; Fernández-Giménez et al., 2015; Ensor et al., 2016, 2018; Ford et al., 2018)
	Social & regional inclusiveness	░	(Brouder and Gomez-Macpherson, 2014; Pittelkow et al., 2014; Ndah et al., 2015; Smith et al., 2017b)	🟧	(Burney and Naylor, 2012; Jägermeyr et al., 2015)	🟧	(Briske et al., 2015; García de Jalón et al., 2017; Thornton et al., 2018)	🟧	(Valdivia et al., 2012; Iiyama et al., 2017; Jacobi et al., 2017)	🟧	(Archer et al., 2014; Wright et al., 2014a; Fernández-Giménez et al., 2015; Sovacool et al., 2015; Ensor et al., 2016, 2018; Ford et al., 2018)
	Intergenerational equity	NA		NA		NA		NE		🟧	(Wright et al., 2014a; Fernández-Giménez et al., 2015)
Environ	Ecological capacity	🟫	(Bhan and Behera, 2014; Palm et al., 2014; Thierfelder et	🟧	(Kirby et al., 2014; Pfeiffer and Lin, 2014; Fishman et	🟫	(Lemaire et al., 2014; Herrero et al., 2015;	🟫	(Lusiana et al., 2012; K Murthy, 2013; Lasco et al., 2014; Barral et al.,	LE	(Wright et al., 2014a; Fernández-Giménez et al., 2015)

		🟫	al., 2015; Prosdocimi et al., 2016)	🟧	al., 2015; Jägermeyr et al., 2015)	🟫	Thornton et al., 2018)	🟫	2015; Coq-Huelva et al., 2017; Quandt et al., 2017; Hernández-Morcillo et al., 2018; Sida et al., 2018)		
	Adaptive capacity/resilience	🟫	(Aleksandrova et al., 2014; Grabowski and Kerr, 2014; Kirkegaard et al., 2014; Pittelkow et al., 2014; Stevenson et al., 2014; Thierfelder et al., 2015; Li et al., 2016; Smith et al., 2017b; Pradhan et al., 2018)	🟧	(Burney and Naylor, 2012; Burney et al., 2014; Levidow et al., 2014; Jägermeyr et al., 2015; Fader et al., 2016; Varela-Ortega et al., 2016; Ashofteh et al., 2017; Hong and Yabe, 2017)	🟫	(Bell et al., 2014; Havet et al., 2014; Lemaire et al., 2014; Thornton and Herrero, 2014; Briske et al., 2015; Herrero et al., 2015; Weindl et al., 2015; Ghahramani and Bowran, 2018)	🟫	(Sendzimir et al., 2011; Lusiana et al., 2012; K Murthy, 2013; Lasco et al., 2014; Mbow et al., 2014a; Varela-Ortega et al., 2016; Clark and Tilman, 2017; Coq-Huelva et al., 2017; Coulibaly et al., 2017; Quandt et al., 2017; Thierfelder et al., 2017; Hernández-Morcillo et al., 2018)	🟧	(Mannke, 2011; Archer et al., 2014; Ayers et al., 2014; Wright et al., 2014a; Reid and Huq, 2014; Wise et al., 2014; Fernández-Giménez et al., 2015; Ensor et al., 2016, 2018; Ford et al., 2018; Singh, 2018)
Geophysical	Physical feasibility	🟧	(Stevenson et al., 2014; Giller et al., 2015; Thierfelder et al., 2017)	🟧	(Levidow et al., 2014; Fishman et al., 2015; Jägermeyr et al., 2015)	🟧	(Weindl et al., 2015; Thornton et al., 2018)	🟧	(Coulibaly et al., 2017; Hernández-Morcillo et al., 2018)	NA	
	Land use change enhancement potential	🟫	(Grabowski and Kerr, 2014; Stevenson et al., 2014; Giller et al., 2015; Prosdocimi et al., 2016; Cui et al., 2018; Pradhan et al., 2018)	🟧	(Fader et al., 2016)	🟫	(Briske et al., 2015; Weindl et al., 2015)	🟫	(Lasco et al., 2014; Mbow et al., 2014a; Coulibaly et al., 2017; Hernández-Morcillo et al., 2018)	LE	(Wright et al., 2014a)
	Hazard risk reduction potential	NE		NA		NA		🟫	(Lasco et al., 2014; Mbow et al., 2014a; Coulibaly et al., 2017; Abdulai et al., 2018; Hernández-Morcillo et al., 2018)	🟧	(Mannke, 2011; Archer et al., 2014; Wright et al., 2014a; Fernández-Giménez et al., 2015; Ensor et al., 2016, 2018; Ford et al., 2018)

Supplementary Material 4.D.3.ii, Table 2: Feasibility assessment of land and ecosystem transition adaptation options: Ecosystem restoration & avoided deforestation; Biodiversity management; Coastal defense and hardening; and Sustainable aquaculture. For methodology, see Supplementary Material 4.D.1.

		Ecosystem restoration & avoided deforestation		Biodiversity management		Coastal defense and hardening		Sustainable aquaculture	
	Evidence	Robust		Medium		Robust		Limited	
	Agreement	Medium		Medium		Medium		Medium	
Economic	Micro-economic viability	▒	(Dang Phan et al., 2014; Ingalls and Dwyer, 2016; Rakatama et al., 2017; Spencer et al., 2017)	▒	(Rodrigues et al., 2009; Alagador et al., 2014; Mantyka-Pringle et al., 2016; Gómez-Aíza et al., 2017; Reside et al., 2017b; Monahan and Theobald, 2018)	░	(Firth et al., 2014; Barbier, 2015a; Elliott and Wolanski, 2015; Diaz, 2016; Betzold and Mohamed, 2017)	▒	(Boonstra and Hanh, 2015; Joffre et al., 2015; FAO, 2016; FAO et al., 2017; Pérez-Escamilla, 2017)
	Macro-economic viability	▒	(Dang Phan et al., 2014; Rakatama et al., 2017; Spencer et al., 2017; Turnhout et al., 2017; Well and Carrapatoso, 2017)	NE		LE	(Hinkel et al., 2014; Estrada et al., 2017)	LE	(UNEP, 2013; Edwards, 2015; Moffat, 2017)
	Socio-economic vulnerability reduction potential	▓	(Atela et al., 2015; Elmqvist et al., 2015; Camps-Calvet et al., 2016; Ingalls and Dwyer, 2016; McPhearson et al., 2016; Collas et al., 2017; Ngendakumana et al., 2017; Spencer et al., 2017)	▒	(Rodrigues et al., 2009; Berrang-Ford et al., 2012; Pullin et al., 2013; Brockington and Wilkie, 2015; Newbold et al., 2015; Oldekop et al., 2016; Griscom et al., 2017; Milman and Jagannathan, 2017; Terraube et al., 2017; Essl and Mauerhofer, 2018)	▓	(Rabbani et al., 2010b, 2010a; Gutiérrez et al., 2012; Arkema et al., 2013, 2017; Neumann et al., 2015; Sovacool et al., 2015; Sutton-Grier et al., 2015; Betzold and Mohamed, 2017)	▒	(Bell et al., 2011; Smith et al., 2013; Orchard et al., 2015; Béné et al., 2016; Jennings et al., 2016; Mycoo, 2017; Ahmed et al., 2018)
	Employment & productivity enhancement potential	▓	(Ingalls and Dwyer, 2016; Spencer et al., 2017; Turnhout et al., 2017)	NE		NE		▒	(Sánchez et al., 2002; De Silva and Davy, 2010; Ahmed et al., 2014; Boonstra and Hanh, 2015; Lacoue-Labarthe et al., 2016; Asiedu et al., 2017a)

Technological	Technical resource availability	▓	(Ingalls and Dwyer, 2016; Spencer et al., 2017; Turnhout et al., 2017)	░	(Nadeau et al., 2015; Schmitz et al., 2015; Thomas and Gillingham, 2015; Jones et al., 2016a; Urban et al., 2016; Milman and Jagannathan, 2017; Reside et al., 2017b)	▒	(Arkema et al., 2013; Bosello and De Cian, 2014; Smajgl et al., 2015; Hauer et al., 2016; Betzold and Mohamed, 2017; Williams et al., 2018)	░	(UNEP, 2013; Ahmed et al., 2014, 2018; Brillant, 2014; Edwards, 2015; Lucas, 2015; Fidelman et al., 2017)
	Risks mitigation potential	LE	(Spencer et al., 2017; Turnhout et al., 2017)	LE		▒	(Firth et al., 2014; Sovacool et al., 2015; André et al., 2016; Cashman and Nagdee, 2017; Brown et al., 2018; Storlazzi et al., 2018; Williams et al., 2018)	▒	(Boonstra and Hanh, 2015; Blanchard et al., 2017)
Institutional	Political acceptability	▒	(Sunderlin et al., 2014; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017)	LE	(Milman and Jagannathan, 2017; Essl and Mauerhofer, 2018)	▒	(Duvat, 2013; Nordstrom, 2014; Sovacool et al., 2015; Betzold and Mohamed, 2017)	▒	(Brander, 2007; Bell et al., 2011; Bell and Taylor, 2015; FAO, 2016; Weatherdon et al., 2016; Asiedu et al., 2017a; Ertör and Ortega-Cerdà, 2017)
	Legal & regulatory acceptability	LE	(Sunderlin et al., 2014; Turnhout et al., 2017)	░	(Dallimer and Strange, 2015; Jones et al., 2016a; Drielsma et al., 2017; Essl and Mauerhofer, 2018; Monahan and Theobald, 2018; Triviño et al., 2018)	NE		LE	(Broitman et al., 2017; Fidelman et al., 2017)
	Institutional capacity & Administrative feasibility	▒	(Jagger et al., 2014; Sunderlin et al., 2014; Wallbott, 2014; Atela et al., 2015; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; Spencer et al., 2017; Turnhout et al., 2017; Well and Carrapatoso, 2017; Wehkamp et al., 2018a)	░	(Dallimer and Strange, 2015; Thomas and Gillingham, 2015; Jones et al., 2016a; Essl and Mauerhofer, 2018; Monahan and Theobald, 2018)	▒	(Hallegatte et al., 2013; Spalding et al., 2014; Mills et al., 2016; Estrada et al., 2017)	LE	(Ahmed et al., 2014; Broitman et al., 2017; Fidelman et al., 2017)
	Transparency & accountability potential	░	(Jagger et al., 2014; Sunderlin et al., 2014; Atela et al., 2015; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017;	LE		NE		NE	

		░	Turnhout et al., 2017; Well and Carrapatoso, 2017; Wehkamp et al., 2018a)						
Socio-cultural	Social co-benefits (health, education)	🟫	(Sunderlin et al., 2014; Jagger et al., 2014; Atela et al., 2015; Elmqvist et al., 2015; Camps-Calvet et al., 2016; Ingalls and Dwyer, 2016; McPhearson et al., 2016; Turnhout et al., 2017; Collas et al., 2017; Li et al., 2017; Ngendakumana et al., 2017; Spencer et al., 2017)	🟧	(Rodrigues et al., 2009; Berrang-Ford et al., 2012; Pullin et al., 2013; Brockington and Wilkie, 2015; Oldekop et al., 2016; Clark and Tilman, 2017; Terraube et al., 2017; Essl and Mauerhofer, 2018)	🟧	(Sovacool et al., 2015; Sutton-Grier et al., 2015; Arkema et al., 2017; Betzold and Mohamed, 2017)	LE	(Weatherdon et al., 2016; Fidelman et al., 2017)
	Socio-cultural acceptability	░	(Sunderlin et al., 2014; Wallbott, 2014; Atela et al., 2015; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; Spencer et al., 2017)	🟧	(Pullin et al., 2013; Brockington and Wilkie, 2015; Oldekop et al., 2016; Milman and Jagannathan, 2017)	🟧	(Sovacool et al., 2015; Gibbs, 2016; Morris et al., 2016; Betzold and Mohamed, 2017; Marengo et al., 2017)	LE	(Asiedu et al., 2017a; Fidelman et al., 2017)
	Social & regional inclusiveness	LE	(Ingalls and Dwyer, 2016; Spencer et al., 2017)	🟧	(Pullin et al., 2013; Brockington and Wilkie, 2015; Oldekop et al., 2016; Milman and Jagannathan, 2017; Terraube et al., 2017)	NA		NE	
	Intergenerational equity	🟧	(Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; Spencer et al., 2017)	NE		NE		NA	
Environmental/ ecological	Ecological capacity	🟧	(Sunderlin et al., 2014; Spencer et al., 2017; Turnhout et al., 2017)	🟧	(Rodrigues et al., 2009; Virkkala et al., 2014; Thomas and Gillingham, 2015; Gillingham et al., 2015; Nadeau et al., 2015; Schmitz et al., 2015; Feeley and Silman, 2016; Gaüzère et al., 2016; Greenwood et al., 2016; Gómez-Aíza et al., 2017; Mingarro and	░	(Bilkovic and Mitchell, 2013; Spalding et al., 2014; Joffre et al., 2015; Sutton-Grier et al., 2015)	🟧	(David et al., 2015; Joffre et al., 2015; Blanchard et al., 2017; Broitman et al., 2017; Ahmed et al., 2018)

		🟧		🟧	Lobo, 2018; Monahan and Theobald, 2018)	⬜		🟧	
	Adaptive capacity/resilience	🟧	(Sunderlin et al., 2014; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; Spencer et al., 2017; Turnhout et al., 2017)	🟧	(Rodrigues et al., 2009; Pullin et al., 2013; Oldekop et al., 2016; Gómez-Aíza et al., 2017; Terraube et al., 2017; Monahan and Theobald, 2018)	LE	(Spalding et al., 2014; Orchard et al., 2015; Fidelman et al., 2017)	🟧	(Boonstra and Hanh, 2015; Orchard et al., 2015; Blanchard et al., 2017; Fidelman et al., 2017; Cinner et al., 2018)
Geophysical	Physical feasibility	🟧	(Dang Phan et al., 2014; Sunderlin et al., 2014; Ngendakumana et al., 2017; Spencer et al., 2017; Turnhout et al., 2017)	NE		🟧	(Duvat, 2013; Hinkel et al., 2014; Smith et al., 2015; André et al., 2016; Cooper et al., 2016; Vousdoukas et al., 2016; Arkema et al., 2017)	🟧	(David et al., 2015; Adhikari et al., 2018b; Ahmed et al., 2018)
	Land use change enhancement potential	🟫	(Dang Phan et al., 2014; Sunderlin et al., 2014; Ingalls and Dwyer, 2016; Ngendakumana et al., 2017; Turnhout et al., 2017; Houghton and Nassikas, 2018; Wehkamp et al., 2018a)	LE	(Schmitz et al., 2015; Reside et al., 2017b, 2017a)	LE	(Sutton-Grier et al., 2015)	LE	(Mialhe et al., 2016)
	Hazard risk reduction potential	🟧	(Ingalls and Dwyer, 2016; Spencer et al., 2017)	NE		🟧	(Luisetti et al., 2013; Firth et al., 2014; Spalding et al., 2014; Barbier, 2015b; Sutton-Grier et al., 2015; André et al., 2016; Narayan et al., 2016; Arkema et al., 2017; Fu and Song, 2017)	🟫	(Joffre et al., 2015; Blanchard et al., 2017; Daly et al., 2017; Hung et al., 2018)

Supplementary Material 4.D.3.iii Feasbility assessment of adaptation options in urban & infrastructure system transitions

Supplementary Material 4.D.3.iii, Table 1: Feasibility assessment of urban and infrastructure transition adaptation options: Sustainable land-use & urban planning; and Sustainable water management. For methodology, see Supplementary Material 4.D.1.

		Sustainable land-use & urban planning		Sustainable water management	
	Evidence	Medium		Robust	
	Agreement	Medium		Medium	
Economic	Micro-economic viability	🟧	(Eberhard et al., 2011; Kiunsi, 2013; Watkins, 2015; Archer, 2016; Eberhard et al., 2016; Eisenberg, 2016; Ewing et al., 2016; Ziervogel et al., 2016a; Hess and Kelman, 2017; Mavhura et al., 2017; Ziervogel et al., 2017)	🟫	(Liu et al., 2014; Lamond et al., 2015; Voskamp and Van de Ven, 2015; Xue et al., 2015; Costa et al., 2016; Mguni et al., 2016; Poff et al., 2016; Ossa-Moreno et al., 2017; Vincent et al., 2017; Xie et al., 2017)
	Macro-economic viability	🟧	(Eberhard et al., 2011; Measham et al., 2011; Aerts et al., 2014; Jaglin, 2014; Beccali et al., 2015; Boughedir, 2015; Watkins, 2015; Eberhard et al., 2016; Ziervogel et al., 2016a; Chu et al., 2017; Hess and Kelman, 2017; Ziervogel et al., 2017)	NE	
	Socio-economic vulnerability reduction potential	🟧	(Measham et al., 2011; Eberhard et al., 2011, 2016; Kiunsi, 2013; Aerts et al., 2014; Jaglin, 2014; Boughedir, 2015; Broto et al., 2015; Carter et al., 2015; Archer, 2016; Shi et al., 2016; Ziervogel et al., 2016a, 2017; Hetz, 2016; Mavhura et al., 2017)	🟫	(Villarroel Walker et al., 2014; Ziervogel and Joubert, 2014; Brown and McGranahan, 2016; Chu et al., 2016; Chant et al., 2017; Dodman et al., 2017b, 2017a; Ossa-Moreno et al., 2017; Gunasekara et al., 2018)
	Employment & productivity enhancement potential	░	(Eberhard et al., 2011; Measham et al., 2011; Watkins, 2015; Archer, 2016; Eberhard et al., 2016; Ziervogel et al., 2016a)	NE	
Technological	Technical resource availability	🟧	(Aerts et al., 2014; Kettle et al., 2014; Beccali et al., 2015; Boughedir, 2015; Archer, 2016; Woodruff and Stults, 2016; Mavhura et al., 2017; Siders, 2017; Stults and Woodruff, 2017)	🟫	(Liu et al., 2014; Lamond et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Soz et al., 2016; Xie et al., 2017)
	Risks mitigation potential	🟧	(Measham et al., 2011; Kiunsi, 2013; Aerts et al., 2014; Boughedir, 2015; Eisenberg, 2016; Siders, 2017; Stults and Woodruff, 2017)	🟫	(Liu et al., 2014; Lamond et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017; Gunasekara et al., 2018)

Institutional	Political acceptability	░	(Measham et al., 2011; Aerts et al., 2014; Rivera and Wamsler, 2014; Boughedir, 2015; Carter et al., 2015; Landauer et al., 2015; Araos et al., 2016b; Woodruff and Stults, 2016; Hetz, 2016; Siders, 2017; Chu et al., 2017; Di Gregorio et al., 2017b; Mahlkow and Donner, 2017)	░	(Leck et al., 2015; Padawangi and Douglass, 2015; Chen and Chen, 2016; Mguni et al., 2016)
	Legal & regulatory acceptability	▒	(Eberhard et al., 2011; Measham et al., 2011; Aerts et al., 2014; Rivera and Wamsler, 2014; Boughedir, 2015; Carter et al., 2015; Landauer et al., 2015; Eberhard et al., 2016; Eisenberg, 2016; King et al., 2016; Dhar and Khirfan, 2017; Di Gregorio et al., 2017b; Francesch-Huidobro et al., 2017; Hess and Kelman, 2017)	░	(Padawangi and Douglass, 2015) (Bettini et al., 2015; Deng and Zhao, 2015; Hill Clarvis and Engle, 2015; Leck et al., 2015; Lemos, 2015; Margerum and Robinson, 2015; Chen and Chen, 2016)
	Institutional capacity & Administrative feasibility	▒	(Eberhard et al., 2011, 2016; Measham et al., 2011; Kiunsi, 2013; Aerts et al., 2014; Jaglin, 2014; Rivera and Wamsler, 2014; Archer et al., 2014; Landauer et al., 2015; Boughedir, 2015; Broto et al., 2015; Carter et al., 2015; Araos et al., 2016b; Hetz, 2016; Archer, 2016; Shi et al., 2016; Woodruff and Stults, 2016; Ziervogel et al., 2016a; Campos et al., 2016; Di Gregorio et al., 2017b; Francesch-Huidobro et al., 2017; Mahlkow and Donner, 2017; Mavhura et al., 2017; Siders, 2017; Tait and Euston-Brown, 2017; Chu et al., 2017; Dhar and Khirfan, 2017)	░	(Ziervogel and Joubert, 2014; Bettini et al., 2015; Deng and Zhao, 2015; Hill Clarvis and Engle, 2015; Lamond et al., 2015; Lemos, 2015; Margerum and Robinson, 2015)
	Transparency & accountability potential	▒	(Eberhard et al., 2011, 2016; Measham et al., 2011; Kettle et al., 2014; Broto et al., 2015; Landauer et al., 2015; Shi et al., 2016; Woodruff and Stults, 2016; Chu et al., 2017; Stults and Woodruff, 2017)	NE	
Socio-cultural	Social co-benefits (health, education)	█	(Eberhard et al., 2011; Archer et al., 2014; Kettle et al., 2014; Beccali et al., 2015; Landauer et al., 2015; Parnell, 2015; Watkins, 2015; Archer, 2016; Campos et al., 2016; Eberhard et al., 2016; Ziervogel et al., 2016a; Hess and Kelman, 2017; Ziervogel et al., 2017; Chu et al., 2018)	█	(Liu et al., 2014; Lamond et al., 2015; Leck et al., 2015; Padawangi and Douglass, 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Nur and Shrestha, 2017; Xie et al., 2017; Gunasekara et al., 2018)
	Socio-cultural acceptability	░	(Kiunsi, 2013; Aerts et al., 2014; Archer et al., 2014; Jaglin, 2014; Kettle et al., 2014; Broto et al., 2015; Carter et al., 2015; Parnell, 2015; Watkins, 2015; Archer, 2016; Campos et al., 2016; Eberhard et al., 2016; Ewing et al., 2016; Newman et al., 2016; Shi et al., 2016; Ziervogel et al., 2016a; Chu et al., 2017; Siders, 2017; Stults and Woodruff, 2017; Ziervogel et al., 2017; Chu et al., 2018)	▒	(Lamond et al., 2015; Leck et al., 2015; Padawangi and Douglass, 2015; Nur and Shrestha, 2017; Xie et al., 2017)

	Social & regional inclusiveness	🟧	(Eberhard et al., 2011; Archer et al., 2014; Jaglin, 2014; Kettle et al., 2014; Broto et al., 2015; Parnell, 2015; Watkins, 2015; Araos et al., 2016b; Archer, 2016; Campos et al., 2016; Eberhard et al., 2016; King et al., 2016; Shi et al., 2016; Ziervogel et al., 2016a; Chu et al., 2017; Dhar and Khirfan, 2017; Mahlkow and Donner, 2017; Mavhura et al., 2017; Ziervogel et al., 2017; Chu et al., 2018)	🟧	(Rasul and Sharma, 2016)
	Intergenerational equity	🟧	(Parnell, 2015; King et al., 2016; Shi et al., 2016; Chu et al., 2017; Ziervogel et al., 2017)	🟫	(Tacoli et al., 2013; Xue et al., 2015; Poff et al., 2016)
Environmental/ ecological	Ecological capacity	🟧	(Kiunsi, 2013; Aerts et al., 2014; Kettle et al., 2014; King et al., 2016; Ziervogel et al., 2016a; Mavhura et al., 2017)	🟧	(Ziervogel and Joubert, 2014; Lamond et al., 2015; Soz et al., 2016)
	Adaptive capacity/ resilience	🟫	(Eberhard et al., 2011; Kiunsi, 2013; Aerts et al., 2014; Archer et al., 2014; Jaglin, 2014; Kettle et al., 2014; Rivera and Wamsler, 2014; Carter et al., 2015; Parnell, 2015; Watkins, 2015; Archer, 2016; Eberhard et al., 2016; Hetz, 2016; King et al., 2016; Shi et al., 2016; Ziervogel et al., 2016a; Chu et al., 2017; Hess and Kelman, 2017; Stults and Woodruff, 2017; Ziervogel et al., 2017)	🟫	(Angotti, 2015; Bell et al., 2015; Biggs et al., 2015; Gwedla and Shackleton, 2015; Lwasa et al., 2015; Chen and Chen, 2016; Yang et al., 2016; Sanesi et al., 2017; Gunasekara et al., 2018)
Geophysical	Physical feasibility	🟧	(Aerts et al., 2014; Boughedir, 2015; Hetz, 2016; King et al., 2016; Newman et al., 2016; Woodruff and Stults, 2016; Ziervogel et al., 2016a; Stults and Woodruff, 2017)	🟧	(Ziervogel and Joubert, 2014; Lamond et al., 2015; Soz et al., 2016)
	Land use change enhancement potential	🟫	(Kiunsi, 2013; Landauer et al., 2015; Parnell, 2015; Hetz, 2016; Newman et al., 2016; Mavhura et al., 2017)	🟫	(Lamond et al., 2015; Leck et al., 2015; Padawangi and Douglass, 2015; Rasul and Sharma, 2016; Soz et al., 2016)
	Hazard risk reduction potential	🟫	(Kiunsi, 2013; Aerts et al., 2014; Watkins, 2015; Boughedir, 2015; Archer, 2016; Woodruff and Stults, 2016; Eisenberg, 2016; Hetz, 2016; King et al., 2016; Mahlkow and Donner, 2017; Mavhura et al., 2017; Stults and Woodruff, 2017)	🟫	(Liu et al., 2014; Angotti, 2015; Bell et al., 2015; Voskamp and Van de Ven, 2015; Biggs et al., 2015; Gwedla and Shackleton, 2015; Lamond et al., 2015; Lwasa et al., 2015; Mguni et al., 2016; Yang et al., 2016; Chen and Chen, 2016; Costa et al., 2016; Sanesi et al., 2017; Xie et al., 2017; Gunasekara et al., 2018)

Supplementary Material 4.D.3.iii, Table 2: Feasibility assessment of urban and infrastructure transition adaptation options: Green infrastructure and ecosystem services; and Building codes and standards. For methodology, see Supplementary Material 4.D.1.

		Green infrastructure and ecosystem services		Building codes and standards	
	Evidence	Medium		Limited	
	Agreement	High		Medium	
Economic	Micro-economic viability	🟧	(Elmqvist et al., 2015; Soderlund and Newman, 2015; McPhearson et al., 2016; Zinia and McShane, 2018)	🟧	(Steenhof and Sparling, 2011; Bendito and Barrios, 2016; Ruparathna et al., 2016; Mavhura et al., 2017; Wells et al., 2018)
	Macro-economic viability	LE	(Culwick and Bobbins, 2016)	🟧	(Steenhof and Sparling, 2011; Aerts et al., 2014; Späth and Rohracher, 2015; Chandel et al., 2016; Shapiro, 2016; Hess and Kelman, 2017; Wells et al., 2018)
	Socio-economic vulnerability reduction potential	🟫	(Tallis et al., 2011; Elmqvist et al., 2015; Soderlund and Newman, 2015; Camps-Calvet et al., 2016; McPhearson et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Li et al., 2017; White et al., 2017b; Zinia and McShane, 2018)	🟫	(Steenhof and Sparling, 2011; FEMA, 2014; Bendito and Barrios, 2016; Hess and Kelman, 2017; Reckien et al., 2017)
	Employment & productivity enhancement potential	NE		NE	
Technological	Technical resource availability	NA		🟫	(Steenhof and Sparling, 2011; Aerts et al., 2014; Bendito and Barrios, 2016; Chandel et al., 2016; Ruparathna et al., 2016; Garsaball and Markov, 2017; Tait and Euston-Brown, 2017; Wells et al., 2018)
	Risks mitigation potential (stranded Assets, unforeseen Impacts)	🟫	(Tallis et al., 2011; Elmqvist et al., 2013b; Buckeridge, 2015; Elmqvist et al., 2015; Soderlund and Newman, 2015; Camps-Calvet et al., 2016; McPhearson et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Li et al., 2017; White et al., 2017b; Zinia and McShane, 2018)	🟧	(Aerts et al., 2014; Ruparathna et al., 2016)
Institutional	Political acceptability	LE	(Brown and McGranahan, 2016; Ziervogel et al., 2016b)	🟧	(Aerts et al., 2014; Späth and Rohracher, 2015; Chandel et al., 2016; Eisenberg, 2016; Shapiro, 2016; Tait and Euston-Brown, 2017; Wells et al., 2018)
	Legal & regulatory acceptability	🟧	(Brown and McGranahan, 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; Sirakaya et al., 2018)	🟧	(Steenhof and Sparling, 2011; Burch et al., 2014; Späth and Rohracher, 2015; Eisenberg, 2016; Ruparathna et al., 2016; Shapiro, 2016; Hess and Kelman, 2017; Stults and Woodruff, 2017)

	Institutional capacity & Administrative feasibility	🟧	(Brown and McGranahan, 2016; Culwick and Bobbins, 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; Prudencio and Null, 2018)	🟧	(Aerts et al., 2014; Chandel et al., 2016; Eisenberg, 2016; Shapiro, 2016; Garsaball and Markov, 2017; Hess and Kelman, 2017; Mavhura et al., 2017; Stults and Woodruff, 2017; Tait and Euston-Brown, 2017)
	Transparency & accountability potential	LE	(Li et al., 2017)	🟧	(Steenhof and Sparling, 2011; Aerts et al., 2014; Späth and Rohracher, 2015; Chandel et al., 2016; Shapiro, 2016)
Socio-cultural	Social co-benefits (health, education)	🟫	(Beatley, 2011; Tallis et al., 2011; Elmqvist et al., 2013b; Demuzere et al., 2014; Liu et al., 2014; Buckeridge, 2015; Elmqvist et al., 2015; Lamond et al., 2015; Mullaney et al., 2015; Norton et al., 2015; Skougaard Kaspersen et al., 2015; Soderlund and Newman, 2015; Voskamp and Van de Ven, 2015; Beaudoin and Gosselin, 2016; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; Costa et al., 2016; Culwick and Bobbins, 2016; Green et al., 2016; McPhearson et al., 2016; Mguni et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Collas et al., 2017; Li et al., 2017; Lin et al., 2017; Xie et al., 2017; Zinia and McShane, 2018)	NE	
	Socio-cultural acceptability	🟫	(Beatley, 2011; Elmqvist et al., 2015; Beaudoin and Gosselin, 2016; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; McPhearson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; Zinia and McShane, 2018)	🟫	(Späth and Rohracher, 2015; Bendito and Barrios, 2016; Eisenberg, 2016; Tait and Euston-Brown, 2017)
	Social & regional inclusiveness	🟫	(Tallis et al., 2011; Elmqvist et al., 2013b; Buckeridge, 2015; Elmqvist et al., 2015; Beaudoin and Gosselin, 2016; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; Culwick and Bobbins, 2016; McPhearson et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; White et al., 2017b; Prudencio and Null, 2018)	🟧	(Parnell, 2015; Shapiro, 2016; Mavhura et al., 2017; Reckien et al., 2017)
	Intergenerational equity	🟫	(Elmqvist et al., 2013b; Liu et al., 2014; Elmqvist et al., 2015; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; McPhearson et al., 2016; Mguni et al., 2016; Xie et al., 2017)	NE	
Environmental / ecological	Ecological capacity	🟫	(Liu et al., 2014; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Costa et al., 2016; Mguni et al., 2016; Xie et al., 2017)	NE	
	Adaptive capacity/ resilience	🟫	(Beatley, 2011; Elmqvist et al., 2013b, 2015; Voskamp and Van de Ven, 2015; Beaudoin and Gosselin, 2016; Brown and	🟧	(Steenhof and Sparling, 2011; Aerts et al., 2014; Bendito and Barrios, 2016)

		🟫	McGranahan, 2016; Camps-Calvet et al., 2016; McPhearson et al., 2016; Panagopoulos et al., 2016; Collas et al., 2017; Li et al., 2017; Zinia and McShane, 2018)	🟧	
Geophysical	Physical feasibility	🟧	(Liu et al., 2014; Lamond et al., 2015; Skougaard Kaspersen et al., 2015; Voskamp and Van de Ven, 2015; Costa et al., 2016; Mguni et al., 2016; Collas et al., 2017; Xie et al., 2017)	NE	
	Land use change enhancement potential	🟧	(Tallis et al., 2011; Elmqvist et al., 2013b; Buckeridge, 2015; Culwick and Bobbins, 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Collas et al., 2017; White et al., 2017b)	🟧	(Bendito and Barrios, 2016; Reckien et al., 2017)
	Hazard risk reduction potential	🟫	(Nowak et al., 2006; Tallis et al., 2011; Elmqvist et al., 2013b; Buckeridge, 2015; Elmqvist et al., 2015; Soderlund and Newman, 2015; Brown and McGranahan, 2016; Camps-Calvet et al., 2016; Culwick and Bobbins, 2016; McPhearson et al., 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; Ziervogel et al., 2016b; Collas et al., 2017; Li et al., 2017; White et al., 2017b; Zinia and McShane, 2018)	🟧	(Steenhof and Sparling, 2011; FEMA, 2014; Bendito and Barrios, 2016; Garsaball and Markov, 2017; Reckien et al., 2017)

Supplementary Material 4.D.3.iv Feasbility assessment of adaptation options in industrial system transitions

Supplementary Material 4.D.3.iv, Table 1: Feasibility assessment of industrial system transition adaptation option: Intensive industry infrastructure resilience and water management. For methodology, see Supplementary Material 4.D.1.

		Intensive industry infrastructure resilience and water management	
	Evidence	Limited	
	Agreement	High	
Economic	Micro-economic viability	NE	
	Macro-economic viability	NE	
	Socio-economic vulnerability reduction potential	🟧	
	Employment & productivity enhancement potential	NE	
Technological	Technical resource availability	🟫	(Koch and Vögele, 2009; Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)
	Risks mitigation potential	🟧	(Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)
Institutional	Political acceptability	LE	(Murrant et al., 2015)
	Legal & regulatory acceptability	NE	
	Institutional capacity & Administrative feasibility	LE	(Eisenack and Stecker, 2012; Murrant et al., 2015)
	Transparency & accountability potential	NE	
Socio-cultural	Social co-benefits (health, education)	NA	
	Socio-cultural acceptability	NE	
	Social & regional inclusiveness	NA	

	Intergenerational equity	NA	
Environmental/ ecological	Ecological capacity	🟧	(Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)
	Adaptive capacity/resilience	🟫	(Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)
Geophysical	Physical feasibility	🟧	(Eisenack and Stecker, 2012; Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)
	Land use change enhancement potential	LE	(Jahandideh-Tehrani et al., 2014; Parkinson and Djilali, 2015)
	Hazard risk reduction potential	🟧	(Jahandideh-Tehrani et al., 2014; Murrant et al., 2015; Parkinson and Djilali, 2015)

Supplementary Material 4.D.3.v Feasbility assessment of overarching adaptation options

Supplementary Material 4.D.3.v, Table 1: Feasibility assessment of overarching adaptation options: Disaster risk management; Risk spreading and sharing; Climate services; and Indigenous knowledge. For methodology, see Supplementary Material 4.D.1.

		Disaster risk management		Risk spreading and sharing		Climate services		Indigenous knowledge	
	Evidence	Medium		Medium		Medium		Medium	
	Agreement	High		Medium		High		High	
Economic	Micro-economic viability	🟫	(IPCC, 2012; Mavhura et al., 2013; Yu and Gillis, 2014; Johnson and Abe, 2015; Mawere and Mubaya, 2015; Archer, 2016; Kull et al., 2016; Rose, 2016; Watanabe et al., 2016)	🟧	(Panda et al., 2013; Weinhofer and Busch, 2013; Falco et al., 2014; Thornton and Herrero, 2014; Annan and Schlenker, 2015; Bogale, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Akter et al., 2016; Jin et al., 2016; Surminski et al., 2016; Akter et al., 2017; Farzaneh et al., 2017; Glaas et al., 2017; Jensen and Barrett, 2017; Patel et al., 2017; Shively, 2017)	🟧	(Vaughan and Dessai, 2014; Snow et al., 2016; Lechthaler and Vinogradova, 2017; Webber, 2017; Ouédraogo et al., 2018)	🟫	(Berkes et al., 2000; Nakashima et al., 2012; Leonard et al., 2013; McNamara and Prasad, 2014; Pearce et al., 2015; Mapfumo et al., 2016; Altieri and Nicholls, 2017; Nunn et al., 2017; Ruiz-Mallén et al., 2017; Crate et al., 2017; Ingty, 2017; Kihila, 2017; Magni, 2017)
	Macro-economic viability	🟧	(IPCC, 2012; Hinkel et al., 2014; Anacona et al., 2015; Boughedir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Archer, 2016; Diaz, 2016; Haeberli et al., 2016; Kull et al., 2016; Rose, 2016; de Leon and Pittock, 2017; Haeberli et al., 2017; Kelman, 2017)	🟧	(Cook and Dowlatabadi, 2011; Falco et al., 2014; García Romero and Molina, 2015; Joyette et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; Surminski et al., 2016; Glaas et al., 2017; Jenkins et	🟧	(Brasseur and Gallardo, 2016; Rodrigues et al., 2016)	🟧	(Berkes et al., 2000; Leonard et al., 2013; Mapfumo et al., 2016; Ingty, 2017; Magni, 2017; Nunn et al., 2017; Ruiz-Mallén et al., 2017)

		🟧		🟧	al., 2017; Jensen and Barrett, 2017)	🟧		🟧	
	Socio-economic vulnerability reduction potential	🟧	(IPCC, 2012; Mavhura et al., 2013; Boeckmann and Rohn, 2014; McNamara and Prasad, 2014; Anacona et al., 2015; Boughedir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Diaz, 2016; Haeberli et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; Watanabe et al., 2016; de Leon and Pittock, 2017; Granderson, 2017; Haeberli et al., 2017; Wallace, 2017; Brundiers, 2018; Nahayo et al., 2018)	⬜	(Mills, 2007; Panda et al., 2013; Falco et al., 2014; Thornton and Herrero, 2014; Annan and Schlenker, 2015; Bogale, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Wolfrom and Yokoi-Arai, 2015; Jin et al., 2016; O'Hare et al., 2016; Surminski et al., 2016; Akter et al., 2017; Farzaneh et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017; Patel et al., 2017; Surminski and Thieken, 2017)	🟧	(Kadi et al., 2011; Jancloes et al., 2014; Vaughan and Dessai, 2014; Lobo et al., 2017)	🟫	(Berkes and Jolly, 2002; Forbes et al., 2009; Nakashima et al., 2012; Leonard et al., 2013; McNamara and Prasad, 2014; Ford et al., 2014; MacDonald et al., 2015b; Pearce et al., 2015; Harper et al., 2015; Mapfumo et al., 2016; Mistry and Berardi, 2016; Clark et al., 2016; Altieri and Nicholls, 2017; Archer et al., 2017; Magni, 2017; Nunn et al., 2017; Ruiz-Mallén et al., 2017; Russell-Smith et al., 2017; Thornton and Comberti, 2017; Williams et al., 2017; Ingty, 2017; Kihila, 2017)
	Employment & productivity enhancement potential	🟧	(Terrier et al., 2011; IPCC, 2012; Mavhura et al., 2013; Yu and Gillis, 2014; Johnson and Abe, 2015; Mawere and Mubaya, 2015; Terrier et al., 2015; Archer, 2016; Haeberli et al., 2016; Kull et al., 2016; Rose, 2016; Haeberli et al., 2017)	🟧	(Panda et al., 2013; Falco et al., 2014; Thornton and Herrero, 2014; Bogale, 2015; Greatrex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Hansen et al., 2017; Jensen and Barrett, 2017)	NE		🟧	(Berkes et al., 2000; Nakashima et al., 2012; Leonard et al., 2013; Pearce et al., 2015; Harper et al., 2015; Clark et al., 2016; Altieri and Nicholls, 2017; Archer et al., 2017; Ruiz-Mallén et al., 2017; Russell-Smith et al., 2017; Ingty, 2017; Kihila, 2017; Magni, 2017)
Technological	Technical resource availability	🟧	(IPCC, 2012; Mavhura et al., 2013; Boeckmann and Rohn, 2014; McNamara and Prasad, 2014; Yu and Gillis, 2014; Anacona et al., 2015; Boughedir,	🟫	(Falco et al., 2014; García Romero and Molina, 2015; Joyette et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015;	🟫	(Dinku et al., 2014; Jancloes et al., 2014; Gebru et al., 2015; Weisse et al., 2015; Brasseur and Gallardo, 2016; Cortekar	🟫	(Berkes et al., 2000; Ford et al., 2010; Nakashima et al., 2012; Cunsolo Willox et al., 2013; Leonard et al., 2013; Pearce et al., 2015; Johnson

		🟧	2015; Howes et al., 2015; Johnson and Abe, 2015; Mawere and Mubaya, 2015; Allen et al., 2016; Archer, 2016; Diaz, 2016; Haeberli et al., 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Haeberli et al., 2017; Wang et al., 2018)	🟫	Akter et al., 2016; Surminski et al., 2016; Adiku et al., 2017; Jensen and Barrett, 2017)	🟫	et al., 2016; Singh et al., 2016; Snow et al., 2016; Vaughan et al., 2016; Kihila, 2017)	🟫	et al., 2015; MacDonald et al., 2015a; Sherman et al., 2016; Altieri and Nicholls, 2017; Magni, 2017; Nunn et al., 2017; Russell-Smith et al., 2017; Inamara and Thomas, 2017; Ingty, 2017; Kihila, 2017)
	Risks mitigation potential	🟫	(IPCC, 2012; Mavhura et al., 2013; Yu and Gillis, 2014; Boughedir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Haeberli et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; Haeberli et al., 2017; Kita, 2017; Wallace, 2017)	⬜	(Mills, 2007; Cook and Dowlatabadi, 2011; Panda et al., 2013; Weinhofer and Busch, 2013; Falco et al., 2014; Thornton and Herrero, 2014; Annan and Schlenker, 2015; Fabian, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Wolfrom and Yokoi-Arai, 2015; Jin et al., 2016; Surminski et al., 2016; Farzaneh et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017; Surminski and Eldridge, 2017; Surminski and Thieken, 2017)	🟧	(Rogers and Tsirkunov, 2010; WMO, 2015)	🟧	(Nakashima et al., 2012; McNamara and Prasad, 2014; Mapfumo et al., 2016; Kihila, 2017; Magni, 2017)
Institutional	Political acceptability	🟧	(Carey, 2005, 2008; IPCC, 2012; Boughedir, 2015; Johnson and Abe, 2015; Archer, 2016; Haeberli et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Granderson, 2017; Kelman, 2017; Kita, 2017; Ruiz-Rivera and Lucatello, 2017; Rosendo et al., 2018)	🟧	(García Romero and Molina, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Glaas et al., 2017; Jenkins et al., 2017; Jensen and Barrett, 2017)	🟧	(Gebru et al., 2015; Vincent et al., 2015; Cortekar et al., 2016; Singh et al., 2016; Snow et al., 2016; Harjanne, 2017; Webber, 2017)	⬜	(Nakashima et al., 2012; Leonard et al., 2013; Ford et al., 2015; Hooli, 2016; Mistry and Berardi, 2016; Fernández-Llamazares et al., 2017; Russell-Smith et al., 2017; Williams et al., 2017; Ingty, 2017; Kihila, 2017; Magni, 2017; Ruiz-Mallén et al., 2017)

	Legal & regulatory acceptability	🟧	(IPCC, 2012; Boughedir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Haeberli et al., 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; van der Keur et al., 2016; de Leon and Pittock, 2017; Haeberli et al., 2017; Kelman, 2017; Kita, 2017; Ruiz-Rivera and Lucatello, 2017; Serrao-Neumann et al., 2017; Wallace, 2017; Rosendo et al., 2018)	🟧	(Falco et al., 2014; Thornton and Herrero, 2014; García Romero and Molina, 2015; Joyette et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; Surminski et al., 2016; Adiku et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jenkins et al., 2017; Jensen and Barrett, 2017)	🟫	(Mantilla et al., 2014; Coulibaly et al., 2015; Lobo et al., 2017)	🟧	(Berkes et al., 2000; Nakashima et al., 2012; Leonard et al., 2013; Hiwasaki et al., 2014; Ford et al., 2015; Hooli, 2016; Ruiz-Mallén et al., 2017; Russell-Smith et al., 2017; Ingty, 2017; Kihila, 2017; Magni, 2017; Mccubbin et al., 2017)
	Institutional capacity & Administrative feasibility	🟧	(Carey, 2008; IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Boughedir, 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Haeberli et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; van der Keur et al., 2016; Watanabe et al., 2016; Granderson, 2017; Haeberli et al., 2017; Kelman, 2017; Kita, 2017; Ruiz-Rivera and Lucatello, 2017; Serrao-Neumann et al., 2017; Wallace, 2017; Nahayo et al., 2018; Rosendo et al., 2018)	🟫	(Cook and Dowlatabadi, 2011; Weinhofer and Busch, 2013; Falco et al., 2014; Thornton and Herrero, 2014; García Romero and Molina, 2015; Greatrex et al., 2015; Joyette et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; Akter et al., 2016; Surminski et al., 2016; Adiku et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jenkins et al., 2017; Jensen and Barrett, 2017; Surminski and Eldridge, 2017)	🟧	(Dinku et al., 2014; Jancloes et al., 2014; Vaughan and Dessai, 2014; Wood et al., 2014; Vincent et al., 2015; Brasseur and Gallardo, 2016; Lourenço et al., 2016; Snow et al., 2016; Trenberth et al., 2016; Vaughan et al., 2016; Harjanne, 2017; Räsänen et al., 2017; Singh et al., 2017)	⬜	(Berkes et al., 2000; Nakashima et al., 2012; Hiwasaki et al., 2014, 2015; Oteros-Rozas et al., 2015; Ford et al., 2015; Johnson et al., 2015; Sherman et al., 2016; Mistry and Berardi, 2016; Fernández-Llamazares et al., 2017; Ruiz-Mallén et al., 2017; Russell-Smith et al., 2017; Williams et al., 2017; Granderson, 2017; Kihila, 2017; Magni, 2017)
	Transparency & accountability potential	🟧	(Carey, 2005; IPCC, 2012; Howes et al., 2015; Johnson and Abe, 2015; Kaya et al., 2016; Kita, 2017; Ruiz-Rivera and Lucatello, 2017; Rosendo et al., 2018)	🟧	(Thornton and Herrero, 2014; García Romero and Molina, 2015; Greatrex et al., 2015; Joyette et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Jin et al., 2016; Adiku et al.,	🟧	(Vaughan and Dessai, 2014; Harjanne, 2017; Hewitson et al., 2017)	🟧	(Berkes et al., 2000; Nakashima et al., 2012; Leonard et al., 2013; Green and Minchin, 2014; Hiwasaki et al., 2014; Ford et al., 2015; Johnson et al., 2015; Oteros-Rozas et al., 2015; Mistry and Berardi, 2016; Russell-Smith

		🟧		🟧	2017; Hansen et al., 2017; Jensen and Barrett, 2017)	🟧		🟧	et al., 2017; Magni, 2017; Rapinski et al., 2018)
Socio-cultural	Social co-benefits (health, education)	🟫	(IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Mawere and Mubaya, 2015; Samaddar et al., 2015; Archer, 2016; Haeberli et al., 2016; Kull et al., 2016; Rose, 2016; Watanabe et al., 2016; Brundiers, 2018; Nahayo et al., 2018)	🟧	(Panda et al., 2013; Thornton and Herrero, 2014; Greatrex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Adiku et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017)	🟧	(Rogers and Tsirkunov, 2010; Kadi et al., 2011; Hunt et al., 2017)	🟫	(Ford, 2012; Leonard et al., 2013; McNamara and Prasad, 2014; Ford et al., 2014; Green and Minchin, 2014; Cunsolo Willox et al., 2015; Durkalec et al., 2015; MacDonald et al., 2015a, 2015b; Harper et al., 2015; Hiwasaki et al., 2015; Mapfumo et al., 2016; Mistry and Berardi, 2016; Hooli, 2016; Magni, 2017; Kihila, 2017)
	Socio-cultural acceptability	🟫	(Carey, 2005; IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Anacona et al., 2015; Mawere and Mubaya, 2015; Samaddar et al., 2015; Archer, 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; van der Keur et al., 2016; Watanabe et al., 2016; de Leon and Pittock, 2017; Granderson, 2017; Kita, 2017; Serrao-Neumann et al., 2017)	🟧	(Bogale, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Jin et al., 2016; Adiku et al., 2017; Akter et al., 2017; Farzaneh et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017)	🟧	(Sivakumar et al., 2014; Vincent et al., 2015; Brasseur and Gallardo, 2016; Cortekar et al., 2016; Carr and Onzere, 2017; Singh et al., 2017; Webber and Donner, 2017; Guido et al., 2018)	🟫	(Natcher et al., 2007; Ford et al., 2010; Cunsolo Willox et al., 2012; Nakashima et al., 2012; Adger et al., 2013; Leonard et al., 2013; Green and Minchin, 2014; MacDonald et al., 2015a; Hiwasaki et al., 2015; Johnson et al., 2015; Mapfumo et al., 2016; Hooli, 2016; Tschakert et al., 2017; Kihila, 2017; Flynn et al., 2018)
	Social & regional inclusiveness	🟧	(Carey, 2005; IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Mawere and Mubaya, 2015; Samaddar et al., 2015; Archer, 2016; Kaya et al., 2016; Kull et al., 2016; Rose, 2016; Watanabe et al., 2016; de Leon and Pittock, 2017; Granderson, 2017; Kita, 2017; Nahayo et al., 2018)	⬜	(Falco et al., 2014; Bogale, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Joyette et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Akter et al., 2016; Jin et al., 2016; Surminski et al., 2016; Farzaneh et al., 2017; Hansen	🟧	Expert judgement (Sivakumar et al., 2014; Carr and Onzere, 2017; Webber and Donner, 2017)	🟫	(Berkes et al., 2000; Nakashima et al., 2012; Adger et al., 2013; Leonard et al., 2013; Green and Minchin, 2014; McNamara and Prasad, 2014; MacDonald et al., 2015a; Mistry and Berardi, 2016; Hooli, 2016; Nunn et al., 2017; Ruiz-Mallén et al.,

		🟧		⬜	et al., 2017; Jensen and Barrett, 2017; Shively, 2017)	🟧		🟫	2017; Ingty, 2017; Magni, 2017; Flynn et al., 2018)
	Intergenerational equity	🟧	(IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Mawere and Mubaya, 2015; Archer, 2016; Kaya et al., 2016; Granderson, 2017; Nahayo et al., 2018)	🟧	(Linnerooth-Bayer and Hochrainer-Stigler, 2015; O'Hare et al., 2016; Jensen and Barrett, 2017)	NA		🟫	(Berkes et al., 2000; Ford et al., 2010; Nakashima et al., 2012; Leonard et al., 2013; McNamara and Prasad, 2014; Hiwasaki et al., 2015; MacDonald et al., 2015a; Tschakert et al., 2017; Kihila, 2017; Magni, 2017; Nunn et al., 2017)
Environmental/ ecological	Ecological capacity	🟧	(IPCC, 2012; Mavhura et al., 2013; McNamara and Prasad, 2014; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Haeberli et al., 2016; Kull et al., 2016)	NA		NA		🟫	(Berkes et al., 2000; Forbes et al., 2009; Leonard et al., 2013; McNamara and Prasad, 2014; MacDonald et al., 2015b; Altieri and Nicholls, 2017; Russell-Smith et al., 2017; Tschakert et al., 2017; Ingty, 2017; Kihila, 2017; Magni, 2017; Nunn et al., 2017)
	Adaptive capacity/ resilience	🟫	(IPCC, 2012; Mavhura et al., 2013; Boeckmann and Rohn, 2014; McNamara and Prasad, 2014; Yu and Gillis, 2014; Anacona et al., 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Archer, 2016; Haeberli et al., 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; Watanabe et al., 2016; de Leon and Pittock, 2017; Granderson, 2017; Haeberli et al., 2017; Kelman, 2017; Wallace, 2017; Brundiers, 2018)	🟧	(Mills, 2007; Panda et al., 2013; Falco et al., 2014; Thornton and Herrero, 2014; Bogale, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Lashley and Warner, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Nicola, 2015; Wolfrom and Yokoi-Arai, 2015; Jin et al., 2016; O'Hare et al., 2016; Surminski et al., 2016; Adiku et al., 2017; Hansen et al., 2017; Jenkins et al., 2017; Jensen and Barrett, 2017)	🟧	(Jones et al., 2016b; Lourenço et al., 2016; Singh et al., 2017; White et al., 2017a)	🟫	(Berkes et al., 2000; Forbes et al., 2009; Ford et al., 2010; Nakashima et al., 2012; Leonard et al., 2013; McNamara and Prasad, 2014; Pearce et al., 2015; Hiwasaki et al., 2015; Savo et al., 2016; Sherman et al., 2016; Mapfumo et al., 2016; Altieri and Nicholls, 2017; Nunn et al., 2017; Russell-Smith et al., 2017; Kihila, 2017; Magni, 2017; Mccubbin et al., 2017)

Geophysical	Physical feasibility	🟧	(IPCC, 2012; McNamara and Prasad, 2014; Yu and Gillis, 2014; Anacona et al., 2015; Boughedir, 2015; Kelman et al., 2015; Archer, 2016; Diaz, 2016; Haeberli et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Haeberli et al., 2017)	NA		🟧	(Sivakumar et al., 2014; Snow et al., 2016; White et al., 2017a)	NE	
	Land use change enhancement potential	NA		🟧	(Panda et al., 2013; Annan and Schlenker, 2015; Greatrex et al., 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Hansen et al., 2017; Jenkins et al., 2017; Jensen and Barrett, 2017)	NA		🟫	(Berkes et al., 2000; Nakashima et al., 2012; Leonard et al., 2013; McNamara and Prasad, 2014; Pearce et al., 2015; Hiwasaki et al., 2015; MacDonald et al., 2015b; Reyes-García et al., 2016; Mistry and Berardi, 2016; Altieri and Nicholls, 2017; Kihila, 2017; Magni, 2017)
	Hazard risk reduction potential	🟫	(Carey, 2005, 2008; IPCC, 2012; Mavhura et al., 2013; Boeckmann and Rohn, 2014; McNamara and Prasad, 2014; Yu and Gillis, 2014; Anacona et al., 2015; Howes et al., 2015; Johnson and Abe, 2015; Kelman et al., 2015; Mawere and Mubaya, 2015; Boughedir, 2015; Archer, 2016; Kaya et al., 2016; Kull et al., 2016; Muñoz et al., 2016; Rose, 2016; Watanabe et al., 2016; Diaz, 2016; Haeberli et al., 2016, 2017; Kelman, 2017; Kita, 2017; Milner et al., 2017; Wallace, 2017; Brundiers, 2018)	🟧	(Mills, 2007; Falco et al., 2014; Annan and Schlenker, 2015; Linnerooth-Bayer and Hochrainer-Stigler, 2015; Wolfrom and Yokoi-Arai, 2015; García Romero and Molina, 2015; Greatrex et al., 2015; Lashley and Warner, 2015; Surminski et al., 2016; Jin et al., 2016; Patel et al., 2017; Surminski and Eldridge, 2017; Surminski and Thieken, 2017; Farzaneh et al., 2017; Glaas et al., 2017; Hansen et al., 2017; Jensen and Barrett, 2017)	🟫	(Rogers and Tsirkunov, 2010; Lourenço et al., 2016; Singh et al., 2017)	🟫	(Berkes et al., 2000; Nakashima et al., 2012; Leonard et al., 2013; Mistry and Berardi, 2016; Altieri and Nicholls, 2017; Magni, 2017; Nunn et al., 2017; Russell-Smith et al., 2017)

Supplementary Material 4.D.3.v, Table 2: Feasibility assessment of overarching adaptation options: Education and learning; Population health and health system adaptation; Social safety nets; and Human Migration. For methodology, see Supplementary Material 4.D.1.

		Education and learning		Population health and health system adaptation		Social safety nets		Human migration	
	Evidence	Medium		Medium		Medium		Medium	
	Agreement	High		High		Medium		Low	
Economic	Micro-economic viability	▨	(Rumore et al., 2016; Lutz and Muttarak, 2017)	■	(Toloo et al., 2013; Burton et al., 2014; Hoy et al., 2014; Paterson et al., 2014; Smith et al., 2014a; Confalonieri et al., 2015; Araos et al., 2016a; Hess and Ebi, 2016; Ebi and del Barrio, 2017; Gilfillan et al., 2017; Paavola, 2017)	▨	(Shiferaw et al., 2014; Devereux et al., 2015)	□	(Birk and Rasmussen, 2014; Betzold, 2015; Ionesco et al., 2016; Musah-Surugu et al., 2018)
	Macro-economic viability	▨	(Hoffmann and Muttarak, 2017; Lutz and Muttarak, 2017)	■	(Ebi et al., 2004; Hess et al., 2012; Hosking and Campbell-Lendrum, 2012; Bowen et al., 2013; Lesnikowski et al., 2013; Toloo et al., 2013; Hoy et al., 2014; Smith et al., 2014a; Austin et al., 2015; Watts et al., 2015; WHO, 2015; Araos et al., 2016a; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Gilfillan et al., 2017; Nitschke et al., 2017; Paavola, 2017)	▨	(Devereux et al., 2015)	▨	(Grecequet et al., 2017; Hino et al., 2017)
	Socio-economic vulnerability reduction potential	■	(Frankenberg et al., 2013; K.C., 2013; Striessnig et al., 2013; van der Land and Hummel, 2013; Muttarak and Lutz, 2014; Rumore et al., 2016; Hoffmann and Muttarak, 2017; Lutz and Muttarak, 2017)	■	(Ebi et al., 2004; Hess et al., 2012; Hosking and Campbell-Lendrum, 2012; Bowen et al., 2013; Panic and Ford, 2013; Toloo et al., 2013; Boeckmann and Rohn, 2014; Smith et al., 2014a; Austin et al., 2015; Confalonieri et al., 2015; Watts et al., 2015; WHO, 2015; Araos et al., 2016a; Benmarhnia et al., 2016; Ebi et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Ebi and Hess, 2017; Gilfillan	■	(Davies et al., 2013; Weldegebriel and Prowse, 2013; Berhane et al., 2014; Eakin et al., 2014; Leichenko and Silva, 2014; Devereux, 2016; Lemos et al., 2016; Godfrey-Wood and Flower, 2017; Schwan and Yu, 2017)	▨	(Birk and Rasmussen, 2014; Adger et al., 2015; Betzold, 2015; Grecequet et al., 2017; Melde et al., 2017; World Bank, 2017)

		🟫		🟫	et al., 2017; Nitschke et al., 2017; Paavola, 2017; Sen et al., 2017)	🟫		🟧	
	Employment & productivity enhancement potential	🟫	(van der Land and Hummel, 2013; Muttarak and Lutz, 2014; Lutz and Muttarak, 2017)	🟧	(Bowen et al., 2013; Toloo et al., 2013; Burton et al., 2014; Hoy et al., 2014; Smith et al., 2014a; Benmarhnia et al., 2016; Paz et al., 2016; Gilfillan et al., 2017; Nitschke et al., 2017)	🟧	(Davies et al., 2013; Berhane et al., 2014; Shiferaw et al., 2014)	NA	
		🟫		🟧		🟧			
Technological	Technical resource availability	▨	(Chaudhury et al., 2013; Baird et al., 2014; Cloutier et al., 2015; Rumore et al., 2016)	🟧	(Hess et al., 2012; Bowen et al., 2013; Lesnikowski et al., 2013; Panic and Ford, 2013; Toloo et al., 2013; Burton et al., 2014; Hoy et al., 2014; Paterson et al., 2014; Rumsey et al., 2014; Smith et al., 2014a; Austin et al., 2015; Confalonieri et al., 2015; WHO, 2015; Araos et al., 2016a; Benmarhnia et al., 2016; Ebi et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Ebi and Hess, 2017; Nitschke et al., 2017; Paavola, 2017; Sheehan et al., 2017)	🟧	(Kim and Yoo, 2015)	🟧	(Birk and Rasmussen, 2014; Gemenne and Blocher, 2017; Melde et al., 2017)
	Risks mitigation potential	🟫	(Wamsler et al., 2012; Frankenberg et al., 2013; K.C., 2013; Striessnig et al., 2013; van der Land and Hummel, 2013; Muttarak and Lutz, 2014; Harteveld and Suarez, 2015; Lutz and Muttarak, 2017)	🟫	Benmarhnia et al. 2016; Boeckmann and Rohn 2014; Hess and Ebi 2016; Nitschke et al. 2016; Paterson et al. 2014; Ebi and del Barrio 2017; Ebi and Hess 2017)	🟫	(Davies et al., 2013; Rurinda et al., 2014; Shiferaw et al., 2014; Devereux, 2016)	🟧	(Adger et al., 2015; Grecequet et al., 2017) (Tadgell et al., 2017)
Institutional	Political acceptability	LE	(Butler et al., 2015, 2016b; Cloutier et al., 2015)	🟫	(Hess et al., 2012; Bowen et al., 2013; Lesnikowski et al., 2013; Burton et al., 2014; Hoy et al., 2014; Rumsey et al., 2014; Smith et al., 2014a; Austin et al., 2015; Confalonieri et al., 2015; Watts et	🟧	(Porter et al., 2014; Rurinda et al., 2014; Wilhite et al., 2014; Brooks, 2015; Kim and Yoo, 2015; Ravi and	▨	(Kothari, 2014; Methmann and Oels, 2015; Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017; Yamamoto et al.,

				🟫	al., 2015; WHO, 2015; Araos et al., 2016a; Benmarhnia et al., 2016; Ebi et al., 2016; Hess and Ebi, 2016; Ebi and del Barrio, 2017; Gilfillan et al., 2017; Green et al., 2017; Sen et al., 2017)	🟧	Engler, 2015; Schwan and Yu, 2017)	░	2017; Matthews and Potts, 2018)
	Legal & regulatory acceptability	NE		🟫	(Hess et al., 2012; Lesnikowski et al., 2013; Burton et al., 2014; Austin et al., 2015; Watts et al., 2015; WHO, 2015; Araos et al., 2016a; Ebi et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Gilfillan et al., 2017; Shimamoto and McCormick, 2017)	🟧	(Rurinda et al., 2014; Devereux et al., 2015)	░	(Wilmsen and Webber, 2015; Tadgell et al., 2017; Ahmed, 2018; World Bank, 2018)
	Institutional capacity & Administrative feasibility	🟧	(Wamsler et al., 2012; Chaudhury et al., 2013; Odemerho, 2014; Cloutier et al., 2015; Butler et al., 2016b, 2016a)	🟧	(Ebi et al., 2004; Hess et al., 2012; Bowen et al., 2013; Lesnikowski et al., 2013; Panic and Ford, 2013; Toloo et al., 2013; Burton et al., 2014; Hoy et al., 2014; Nigatu et al., 2014; Paterson et al., 2014; Rumsey et al., 2014; Austin et al., 2015; Confalonieri et al., 2015; Watts et al., 2015; WHO, 2015; Araos et al., 2016a; Benmarhnia et al., 2016; Ebi et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Xiao et al., 2016; Ebi and del Barrio, 2017; Ebi and Hess, 2017; Gilfillan et al., 2017; Green et al., 2017; Nitschke et al., 2017; Sheehan et al., 2017; Shimamoto and McCormick, 2017)	🟧	(Davies et al., 2013; Rurinda et al., 2014; Wilhite et al., 2014; Ravi and Engler, 2015; Schwan and Yu, 2017)	░	(Betzold, 2015; Methmann and Oels, 2015; Brzoska and Fröhlich, 2016; Gemenne and Blocher, 2017; Grecequet et al., 2017; Yamamoto et al., 2017; Matthews and Potts, 2018; Thomas and Benjamin, 2018)
	Transparency & accountability potential	🟧	(Chaudhury et al., 2013; Odemerho, 2014; Ensor and Harvey, 2015; Harteveld and Suarez, 2015; Chung Tiam Fook, 2017; Myers et al., 2017; Flynn et al., 2018)	🟫	(Hess et al., 2012; Hosking and Campbell-Lendrum, 2012; Lesnikowski et al., 2013; Panic and Ford, 2013; Hoy et al., 2014; Boeckmann and Rohn, 2014; Austin et al., 2015; Araos et al., 2016a; Benmarhnia et al., 2016; Ebi et al.,	░	(Masud-All-Kamal and Saha, 2014; Devereux et al., 2015; Masiero, 2015; Ravi and Engler, 2015; Schwan and Yu, 2017)	░	(Methmann and Oels, 2015; Brzoska and Fröhlich, 2016; Tadgell et al., 2017)

		🟧		🟫	2016; Sheehan et al., 2017; Ebi and del Barrio, 2017; Ebi and Hess, 2017; Gilfillan et al., 2017)	░		░	
Socio-cultural	Social co-benefits (health, education)	🟫	(Wamsler et al., 2012; Frankenberg et al., 2013; K.C., 2013; van der Land and Hummel, 2013; Muttarak and Lutz, 2014; Chung Tiam Fook, 2017; Hoffmann and Muttarak, 2017; Lutz and Muttarak, 2017)	🟫	(Bowen et al., 2013; Hoy et al., 2014; Smith et al., 2014a; Austin et al., 2015; Confalonieri et al., 2015; Watts et al., 2015; Ebi et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Paavola, 2017; Shimamoto and McCormick, 2017)	🟧	(Berhane et al., 2014; Leichenko and Silva, 2014; Rurinda et al., 2014; Shiferaw et al., 2014; Verguet et al., 2015; Devereux, 2016; Lemos et al., 2016)	░	(Kothari, 2014; Bettini et al., 2016; Gioli et al., 2016; Bhagat, 2017; Melde et al., 2017; Schwan and Yu, 2017; World Bank, 2018)
	Socio-cultural acceptability	🟧	(Chaudhury et al., 2013; Sharma et al., 2013; Demuzere et al., 2014; Odemerho, 2014; Ensor and Harvey, 2015; Butler et al., 2016a; Myers et al., 2017; Flynn et al., 2018)	🟫	(Hess et al., 2012; Bowen et al., 2013; Toloo et al., 2013; Hoy et al., 2014; Smith et al., 2014a; Confalonieri et al., 2015; Watts et al., 2015; WHO, 2015; Ebi et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Nitschke et al., 2017; Sen et al., 2017)	LE	(Rurinda et al., 2014; Wilhite et al., 2014)	░	(Martin et al., 2014; Brzoska and Fröhlich, 2016; Jha et al., 2017; Kelman et al., 2017; Huntington et al., 2018)
	Social & regional inclusiveness	🟧	(Wamsler et al., 2012; Muttarak and Lutz, 2014; Suarez et al., 2014; Ensor and Harvey, 2015; Ford et al., 2016, 2018)	🟧	(Hosking and Campbell-Lendrum, 2012; Bowen et al., 2013; Panic and Ford, 2013; Toloo et al., 2013; Burton et al., 2014; Hoy et al., 2014; Smith et al., 2014a; Confalonieri et al., 2015; Watts et al., 2015; WHO, 2015; Benmarhnia et al., 2016; Ebi et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Paavola, 2017; Sen et al., 2017)	NA		🟧	(Kothari, 2014; Kelman, 2015; Schwan and Yu, 2017; Matthews and Potts, 2018; World Bank, 2018)
	Intergenerational equity	LE	(Striessnig et al., 2013)	🟫	(Ebi et al., 2004; Confalonieri et al., 2015; Benmarhnia et al., 2016; Ebi and del Barrio, 2017; Paavola, 2017)	NA		░	(Wilmsen and Webber, 2015)
Environmenta	Ecological capacity	NA		NA		NA		░	(Niven and Bardsley, 2013; Birk and Rasmussen, 2014)
	Adaptive capacity/resilience	🟫	(K.C., 2013; Sharma et al., 2013; Striessnig et al., 2013; Frankenberg et al., 2013;	🟫	(Hess et al., 2012; Toloo et al., 2013; Smith et al., 2014a; Confalonieri et al., 2015; Watts et al., 2015; WHO,	🟫	(Davies et al., 2013; Weldegebriel and Prowse, 2013; Eakin et	🟧	(Birk and Rasmussen, 2014; Adger et al., 2015; Grecequet et al., 2017;

		🟫	Baird et al., 2014; Lutz et al., 2014; Muttarak and Lutz, 2014; Suarez et al., 2014; Tschakert et al., 2014; Butler and Adamowski, 2015; Oteros-Rozas et al., 2015; Pearce et al., 2015; Ensor and Harvey, 2015; Janif et al., 2016; Butler et al., 2016b; Star et al., 2016; Vinke-de Kruijf and Pahl-Wostl, 2016; Butler et al., 2016a; Harvey et al., 2017; Hoffmann and Muttarak, 2017; Lutz and Muttarak, 2017; Myers et al., 2017; Chung Tiam Fook, 2017; Cochrane et al., 2017; Flynn et al., 2018; Ford et al., 2018)	🟫	2015; Benmarhnia et al., 2016; Hess and Ebi, 2016; Paz et al., 2016; Ebi and del Barrio, 2017; Nitschke et al., 2017; Paavola, 2017; Sen et al., 2017)	🟫	al., 2014; Rurinda et al., 2014; Shiferaw et al., 2014; Lemos et al., 2016; Schwan and Yu, 2017)	🟧	Melde et al., 2017; Tadgell et al., 2017; World Bank, 2018)
Geophysical	Physical feasibility	NA		NA		NA		⬜	(Niven and Bardsley, 2013; Hino et al., 2017; Matthews and Potts, 2018)
	Land use change enhancement potential	NA		NA		NA		LE	(Matthews and Potts, 2018)
	Hazard risk reduction potential	🟫	(Wamsler et al., 2012; Frankenberg et al., 2013; K.C., 2013; Striessnig et al., 2013; Muttarak and Lutz, 2014; Suarez et al., 2014; Harteveld and Suarez, 2015; Hoffmann and Muttarak, 2017; Lutz and Muttarak, 2017)	NA		🟫	(Jones et al., 2010; Davies et al., 2013)	🟧	(Birk and Rasmussen, 2014; Cattaneo and Peri, 2016; Grecequet et al., 2017; Tadgell et al., 2017; Crnčević and Orlović Lovren, 2018; World Bank, 2018)

Supplementary Material 4.E Adaptation and mitigation synergies and trade-offs as discussed in Section 4.5.4

Mitigation options may affect the feasibility of adaptation options, and the other way around. Supplementary Material 4.E.1, Table 1 provides examples of possible positive impacts (synergies) and negative impacts (trade-offs) of mitigation options for adaptation. Supplementary Material 4.E.2, Table 1 lists examples of synergies and trade-offs of adaptation options for mitigation.

Supplementary Material 4.E.1 Mitigation options with adaptation synergies and trade-offs

Supplementary Material 4.E.1, Table 1: Mitigation options with adaptation synergies and trade-offs identified

System	Mitigation option	Synergies	Trade-offs
Energy system transitions	Wind energy (on-shore & off-shore)	Resilience can be increased by wind, solar and bioenergy due to distributed grids (Parkinson and Djilali, 2015), given that energy security standards are in place (Almeida Prado et al., 2016). The use of residential batteries can increase resiliency, especially after extreme weather events (Qazi and Young Jr., 2014; Liu et al., 2017). A shift from coal-generated to natural gas-generated electricity could decrease water consumption (DeNooyer et al., 2016).	Renewable energy infrastructure that does not follow security standards can increase vulnerability (Ley, 2017).
	Solar PV		
	Bioenergy		
	Electricity storage		
	Power sector CCS	NE	Some renewable energy technologies, carbon dioxide capture and storage (CCS), and concentrating solar power (CSP) technologies have substantial water demand associated with their operation (Fricko et al., 2016). In particular, lower power plant efficiency due to CCS increases the vulnerability to water constraints in most regions (McCollum et al., 2013; van Vliet et al., 2016)
	Nuclear energy	Increased safety and protection standards can improve the climate risk profiles (Schneider et al., 2017).	Increased safety and protection standards will increase costs making some electricity systems less reliable (Jacobson and Delucchi, 2009; Lovins et al., 2018).
Land & ecosystem transitions	Reduced food wastage & efficient food production	Reducing food loss and waste can decrease pressure of deforestation (FAO, 2013a), pressure on land use for agriculture (Foley et al., 2011; Hiç et al., 2016), and provide long-term food security (Bajželj et al., 2014).	NA
	Dietary shifts	Shift from animal- to plant-related diets can significantly decrease land use and biodiversity loss due to a decrease in pressure on land use by livestock production (Newbold et al., 2015; Ramankutty et al., 2018;	Shift from animal- to plant-related diets will require improvement of mixed crop-livestock systems, which are more difficult to manage well and need and higher capital to be

		Sparovek et al., 2018) along with health benefits (Tilman and Clark, 2014; Westhoek et al., 2014; Hallström et al., 2017; Song et al., 2017).	established (Ramankutty et al., 2018)
	Sustainable intensification of agriculture	Agroforestry practices increase soil carbon stocks and above-ground biomass as well as diversify incomes, reducing financial risk, and provide shade for protection from rising temperatures (Harvey et al., 2014). Agroforestry can sustain or increase food production in some systems, increasing farmers' resilience to climate change (Jones et al., 2012). Mixed agroforestry systems may simultaneously meet the water, food, energy and income needs of densely populated rural and peri-urban areas (van Noordwijk et al., 2016).	Sustainable intensification can increase offsite impacts from fertiliser, herbicide and pesticide use (Stevens and Quinton 2009), increase costs and increase climate risk. No-tillage without pairing with other agronomic practices can reduce crop yields. No till agriculture can reduce GHG emissions but increase pesticide concentrations (Stevens and Quinton, 2009) Adaptation gains made through improved irrigation efficiency can be undermined by shifts to water-intensive crops for mitigation (e.g. shifting to bioenergy crops) (Chaturvedi et al., 2015) Conservation agriculture agricultural reduces yields 3–5 years after adoption, but enhances productivity and carbon sequestration over longer periods (Harvey et al., 2014). Agroforestry can, in some dry environments, increase competition with crops and pastures decreasing productivity and reduce catchment water yield (Schrobback et al., 2011). Fast-growing tree monocultures or biofuel crops may enhance carbon stocks but reduce downstream water availability and decrease availability of agricultural land (Harvey et al., 2014). Agricultural intensification that improves crop productivity can increase incomes but undermine local livelihoods and wellbeing as seen in shifts to intensified sugarcane production in Ethiopia or more intensive land use in Southeast Asia (Liao and Brown, 2018).
	Ecosystem restoration	Sustainable water management – restored/healthy ecosystems provide water storage, and filtration services (Jones et al., 2012). Restoration of mangroves and coastal wetlands to sequester (blue) carbon increases carbon sinks, reduces coastal erosion, and protects from storm surges and otherwise mitigates impacts of sea level rise and	A focus on mitigation, e.g. through REDD+, can result in conservation-priority sites with lower carbon densities to end up without REDD+ protection (Phelps et al., 2012; Murray et al., 2015; Reside et al., 2017a; Turnhout et al., 2017). Potential conflict with biodiversity goals in habitat restoration

		extreme weather along the coast line (Alongi, 2008; Siikamäki et al., 2012; Romañach et al., 2018). Blue biofuels do not compete for land, water and are not global food staples (posing less of a food security issue). Most farms do not use fertilizer and could even remove excess nutrients, decreasing eutrophication (Turner et al., 2009; Duarte et al., 2013). Stabilization and support of fisheries can add value to marine biodiversity (Turner et al., 2009). Carbon offset funds provide opportunities for protection and restoration of native ecosystems, with corresponding gains for biodiversity and reductions in carbon (Reside et al., 2017). Coupled with biodiversity and conservation interventions, ecosystem restoration and avoided deforestation can complement habitat provision (Felton et al., 2016). Forests (through REDD+) can support economies dependent on climate-sensitive sectors including agriculture, fisheries, and energy (Somorin et al., 2016; Few et al., 2017). REDD+ has the potential to promote sustainable development activities through the cash-flow from donors/international funds to local forest stakeholders (West, 2016) Tropical reforestation for climate change mitigation can help to protect rural economies from impacts of climate variation, reduce impacts of climatic variation on water cycle and associated human uses, reduce local impacts of extreme weather events and reduce climate impacts on biodiversity (Locatelli et al., 2015a).	and forest production efforts (Felton et al., 2016) Some projects world-wide do not target REDD+ projects on adaptation or resilience, nor local contexts, in some cases leaving negative livelihoods impacts (McElwee et al., 2016; Few et al., 2017). In some cases, there is a perception of the inability to reconcile development and environmental interests (Pham et al., 2017). Local benefits, especially for indigenous communities, will only be accrued if land tenure is respected and legally protected, which is not often the case for Indigenous communities (Brugnach et al., 2017).
	Novel technologies	Breeding animals with lower emissions per unit of dry matter intake can reduce GHG emissions; when integrated within broader breeding programmes, can offer synergies with breeding for improved adaptation to local conditions (Pickering et al., 2015; Nguyen et al., 2016)	May have consumer health concerns that need evaluation and addressing (Barrows et al., 2014; Fraser et al., 2016).

Urban & infrastructure system transitions	Land-use & urban planning	Potential for synergies in urban planning at policy, organizational, and practical levels (e.g. urban regeneration, retrofitting, urban greening) (Landauer et al., 2015). Spatial planning can enhance adaptation, mitigation, and sustainable development (Hurlimann and March, 2012; Davidse et al., 2015; King et al., 2016; Francesch-Huidobro et al., 2017). Through the use of integrated approaches there is potential synergy in land use planning (e.g. maintenance of urban forests, urban greening) (Newman et al., 2017). Urban densification to reduce emissions can go along with regenerative qualities for green spaces, reduced urban heat island and flooding impacts by employing biophilic urbanism design (Beatley, 2011; Newman et al., 2017).	Potential conflicts including urban densification to reduce emissions which can intensify heat island effect and increase surface run-off, and may compete with a desire to expand green space, restore local ecosystems, (Landauer et al., 2015; Di Gregorio et al., 2017b; Endo et al., 2017; Ürge-Vorsatz et al., 2018) though demonstrations of biophilic urbanism show this can be managed (Beatley, 2011; Newman et al., 2017). In water-scarce regions, there may be trade-offs between mitigation measures that require water – such as localized cooling – and the population's water needs (Georgescu et al., 2015).
	Sustainable and resilient transport systems	Cities can re-urbanise in ways that promote transport sector adaptation and mitigation (Newman et al., 2017; Salvo et al., 2017; Gota et al., 2018). Cities that reduce the use of private cars, and develop sustainable transport systems can simultaneously benefit from reduced air pollution, congestion and road fatalities while reducing overall energy intensity in the urban transport sector (Goodwin and Van Dender, 2013; Newman and Kenworthy, 2015; Wee, 2015). Non-motorized transport use is associated with lower emissions and better public health in cities. Urbanisation and improved access to basic services correlate with lower short-term morbidity (STM), such as fever, cough and diarrhea (Ahmad et al., 2017). Promoting energy-efficient mobility systems, for instance by a 10% increase in bicycling, could lower chronic conditions like diabetes and cardio-vascular diseases for 0.3 million people while also abating emissions. (Ahmad et al., 2017).	In middle and low income countries urban density of informal settlements is typically associated with a range of water and vector-borne health risks that undermine benefits of energy efficiency, may provide a notable exception to the adaptive advantages of urban density (Mitlin and Satterthwaite, 2013; Lilford et al., 2017) unless new approaches using leapfrog technology are used to upgrade slums in situ (Teferi and Newman, 2017).
	Sharing schemes in transportation	Greater use of sharing schemes can make transport out of vulnerable areas more equitable and ordered (Gomez et al., 2015; Ambrosino et al., 2016; Kent and Dowling, 2016).	Highly ICT dependent sharing schemes may not be resilient during disasters, but this can be managed via local shared

			mobility systems related to local social capital (Mathbor, 2007; Bhakta Bhandari, 2014; McCloud et al., 2014).
	Public transport	Greater use of public transport enables more mass exit strategies from disasters (Wolshon et al., 2013).	Highly ICT dependent public transport may not be resilient during disasters but this can be managed via local shared mobility systems related to local social capital (Mathbor, 2007; Bhakta Bhandari, 2014; McCloud et al., 2014).
	Smart grids	Greater resiliency in electricity due to system feedback to damaged areas and other grid enhancements due to more localised data (Blaabjerg et al., 2004; IRENA, 2013; IEA, 2017c; Majzoobi and Khodaei, 2017).	NA
	Efficient appliances	Energy efficiency appliances (including lighting and ICT) reduce energy consumption and improve grid reliability (Chaturvedi and Shukla, 2014). They can provide demand response to absorb variation in the electricity supply due to disruption. In addition, when coupled with PV and storage, efficient appliances can secure energy supply when energy network are down due to storm, hurricane and other climate induced events.	NA
	Low/zero-energy buildings	Building codes not only improve energy efficiency through insulation and air-tightness in buildings, but also make buildings more capable of maintaining indoor temperature during heatwave or power losses, shelter people for heat waves and provide structural capability to withstand extreme weather and flooding (Houghton, 2011; King et al., 2016). Other examples of synergies are green roofs that provide both insulation, cooling and rain water harvesting (Razzaghmanesh et al., 2016).	NE
Industrial system transitions	Energy efficiency	Reduced competition for resources (Hennessey et al., 2017)	Water -energy tradeoffs exist in the production process adjustment, which is conventionally promoted as a key energy-saving measure in iron and steel industry (Wang et al., 2017a).
	Bio-based & circularity	Reduced competition for resources (Hennessey et al., 2017) Biomass production for industry, if well managed, can diversify local livelihoods, enhance incomes and strengthen local institutions (Locatelli et al., 2015a).	NE
	Electrification & hydrogen	NA	Greater reliance on variable and weather-dependent sources of electricity (Philibert, 2017)
	Industrial CCUS	NA	Cooling requirements for CO_2 capture put pressure on adaptation (Magneschi et al., 2017)
Carbon dioxide	Bioenergy with CCS	Bioenergy if well managed can diversify local livelihoods, enhance incomes and strengthen local institutions (Locatelli et al., 2015a).	Bioenergy plantations can decrease food security, compete for land and provide short-term benefits for only a few stakeholders

removal	(BECCS)	Combining BECCS with soil carbon management, agroforestry and afforestation can remove CO_2, while limiting adverse impacts on water, food and biodiversity (Burns and Nicholson, 2017; Stoy et al., 2018).	(Locatelli et al., 2015b).
	Afforestation & reforestation	Reforestation connecting fragmented forests reduces exposure to forest edge disturbances (Pütz et al., 2014). Reforestation and coastal restoration are associated with improved water filtration, ground water recharge and flood control (Ellison et al., 2017; Griscom et al., 2017) Reduce flooding through decreased peak river flow, improved water quality and groundwater recharge (Berry et al., 2015) Increase diversity and habitat availability (when properly managed) (Berry et al., 2015) Tree planting led to more resilient livestock by providing shade and shelter (Hayman et al., 2012) Forestry if well managed can diversify local livelihoods, enhance incomes and strengthen local institutions (Locatelli et al., 2015b) Afforestation of degraded areas can produce large synergies between mitigation and adaptation through their impact on farmer livelihoods (Rahn et al., 2014).	Water - increase water demand reducing catchment yield (Berry et al 2014) Biodiversity - species and habitat loss due to monocultures, chemical inputs or forest management (Berry et al., 2015) Loss of agricultural land (Berry et al., 2015) Forest plantations can decrease food security, compete for land and provide short-term benefits for only a few stakeholders (Locatelli et al., 2015b). Local benefits, especially for indigenous communities, will only be accrued if land tenure is respected and legally protected, which is not often the case for Indigenous communities (Brugnach et al., 2017).
	Soil carbon sequestration & biochar	With agroforestry, CO_2 is sequestered in trees and soils additionally planted, while tree products provide livelihood to communities (Verchot et al., 2007; Nair et al., 2009; Branca et al., 2013; Lasco et al., 2014; Mbow et al., 2014a; Smith et al., 2014b) Soil organic carbon may foster crop resilience to climate change (Aguilera et al., 2013). Biochar application to soil sequesters CO_2 and at the same time increases crop productivity by up to 10% (Jeffery et al., 2011) and can improve the soil's water balance (Bamminger et al., 2016).	Biochar amendments lead to plant growth and thus, may down-regulate plant defense genes increasing the vulnerability against insects, pathogens, and drought (Viger et al., 2015).
	Enhanced weathering	NE	Potential adverse health effects because of air particles (Taylor et al., 2016)

Supplementary Material 4.E.2 Adaptation options with mitigation synergies and trade-offs

Supplementary Material 4.E.2, Table 1: Adaptation options with mitigation synergies and trade-offs identified

System	Adaptation option	Synergies	Trade-offs
Energy system transitions	Power infrastructure, including water	Some adaptation options can help improve system efficiency and reliability (Cortekar and Groth, 2015; van Vliet et al., 2016) Synergies with Sustainable Development Goals, poverty, and well being (Dagnachew et al., 2018; Fuso Nerini et al., 2018; Gi et al., 2018).	A shift from open-loop to closed-loop cooling technologies could decrease withdrawals, with the trade-off of increasing water consumption for power generation (DeNooyer et al., 2016)
Land & ecosystem transitions	Conservation agriculture	Agro-ecological practices can reduce farm-scale carbon footprint significantly (Rakotovao et al., 2017). Practices such as improved soil conservation practices in coffee agroforestry systems and improved slash and mulch agroforestry in bean-maize cultivation, have low carbon footprint reduction potential (CFRP) and medium carbon sequestration potential (CSP) (Rahn et al., 2014). Land and water management adaptation measures have mitigation co-benefits through soil/atmospheric carbon sequestration, reduced emissions, soil nitrification and reduced use of inorganic fertilisers (Chandra et al., 2016). Conservation agriculture agricultural reduces yields 3–5 years after adoption, but enhances productivity and carbon sequestration over longer periods (Harvey et al., 2014). For conservation agriculture and efficient irrigation, synergies are regionally differentiated: (Lobell et al., 2013).	Technologies enhancing farm productivity (such as adding fertilizers) might improve adaptive capacity through higher incomes but at the same time drive GHG emissions (Harvey et al., 2014; Thornton et al., 2017). In some cases, conservation agriculture practices can increase emissions (Gupta et al., 2016).
	Efficient irrigation	Improving irrigation efficiency have adaptation and mitigation co-benefits (Zou et al., 2012; Adenle et al., 2015; Suckall et al., 2015; Win et al., 2015). Efficient irrigation practices such as drip-irrigation has, on average, 80% lower N_2O emissions than sprinkler systems. Drip-irrigation combined with optimized fertilization reduces direct N_2O emissions up to 50% (Sanz-Cobena et al., 2017). Solar-powered drip irrigation significantly increases household income and	Micro-irrigation technologies such as drip and sprinkler irrigation increase irrigation efficiency but increase energy demand (Rasul and Sharma, 2016). Biomass production for biofuels may contribute to regional water shortages, salinization and water logging (Beringer et al., 2011).

		nutritional intake, enable households to meet daily water needs, and save 0.86 tons of carbon emissions each year against a liquid fuel (e.g. kerosene) alternative (Suckall et al., 2015).	
	Efficient livestock	Strong synergies between climate change adaptation and mitigation in the livestock sector (Weindl et al., 2015; Rivera-Ferre et al., 2016) but these are differentiated by region and type of livestock system (Locatelli et al., 2015b; Thornton et al., 2017). For example, shifting from grazing to mixed livestock systems increase productivity while reducing GHG emissions, by gains in feed and forage productivity through more intensive inputs and management (Rivera-Ferre et al., 2016). Shifting towards mixed crop-livestock systems is a resource- and cost-efficient option (Herrero et al., 2015; Weindl et al., 2015; Thornton et al., 2018). Reducing livestock diseases can improve the productivity of livestock systems and increase their resilience to stresses while reducing the emissions intensity of livestock production (Bartley et al., 2016; FAO & NZAGRC, 2017). Adaptation through livestock supplementation and reducing stocking densities can reduce methane emissions (Locatelli et al., 2015b). Improved grassland management and appropriate stocking density can help to increase soil carbon stocks (Rivera-Ferre et al., 2016; Thornton et al., 2017).	Increased productivity of livestock systems generally increases overall food production and absolute GHG emissions, albeit at lower emissions per unit of food (Gerber et al., 2013; FAO & NZAGRC, 2017). Shifting to rangeland for feed can strongly increase tropical deforestation (Weindl et al., 2015). Shifting to mixed crop-livestock systems is expected to cause additional GHG emissions (Weindl et al., 2015),. Providing cooling and ventilation systems for livestock (as an adaptation to higher temperatures) can increase GHG emissions (Locatelli et al., 2015b). Some adaptation options such as inter-regional livestock trading can increase CO_2 emissions through transportation (Rivera-Ferre et al., 2016).
	Agroforestry	Sequesters carbon through accumulation in woody biomass and soil (Lasco et al., 2014) Reduce GHG emission through reduced deforestation and fossil fuel consumption (Lasco et al., 2014) Coupling native forest regeneration in concert with sugarcane bioethanol production can significantly increase carbon storage in the bioenergy production system and preserve biodiversity (Rodrigues et al., 2009; Buckeridge et al., 2012). The use of fertilizer trees can improve soil fertility through nitrogen fixation, by increasing supply of nutrients for crop production (Coulibaly et al., 2017). Integrating crop, livestock and forestry systems – like in Brazil (Gil et al.,	Lower carbon sequestration potential compared with natural forest and secondary forest (Lasco et al., 2014)

		2015) – can come with significant benefits for local farmers and ecosystems, e.g. by rehabilitation of degraded pasturelands, which can decrease emissions as well.	
	Food loss & waste management	Waste materials can be transformed into products with marketable value (Papargyropoulou et al., 2014), improving economic gain and stimulating decrease of food waste and loss.	NA
	Community-based adaptation	NE – Most literature addresses synergies with sustainable development, poverty and equity	NE - Most literature addresses trade-offs with sustainable development, poverty and equity
	Ecosystem restoration & avoided deforestation	Tropical reforestation as an adaptation measure can also result in significant carbon storage under climate-smart strategies (Locatelli et al., 2015a). Habitat restoration, afforestation & reforestation and urban trees and greenspace all lead to carbon sequestration as well (Berry et al., 2015)	Failure to consider mitigation in adaptation initiatives may lead to adaptation measures that increase greenhouse gas emissions, which is one type of maladaptation.(Porter and Xie, 2014; Kongsager et al., 2016)
	Biodiversity management	Biodiversity has value in terms of ecosystem services as well protection/defence against invading species and disease organisms. Maintaining for high levels of biodiversity also recognises the fact that many species, biological processes and molecules in nature are as yet unexplored yet have potential to provide enormous benefits to human beings (Knowlton et al., 2010; Pereira et al., 2010; Onaindia et al., 2013; Pistorious and Kiff, 2017; Price et al., 2018).	Areas with greatest potential for protecting biodiversity may not overlap with areas with most potential for carbon sequestration (Essi and Mauerhofer 2018(Phelps et al., 2012)).
	Coastal defense & hardening	NE	An alternative strategy is not to ‘defend’ using harden structures along coastlines, but rather to retreat as sea levels rise and storm surge goes further inland. The strategy of ‘retreat’ tends to make economic sense while at the same time accommodating the transition from terrestrial to marine systems (e.g. migration of salt marsh, mangroves and seagrass towards the land as sea levels rise (Brown et al., 2016a; Mills et al., 2016). There has been an increasing focus on natural barriers to storm surge and erosion, such as mangroves, oyster banks, coral reefs and seagrass meadows. Within these broad options, there are trade-offs that involve direct human intervention (e.g. coastal hardening, seawalls and artificial reefs) (Rinkevich, 2014, 2015; André et al., 2016; Cooper et al., 2016; Narayan et al., 2016), while there are others that exploit the opportunities for increasing coastal protection by involving a naturally occurring oyster banks, coral reefs, mangroves, seagrass, and other ecosystems (UNEP-WCMC, 2006; Scyphers et al.,

			2011; Zhang et al., 2012; Ferrario et al., 2014; Cooper et al., 2016). Protection using materials such as concrete to provide a barrier against the ocean. These structures can be installed quickly but the trade-off is that they have a range of negative consequences such as being expensive, interrupting natural ecosystems (Mills et al., 2016; Wernberg et al., 2016), being ultimately short-term solutions to the long-term problem of sea level rise and intensifying storm systems (Brooke et al., 1992; Wescott, 2010; Mills et al., 2016).
	Sustainable aquaculture	NE	Regulating and avoiding next loss of coastal ecosystems such as mangroves and seagrass, while the same time as developing food materials that have much lower impact on the environment (Schlag, 2010; Asiedu et al., 2017b, 2017a).
	Fisheries restoration	Development of more sustainable practices also has benefits for ocean ecosystems in general. Fish play a crucial role in everything from maintaining ecological balances through their feeding habits to playing important roles within nutrient cycles in a range of habitats (Holmlund and Hammer, 1999).	NE
	Coastal & marine biodiversity management	NE	Planning for multiple objectives (e.g. biodiversity protection and carbon sequestration) increases the complexity of planning processes and data needs, an accompanying increase in technical capacity by planners (Reside et al., 2018)
	Integrated coastal zone management	Mangroves serve as sinks for carbon, through accumulation of living biomass and through litter and dead wood deposition, including the trapping of sediments delivered from the uplands (Romañach et al., 2018).	NE
Urban & infrastructure system transitions	Sustainable land-use & urban planning	Potential for synergies in urban planning at policy, organizational, and practical levels e.g. urban regeneration or retrofitting policies, urban greening (Landauer et al., 2015; Ürge-Vorsatz et al., 2018), including generating a shared sense of risks and promotion of local participation (Archer et al., 2014; Kettle et al., 2014; Campos et al., 2016; Siders, 2017)) Urban planning can enhance adaptation, mitigation, and sustainable development (Hurlimann and March, 2012; Davidse et al., 2015; King et al., 2016; Francesch-Huidobro et al., 2017). Land use management for co-benefits can result in carbon sequestration (Duguma et al., 2014; Woolf et al., 2018)	Promotion of green spaces to reduce flood risk and heat island effects may reduce potential for the promotion of urban densification (Landauer et al., 2015; Di Gregorio et al., 2017b; Endo et al., 2017; Ürge-Vorsatz et al., 2018).
	Sustainable	Strong co-benefits to the implementation of demand-side management	Increasing water quality is linked to increasing energy use in the

	water management	measures, such as reducing leakages and water loss (Wang et al., 2011; Deng and Zhao, 2015), while minimizing the need to address the environmental and energy implications of supply measures such as desalination (Miller et al., 2015)	water sector (Rothausen and Conway, 2011; Mamais et al., 2015),
	Green infrastructure & ecosystem services	Urban canopy is a cooling mechanism that can help decrease heat and water stress (Hines, 2017)	Not considering the role green cover and vegetation has within the heat-water-vegetation nexus can worsen heat and water stress (Hines, 2017)
	Building codes & standards	Sustainable construction materials, reduced building energy consumption, and construction designed to reduce the urban heat island effect can have adaptation and mitigation benefits (Steenhof and Sparling, 2011; Aerts et al., 2014; Stewart, 2015; Shapiro, 2016; Ürge-Vorsatz et al., 2018)	NE
Industrial system transitions	Intensive industry infrastructure resilience and water management	Some adaptation options can help improve system efficiency when implementing water management and cooling practices.	NE
Overarching adaptation options	Disaster risk management	Incorporating environmental considerations into recovery decision-making (Amin Hosseini et al., 2016), implementing disaster risk management plans and increasing ex-ante resilience to disasters are important to reduce the extent of rebuilding following disasters, and the emissions associated with recovery. Post-disaster recovery can help rebuild in a more resilient way with less GHG emissions, or to "build back better", particularly where immediate impact is substantial but not overwhelming (Guarnacci, 2012; Mochizuki and Chang, 2017). Effective disaster risk management may reduce the need for international transport of materials and other forms of aid, which can be emissions-intensive (Abrahams 2014).	The urgency of recovery and the surge in demand for construction materials have been observed to promote unsustainable behaviours, including deforestation (Nazara and Resosudarmo, 2007; Chang et al., 2010) or uncontrolled extraction of sand and gravel (Abrahams, 2014). 'Building back better' requires capacity, time, and mechanisms for balancing competing desires and perspectives that are not necessarily available after severe disasters, and may be challenged by both local and external influences in the rebuilding process (Abrahams, 2014; O'Hare et al., 2016; Paidakaki and Moulaert, 2017).
	Risk spreading and sharing	In response to the substantial risk posed to the insurance industry by climate change (Bank of England, 2015; Glaas et al., 2017), insurance companies are mobilizing their role as investment manager to promote climate mitigation; for example, in 2014, insurance companies pledged to invest USD 420 billion over five years in renewable energy, energy efficiency, and sustainable agriculture projects (Fabian, 2015; Webster and Clarke, 2017).	Agricultural insurance may have unintended impacts, promoting the intensification of land use in some cases (Annan and Schlenker, 2015; Müller and Kreuer, 2016; Müller et al., 2017).
	Climate	Climate services aid adaptation decision-making and can help mitigate GHGs	NE

	services	through improving farm practices (e.g. matching fertilizer use with existing weather conditions so that less GHGs are emitted) (Thornton et al., 2017).	
	Indigenous knowledge	Revitalization of traditional management of agriculture may simultaneously increase resilience, improve biodiversity, and reduce emissions by eliminating agrochemical inputs production to food production (Nyong et al., 2007; Niggli et al., 2009; Altieri and Nicholls, 2017). Recognizing and supporting Indigenous management of blue carbon habitats (Vierros, 2017) and grasslands (Dong, 2017; Russell-Smith et al., 2017), and utilizing new technologies to revitalize traditional forms of energy provision (Thornton and Comberti, 2017), can provide mitigation and adaptation benefits.	Projects that use a single dimension of Indigenous knowledge (e.g. savannah burning for carbon sequestration) without considering the full context of that knowledge risk limiting associated adaptation-mitigation synergies and losing the complexities of Indigenous knowledge systems (Mistry et al., 2016).
	Population health and health system	Forest retention and urban agricultural land are forms of urban green infrastructure that can simultaneously mediate floods, promote healthy lifestyles, and reduce emissions and air pollution. (Nowak et al., 2006; Tallis et al., 2011; Elmqvist et al., 2013a; Buckeridge, 2015; Culwick and Bobbins, 2016; Panagopoulos et al., 2016; Stevenson et al., 2016; White et al., 2017b)	The use of air conditioners to meet health standards could result in increased emissions (Ürge-Vorsatz et al., 2018).
	Social safety nets	Public work programmes structured to address climate risks, for instance, Ethiopia's Productive Safety Net Programme has been used to employ locals suffering from food insecurity to work on water-shed management interventions, sequestering carbon in the soil and reducing greenhouse gas emissions (Jirka et al., 2015).	Where cash transfers to households to build adaptive capacity are not conditional, limited increases in purchasing power can prompt families to invest in additional consumption, transport, or agricultural equipment as part of a general risk reduction strategy (Lemos et al., 2016; Nelson et al., 2016); Aggregated, these individual investments could lead to increased emissions.

References

Abanades, J.C., M. Alonso, and N. Rodríguez, 2011: Biomass combustion with in situ CO_2 capture with CaO. I. process description and economics. *Industrial and Engineering Chemistry Research*, **50(11)**, 6972-6981, doi:10.1021/ie102353s.

Abanades, J.C. et al., 2015: Emerging CO_2 capture systems. *International Journal of Greenhouse Gas Control*, **40**, 126-166, doi:10.1016/j.ijggc.2015.04.018.

Abdulai, I. et al., 2018: Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. *Global Change Biology*, **24(1)**, 273-286, doi:10.1111/gcb.13885.

Abi Ghanem, D. and S. Mander, 2014: Designing consumer engagement with the smart grids of the future: bringing active demand technology to everyday life. *Technology Analysis & Strategic Management*, **26(10)**, 1163-1175, doi:10.1080/09537325.2014.974531.

Abrahams, D., 2014: The barriers to environmental sustainability in post-disaster settings: a case study of transitional shelter implementation in Haiti. *Disasters*, **38(s1)**, S25-S49, doi:10.1111/disa.12054.

ACOLA, 2017: *The Role of Energy Storage in Australia's Future Energy Supply Mix*. Australian Council of Learned Academics, Melbourne, VIC, 158 pp.

Adenle, A.A., H. Azadi, and J. Arbiol, 2015: Global assessment of technological innovation for climate change adaptation and mitigation in developing world. *Journal of Environmental Management*, **161**, 261-275, doi:10.1016/J.JENVMAN.2015.05.040.

Adger, W.N., J. Barnett, K. Brown, N. Marshall, and K. O'Brien, 2013: Cultural dimensions of climate change impacts and adaptation. *Nature Climate Change*, **3(2)**, 112-117, doi:10.1038/nclimate1666.

Adger, W.N. et al., 2015: Focus on environmental risks and migration: causes and consequences. *Environmental Research Letters*, **10(6)**, 60201, doi:10.1088/1748-9326/10/6/060201.

Adhikari, P. et al., 2018: System of crop intensification for more productive, resource-conserving, climate-resilient, and sustainable agriculture: experience with diverse crops in varying agroecologies. *International Journal of Agricultural Sustainability*, **16(1)**, 1-28, doi:10.1080/14735903.2017.1402504.

Adhikari, S. et al., 2018: Adaptation and Mitigation Strategies of Climate Change Impact in Freshwater Aquaculture in some states of India. *Journal of FisheriesSciences.com*, **12(1)**, 16-21.

Adiku, S.G.K., E. Debrah-Afanyede, H. Greatrex, R.B. Zougmoré, and D.S. MacCarthy, 2017: Weather-index based crop insurance as a social adaptation to climate change and variability in the Upper West Region of Ghana: Developing a participatory approach.

Aerts, J.C.J.H. et al., 2014: Evaluating Flood Resilience Strategies for Coastal Megacities. *Science*, **344(6183)**, 473-475, doi:10.1126/science.1248222.

Agee, E.M., A. Orton, E.M. Agee, and A. Orton, 2016: An Initial Laboratory Prototype Experiment for Sequestration of Atmospheric CO 2. *Journal of Applied Meteorology and Climatology*, **55(8)**, 1763-1770, doi:10.1175/JAMC-D-16-0135.1.

Agoramoorthy, G., M.J. Hsu, S. Chaudhary, and P.–C. Shieh, 2009: Can biofuel crops alleviate tribal poverty in India's drylands? *Applied Energy*, **86**, S118-S124, doi:10.1016/J.APENERGY.2009.04.008.

Aguilera, E., L. Lassaletta, A. Gattinger, and B.S. Gimeno, 2013: Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, Ecosystems & Environment*, **168**, 25-36, doi:10.1016/j.agee.2013.02.003.

Aha, B. and J.Z. Ayitey, 2017: Biofuels and the hazards of land grabbing: Tenure (in)security and indigenous farmers' investment decisions in Ghana. *Land Use Policy*, **60**, 48-59, doi:10.1016/J.LANDUSEPOL.2016.10.012.

Ahlfeldt, G. and E. Pietrostefani, 2017: *Demystifying Compact Urban Growth: Evidence From 300 Studies From Across the World*. Coalition for Urban Transitions, OECD, 1-84 pp.

Ahmad, S., S. Pachauri, and F. Creutzig, 2017: Synergies and trade-offs between energy-efficient urbanization and health. *Environmental Research Letters*, **12(11)**, 114017, doi:10.1088/1748-9326/aa9281.

Ahmad, S., R. Avtar, M. Sethi, and A. Surjan, 2016: Delhi's land cover change in post transit era. *Cities*, **50**, 111-118, doi:10.1016/j.cities.2015.09.003.

Åhman, M., L.J. Nilsson, and B. Johansson, 2016: Global climate policy and deep decarbonization of energy-intensive industries. *Climate Policy*, **17(5)**, 634-649, doi:10.1080/14693062.2016.1167009.

Ahmed, B., 2018: Who takes responsibility for the climate refugees? *International Journal of Climate Change Strategies and Management*, **10(1)**, 5-26.

Ahmed, N., S.W. Bunting, S. Rahman, and C.J. Garforth, 2014: Community-based climate change adaptation strategies for integrated prawn-fish-rice farming in Bangladesh to promote social-ecological resilience. *Reviews in Aquaculture*, **6(1)**, 20-35, doi:10.1111/raq.12022.

Ahmed, N., J.D. Ward, S. Thompson, C.P. Saint, and J.S. Diana, 2018: Blue-Green Water Nexus in Aquaculture for Resilience to Climate Change. *Reviews in Fisheries Science and Aquaculture*, **26(2)**, 139-154, doi:10.1080/23308249.2017.1373743.

Ahn, S.E., 2008: How Feasible is Carbon Sequestration in Korea? A Study on the Costs of Sequestering Carbon in Forest. *Environmental and Resource Economics*, **41(1)**, 89-109, doi:10.1007/s10640-007-9182-8.

Akgul, O., N. Mac Dowell, L.G. Papageorgiou, and N. Shah, 2014: A mixed integer nonlinear programming (MINLP) supply chain optimisation framework for carbon negative electricity generation using biomass to energy with CCS (BECCS) in the UK. *International Journal of Greenhouse Gas Control*, **28**, 189-202, doi:10.1016/j.ijggc.2014.06.017.

Akter, S., T.J. Krupnik, and F. Khanam, 2017: Climate change skepticism and index versus standard crop insurance demand in coastal Bangladesh. *Regional Environmental Change*, **17(8)**, 2455-2466, doi:10.1007/s10113-017-1174-9.

Akter, S., T.J. Krupnik, F. Rossi, and F. Khanam, 2016: The influence of gender and product design on farmers' preferences for weather-indexed crop insurance. *Global Environmental Change*, **38**, 217-229, doi:10.1016/j.gloenvcha.2016.03.010.

Alagador, D., J.O. Cerdeira, and M.B. Araújo, 2014: Shifting protected areas: Scheduling spatial priorities under climate change. *Journal of Applied Ecology*, **51(3)**, 703-713, doi:10.1111/1365-2664.12230.

Alcalde, J. et al., 2018: Estimating geological CO_2 storage security to deliver on climate mitigation. *Nature Communications*, doi:10.1038/s41467-018-04423-1.

Aleksandrova, M., J.P.A. Lamers, C. Martius, and B. Tischbein, 2014: Rural vulnerability to environmental change in the irrigated lowlands of Central Asia and options for policy-makers: A review. *Environmental Science & Policy*, **41**, 77-88, doi:10.1016/j.envsci.2014.03.001.

Alexander, P., C. Brown, A. Arneth, J. Finnigan, and M.D.A. Rounsevell, 2016: Human appropriation of land for food: The role of diet. *Global Environmental Change*, **41**, 88-98, doi:10.1016/j.gloenvcha.2016.09.005.

Alexander, P. et al., 2017: Losses, inefficiencies and waste in the global food system. *Agricultural Systems*, **153**, 190-200, doi:10.1016/j.agsy.2017.01.014.

Ali, S.H. et al., 2017: Mineral supply for sustainable development requires resource governance. *Nature*, **543**, 367, doi:10.1038/nature21359.

Allen, S.K. et al., 2016: Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats. *Natural Hazards*, **84(3)**, 1741-1763, doi:10.1007/s11069-016-2511-x.

Al-Maghalseh, M.M. and E.M. Maharmeh, 2016: Economic and Technical Analysis of Distributed Generation Connection: A Wind Farm Case Study. *Procedia Computer Science*, **83**, 790-798, doi:10.1016/j.procs.2016.04.168.

Almeida Prado, F. et al., 2016: How much is enough? An integrated examination of energy security, economic growth and climate change related to hydropower expansion in Brazil. *Renewable and Sustainable Energy Reviews*, **53**, 1132-1136, doi:10.1016/j.rser.2015.09.050.

Alongi, D.M., 2008: Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, **76(1)**, 1-13, doi:10.1016/j.ecss.2007.08.024.

Al-Qayim, K., W. Nimmo, and M. Pourkashanian, 2015: Comparative techno-economic assessment of biomass and coal with CCS technologies in a pulverized combustion power plant in the United Kingdom. *International Journal of Greenhouse Gas Control*, **43**, 82-92, doi:10.1016/j.ijggc.2015.10.013.

Altieri, M.A. and C.I. Nicholls, 2017: The adaptation and mitigation potential of traditional agriculture in a changing climate. *Climatic Change*, **140(1)**, 33-45, doi:10.1007/s10584-013-0909-y.

Ambrosino, G., J.D. Nelson, M. Boero, and I. Pettinelli, 2016: Enabling intermodal urban transport through complementary services: From Flexible Mobility Services to the Shared Use Mobility Agency: Workshop 4. Developing inter-modal transport systems: Workshop 4. Developing inter-modal transport systems. *Research in Transportation Economics*, **59**, 179-184, doi:10.1016/j.retrec.2016.07.015.

Amin Hosseini, S.M., A. de la Fuente, and O. Pons, 2016: Multi-criteria decision-making method for assessing the sustainability of post-disaster temporary housing units technologies: A case study in Bam, 2003. *Sustainable Cities and Society*, **20(Supplement C)**, 38-51, doi:10.1016/j.scs.2015.09.012.

Aminu, M.D., S.A. Nabavi, C.A. Rochelle, and V. Manovic, 2017: A review of developments in carbon dioxide storage. *Applied Energy*, **208**, 1389-1419, doi:10.1016/j.apenergy.2017.09.015.

Amos, R., 2016: Bioenergy Carbon Capture and Storage in Global Climate Policy: Examining the Issues. *Carbon & Climate Law Review*, **10**, 187-193, doi:10.2307/44134898.

Anacona, P.I., A. Mackintosh, and K. Norton, 2015: Reconstruction of a glacial lake outburst flood (GLOF) in the Engaño Valley, Chilean Patagonia: Lessons for GLOF risk management. *Science of The Total Environment*, **527-528(Supplement C)**, 1-11, doi:https://doi.org/10.1016/j.scitotenv.2015.04.096.

Anderson, K. and G. Peters, 2016: The trouble with negative emissions. *Science*, **354(6309)**, 182-183, doi:10.1126/science.aah4567.

Anderson, R.G. et al., 2011: Biophysical considerations in forestry for climate protection. *Frontiers in Ecology and the Environment*, **9**, 174-182, doi:10.1890/090179.

André, C., D. Boulet, H. Rey-Valette, and B. Rulleau, 2016: Protection by hard defence structures or relocation of assets exposed to coastal risks: Contributions and drawbacks of cost-benefit analysis for long-term adaptation choices to climate change. *Ocean and Coastal Management*, **134**, 173-182, doi:10.1016/j.ocecoaman.2016.10.003.

Anenberg, S.C. et al., 2013: Cleaner cooking solutions to achieve health, climate, and economic cobenefits. *Environmental Science and Technology*, **47(9)**, 3944-3952, doi:10.1021/es304942e.

Angotti, T., 2015: Urban agriculture: long-term strategy or impossible dream? *Public Health*, **129(4)**, 336-341, doi:10.1016/j.puhe.2014.12.008.

Annan, F. and W. Schlenker, 2015: Federal crop insurance and the disincentive to adapt to extreme heat. *The American Economic Review*, **105(5)**, 262-266.

Araos, M., S.E. Austin, L. Berrang-Ford, and J.D. Ford, 2016a: Public health adaptation to climate change in large cities: A global baseline. *International Journal of Health Services*, **46(1)**, 53-78, doi:10.1177/0020731415621458.

Araos, M. et al., 2016b: Climate change adaptation planning in large cities: A systematic global assessment. *Environmental Science and Policy*, **66**, 375-382, doi:10.1016/j.envsci.2016.06.009.

Arasto, A., K. Onarheim, E. Tsupari, and J. Kärki, 2014: Bio-CCS: Feasibility comparison of large scale carbon-negative solutions. *Energy Procedia*, **63**, 6756-6769, doi:10.1016/j.egypro.2014.11.711.

Archer, D., 2016: Building urban climate resilience through community-driven approaches to development. *International Journal of Climate Change Strategies and Management*, **8(5)**, 654-669, doi:10.1108/IJCCSM-03-2014-0035.

Archer, D. et al., 2014: Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale. *Climate and Development*, **6(4)**, 345-356, doi:10.1080/17565529.2014.918868.

Archer, L. et al., 2017: Longitudinal assessment of climate vulnerability: a case study from the Canadian Arctic. *Sustainability Science*, **12(1)**, 15-29, doi:10.1007/s11625-016-0401-5.

Arkema, K.K. et al., 2013: Coastal habitats shield people and property from sea-level rise and storms. *Nature Climate Change*, **3(10)**, 913-918, doi:10.1038/nclimate1944.

Arkema, K.K. et al., 2017: Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. *Annals of the New York Academy of Sciences*, **1399(1)**, 5-26, doi:10.1111/nyas.13322.

Arndt, C., S. Msangi, and J. Thurlow, 2011a: Are biofuels good for African development? An analytical framework with evidence from Mozambique and Tanzania. *Biofuels***, 2(2)**, 221-234, doi:10.4155/bfs.11.1.

Arndt, C., S. Robinson, and D. Willenbockel, 2011b: Ethiopia's growth prospects in a changing climate: A stochastic general equilibrium approach. *Global Environmental Change***, 21(2)**, 701-710, doi:10.1016/J.GLOENVCHA.2010.11.004.

Arora, V.K. and A. Montenegro, 2011: Small temperature benefits provided by realistic afforestation efforts. *Nature Geoscience***, 4(8)**, 514-518, doi:10.1038/Ngeo1182.

Asfaw, S. and B. Davis, 2018: Can Cash Transfer Programmes Promote Household Resilience? Cross-Country Evidence from Sub-Saharan Africa. In: *Climate Smart Agriculture : Building Resilience to Climate Change* [Lipper, L., N. McCarthy, D. Zilberman, S. Asfaw, and G. Branca (eds.)]. Springer International Publishing, Cham, pp. 227-250.

Asfaw, S., A. Carraro, B. Davis, S. Handa, and D. Seidenfeld, 2017: Cash transfer programmes, weather shocks and household welfare: evidence from a randomised experiment in Zambia. *Journal of Development Effectiveness***, 9(4)**, 419-442, doi:10.1080/19439342.2017.1377751.

Ashofteh, P.–S., O. Bozorg-Haddad, and H.A. Loáiciga, 2017: Development of adaptive strategies for irrigation water demand management under climate change. *Journal of Irrigation and Drainage Engineering***, 143(2)**, 4016077.

Ashworth, P., S. Wade, D. Reiner, and X. Liang, 2015: Developments in public communications on CCS. *International Journal of Greenhouse Gas Control***, 40**, 449-458, doi:10.1016/j.ijggc.2015.06.002.

Asiedu, B., F.K.E. Nunoo, and S. Iddrisu, 2017: Prospects and sustainability of aquaculture development in Ghana, West Africa. *Cogent Food & Agriculture***, 3(1)**, doi:10.1080/23311932.2017.1349531.

Atela, J.O., C.H. Quinn, and P.A. Minang, 2014: Are REDD projects pro-poor in their spatial targeting? Evidence from Kenya. *Applied Geography***, 52**, 14-24, doi:10.1016/J.APGEOG.2014.04.009.

Atela, J.O., C.H. Quinn, P.A. Minang, and L.A. Duguma, 2015: Implementing REDD+ in view of integrated conservation and development projects: Leveraging empirical lessons. *Land Use Policy***, 48**, 329-340, doi:10.1016/j.landusepol.2015.06.011.

Augusto Horta Nogueira, L. and R. Silva Capaz, 2013: Biofuels in Brazil: Evolution, achievements and perspectives on food security. *Global Food Security***, 2(2)**, 117-125, doi:10.1016/J.GFS.2013.04.001.

Austin, S.E. et al., 2015: Public health adaptation to climate change in canadian jurisdictions. *International Journal of Environmental Research and Public Health***, 12(1)**, 623-651, doi:10.3390/ijerph120100623.

Austin, S.E. et al., 2016: Public health adaptation to climate change in OECD countries. *International Journal of Environmental Research and Public Health***, 13(9)**, doi:10.3390/ijerph13090889.

Ayers, J.M., S. Huq, A.M. Faisal, and S.T. Hussain, 2014: Mainstreaming climate change adaptation into development: a case study of Bangladesh. *Wiley Interdisciplinary Reviews: Climate Change***, 5(1)**, 37-51, doi:10.1002/wcc.226.

Azar, C., D.J. Johansson, and N. Mattsson, 2013: Meeting global temperature targets - the role of bioenergy with carbon capture and storage. *Environmental Research Letters***, 8(3)**, 1-8, doi:10.1088/1748-9326/8/3/034004.

Azar, C., K. Lindgren, E. Larson, and K. Möllersten, 2006: Carbon Capture and Storage From Fossil Fuels and Biomass - Costs and Potential Role in Stabilizing the Atmosphere. *Climatic Change***, 74(1-3)**, 47-79, doi:10.1007/s10584-005-3484-7.

Azar, C. et al., 2010: The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change***, 100(1)**, 195-202, doi:10.1007/s10584-010-9832-7.

Azhoni, A., I. Holman, and S. Jude, 2017: Adapting water management to climate change: Institutional involvement, inter-institutional networks and barriers in India. *Global Environmental Change***, 44**, 144-157, doi:10.1016/j.gloenvcha.2017.04.005.

Bahill, A.T. and A. Chaves, 2013: 9.4.1 Risk Analysis of Solar Photovoltaic Systems. *INCOSE International Symposium***, 23(1)**, 785-802, doi:10.1002/j.2334-5837.2013.tb03054.x.

Bailly du Bois, P. et al., 2012: Estimation of marine source-term following Fukushima Dai-ichi accident. *Journal of Environmental Radioactivity*, **114**, 2-9, doi:10.1016/j.jenvrad.2011.11.015.

Baird, J., R. Plummer, and K. Pickering, 2014: Priming the Governance System for Climate Change Adaptation: The Application of a Social-Ecological Inventory to Engage Actors in Niagara, Canada. *Ecology and Society*, **19(1)**, doi:10.5751/ES-06152-190103.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924-929, doi:10.1038/nclimate2353.

Baker, L., 2015: The evolving role of finance in South Africa's renewable energy sector. *Geoforum*, **64**, 146-156, doi:https://doi.org/10.1016/j.geoforum.2015.06.017.

Bakker, S. and J. Trip, 2013: Policy options to support the adoption of electric vehicles in the urban environment. *Transportation Research Part D*, **25**, 18-23, doi:10.1016/j.trd.2013.07.005.

Balaban, O. and J.A. Puppim de Oliveira, 2017: Sustainable buildings for healthier cities: assessing the co-benefits of green buildings in Japan. *Journal of Cleaner Production*, **163**, S68-S78, doi:10.1016/j.jclepro.2016.01.086.

Ballarini, I., V. Corrado, F. Madonna, S. Paduos, and F. Ravasio, 2017: Energy refurbishment of the Italian residential building stock: energy and cost analysis through the application of the building typology. *Energy Policy*, **105**, 148-160, doi:10.1016/j.enpol.2017.02.026.

Baltenweck, I. et al., 2003: *Crop-livestock intensification and interactions across three continents: main report*. ILRI.

Bamminger, C. et al., 2016: Short-term response of soil microorganisms to biochar addition in a temperate agroecosystem under soil warming. *Agriculture, Ecosystems & Environment*, **233**, 308-317, doi:10.1016/j.agee.2016.09.016.

Bank of England, 2015: *The impact of climate change on the UK insurance sector - A Climate Change Adaptation Report by the Prudential Regulation Authority*. 1-87 pp.

Baral, A. and G.S. Guha, 2004: Trees for carbon sequestration or fossil fuel substitution: the issue of cost vs. carbon benefit. *Biomass and Bioenergy*, **27(1)**, 41-55, doi:10.1016/J.BIOMBIOE.2003.11.004.

Barbier, E.B., 2015a: Climate change impacts on rural poverty in low-elevation coastal zones. *Estuarine, Coastal and Shelf Science*, **165**, A1-A13, doi:10.1016/j.ecss.2015.05.035.

Barbier, E.B., 2015b: Valuing the storm protection service of estuarine and coastal ecosystems. *Ecosystem Services*, **11**, 32-38, doi:10.1016/j.ecoser.2014.06.010.

Barlow, J. et al., 2007: Quantifying the biodiversity value of tropical primary, secondary, and plantation forests.. *Proceedings of the National Academy of Sciences of the United States of America*, **104(47)**, 18555-60, doi:10.1073/pnas.0703333104.

Barral, M.P., J.M. Rey Benayas, P. Meli, and N.O. Maceira, 2015: Quantifying the impacts of ecological restoration on biodiversity and ecosystem services in agroecosystems: A global meta-analysis. *Agriculture, Ecosystems and Environment*, **202**, 223-231, doi:10.1016/j.agee.2015.01.009.

Barrows, G., S. Sexton, and D. Zilberman, 2014: Agricultural Biotechnology: The Promise and Prospects of Genetically Modified Crops. *Journal of Economic Perspectives*, **28(1)**, 99-120, doi:10.1257/jep.28.1.99.

Bartley, D.J., P.J. Skuce, R.N. Zadoks, and M. MacLeod, 2016: Endemic sheep and cattle diseases and greenhouse gas emissions. *Advances in Animal Biosciences*, **7(03)**, 253-255, doi:10.1017/S2040470016000327.

Bataille, C. et al., 2018: Technology and policy options for making heavy industry products consistent with 1.5-2°C compatible deep decarbonization pathways. *Journal of Cleaner Production*, **187**, 960-973.

Batjes, N.H., 1998: Mitigation of atmospheric CO_2 concentrations by increased carbon sequestration in the soil. *Biology and Fertility of Soils*, **27(3)**, 230-235, doi:10.1007/s003740050425.

Baudron, F., C. Thierfelder, I. Nyagumbo, and B. Gérard, 2015: Where to target conservation agriculture for African smallholders? How to overcome challenges associated with its implementation? Experience from Eastern and Southern Africa. *Environments*, **2(3)**, 338-357.

Baul, T.K., A. Alam, H. Strandman, and A. Kilpelï¿½inen, 2017: Net climate impacts and economic profitability of forest biomass production and utilization in fossil fuel and fossil-based material substitution under alternative forest management. *Biomass and Bioenergy*, **98**, 291-305, doi:10.1016/j.biombioe.2017.02.007.

Beatley, T., 2011: *Biophilic Cities: Integrating Nature into Urban Design and Planning*. Island Press, Washington DC, USA, 208 pp.

Beaudoin, M. and P. Gosselin, 2016: An effective public health program to reduce urban heat islands in Québec, Canada. *Revista Panamericana de Salud Publica*, **40(3)**, 160-166.

Beccali, M., M. Bonomolo, G. Ciulla, A. Galatioto, and V. Lo Brano, 2015: Improvement of energy efficiency and quality of street lighting in South Italy as an action of Sustainable Energy Action Plans. The case study of Comiso (RG). *Energy*, **92(3)**, 394-408, doi:10.1016/j.energy.2015.05.003.

Bell, J. and M. Taylor, 2015: Building Climate-Resilient Food Systems for Pacific Islands. *WorldFish*, 72.

Bell, J.D., J.E. Johnson, and A.J. Hobday, 2011: *Vulnerability of tropical pacific fisheries and aquaculture to climate change*. 925 pp.

Bell, L.W., A.D. Moore, and J.A. Kirkegaard, 2014: Evolution in crop-livestock integration systems that improve farm productivity and environmental performance in Australia. *European Journal of Agronomy*, **57**, 10-20.

Benbi, D.K., 2013: Greenhouse Gas Emissions from Agricultural Soils: Sources and Mitigation Potential. *Journal of Crop Improvement*, **27(6)**, 752-772, doi:10.1080/15427528.2013.845054.

Bendito, A. and E. Barrios, 2016: Convergent Agency: Encouraging Transdisciplinary Approaches for Effective Climate Change Adaptation and Disaster Risk Reduction. *International Journal of Disaster Risk Science*, **7(4)**, 430-435, doi:10.1007/s13753-016-0102-9.

Béné, C. et al., 2016: Contribution of Fisheries and Aquaculture to Food Security and Poverty Reduction: Assessing the Current Evidence. *World Development*, **79**, 177-196, doi:10.1016/j.worlddev.2015.11.007.

Benítez, P.C. and M. Obersteiner, 2006: Site identification for carbon sequestration in Latin America: A grid-based economic approach. *Forest Policy and Economics*, **8(6)**, 636-651, doi:10.1016/J.FORPOL.2004.12.003.

Benmarhnia, T. et al., 2016: A Difference-in-Differences Approach to Assess the Effect of a Heat Action Plan on Heat-Related Mortality, and Differences in Effectiveness According. *Environmental Health Perspectives*, **124(11)**, 1694-1699.

Benson, R.D., 2018: Reviewing reservoir operations in the North American West: an opportunity for adaptation. *Regional Environmental Change*, 1-11, doi:10.1007/s10113-018-1330-x.

Benton, T.G. et al., 2018: Designing sustainable landuse in a 1.5 °C world: the complexities of projecting multiple ecosystem services from land. *Current Opinion in Environmental Sustainability*, **31**, 88-95, doi:10.1016/J.COSUST.2018.01.011.

Beresford, N.A. et al., 2016: Thirty years after the Chernobyl accident: What lessons have we learnt? *Journal of Environmental Radioactivity*, **157**, 77-89, doi:10.1016/j.jenvrad.2016.02.003.

Berhane, G., D.O. Gilligan, J. Hoddinott, N. Kumar, and A.S. Taffesse, 2014: Can social protection work in Africa? The impact of Ethiopia's productive safety net programme. *Economic Development and Cultural Change*, **63(1)**, 1-26.

Beringer, T., W. Lucht, and S. Schaphoff, 2011: Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, **3(4)**, 299-312, doi:10.1111/j.1757-1707.2010.01088.x.

Berkes, F. and D. Jolly, 2002: Adapting to climate change: Social-ecological resilience in a Canadian western arctic community. *Ecology and Society*, **5(2)**, doi:18.

Berkes, F., J. Colding, and C. Folke, 2000: Rediscovery of Traditional Ecological Knowledge as adaptive management. *Ecological Applications*, **10(5)**, 1251-1262, doi:10.1890/1051-0761(2000)010[1251:ROTEKA]2.0.CO;2.

Bernesson, S., D. Nilsson, and P.–A. Hansson, 2004: A limited LCA comparing large- and small-scale production of rape methyl ester (RME) under Swedish conditions. *Biomass and Bioenergy*, **26(6)**, 545-559, doi:10.1016/J.BIOMBIOE.2003.10.003.

Berrang-Ford, L. et al., 2012: Vulnerability of indigenous health to climate change: A case study of Uganda's Batwa Pygmies. *Social Science and Medicine*, **75(6)**, 1067-1077, doi:10.1016/j.socscimed.2012.04.016.

Berry, P. and G.R.A. Richardson, 2016: Approaches for Building Community Resilience to Extreme Heat. In: *Extreme Weather, Health, and Communities: Interdisciplinary Engagement Strategies* [Steinberg, S.L. and W.A. Sprigg (eds.)]. Springer International Publishing, Cham, pp. 351-388.

Berry, P.M. et al., 2015: Cross-sectoral interactions of adaptation and mitigation measures. *Climatic Change*, **128(3-4)**, 381-393, doi:10.1007/s10584-014-1214-0.

Berti, G. and C. Mulligan, 2016: Competitiveness of Small Farms and Innovative Food Supply Chains: The Role of Food Hubs in Creating Sustainable Regional and Local Food Systems. *Sustainability*, **8(7)**, 616, doi:10.3390/su8070616.

Bettini, G., S.L. Nash, and G. Gioli, 2016: One step forward, two steps back? The fading contours of (in)justice in competing discourses on climate migration. *Geographical Journal*, doi:10.1111/geoj.12192.

Bettini, Y., R.R. Brown, and F.J. de Haan, 2015: Exploring institutional adaptive capacity in practice: examining water governance adaptation in Australia. *Ecology and Society*, **20(1)**, art47, doi:10.5751/ES-07291-200147.

Betzold, C., 2015: Adapting to climate change in small island developing states. *Climatic Change*, **133(3)**, 481-489, doi:10.1007/s10584-015-1408-0.

Betzold, C. and I. Mohamed, 2017: Seawalls as a response to coastal erosion and flooding: a case study from Grande Comore, Comoros (West Indian Ocean). *Regional Environmental Change*, **17(4)**, 1077-1087, doi:10.1007/s10113-016-1044-x.

Bhagat, R., 2017: Migration, Gender and Right to the City. *Economic & Political Weekly*, **LII(32)**, 35-40.

Bhakta Bhandari, R., 2014: Social capital in disaster risk management; a case study of social capital mobilization following the 1934 Kathmandu Valley earthquake in Nepal. *Disaster Prevention and Management: An International Journal*, **23(4)**, 314-328, doi:10.1108/DPM-06-2013-0105.

Bhan, S. and U.K. Behera, 2014: Conservation agriculture in India - Problems, prospects and policy issues. *International Soil and Water Conservation Research*, **2(4)**, 1-12, doi:10.1016/S2095-6339(15)30053-8.

Bhave, A. et al., 2017: Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO_2 targets. *Applied Energy*, **190**, 481-489, doi:10.1016/J.APENERGY.2016.12.120.

Bigerna, S., C.A. Bollino, and S. Micheli, 2016: Socio-economic acceptability for smart grid development - a comprehensive review. *Journal of Cleaner Production*, **131**, 399-409, doi:10.1016/j.jclepro.2016.05.010.

Biggs, E.M. et al., 2015: Sustainable development and the water-energy-food nexus: A perspective on livelihoods. *Environmental Science & Policy*, **54**, 389-397, doi:10.1016/j.envsci.2015.08.002.

Bilkovic, D.M. and M.M. Mitchell, 2013: Ecological tradeoffs of stabilized salt marshes as a shoreline protection strategy: Effects of artificial structures on macrobenthic assemblages. *Ecological Engineering*, **61**, 469-481, doi:10.1016/j.ecoleng.2013.10.011.

Birk, T. and K. Rasmussen, 2014: Migration from atolls as climate change adaptation: Current practices, barriers and options in Solomon Islands. *Natural Resources Forum*, **38(1)**, 1-13, doi:10.1111/1477-8947.12038.

Bistline, J.E., 2017: Economic and technical challenges of flexible operations under large-scale variable renewable deployment. *Energy Economics*, **64**, 363-372, doi:10.1016/j.eneco.2017.04.012.

Bjornlund, H., A. van Rooyen, and R. Stirzaker, 2017: Profitability and productivity barriers and opportunities in small-scale irrigation schemes. *International Journal of Water Resources Development*, **33(5)**, 690-704, doi:10.1080/07900627.2016.1263552.

Blaabjerg, F., Z. Chen, and S.B. Kjaer, 2004: Power Electronics as Efficient Interface in Dispersed Power Generation Systems. *IEEE Transactions on Power Electronics*, **19(5)**, 1184-1194, doi:10.1109/TPEL.2004.833453.

Blackman, A. and J. Rivera, 2011: Producer-Level Benefits of Sustainability Certification. *Conservation Biology*, **25(6)**, 1176-1185, doi:10.1111/j.1523-1739.2011.01774.x.

Blanc, E., J. Caron, C. Fant, and E. Monier, 2017: Is current irrigation sustainable in the United States? An integrated assessment of climate change impact on water resources and irrigated crop yields. *Earth's Future*, **5(8)**, 877-892, doi:10.1002/2016EF000473.

Blanchard, J.L. et al., 2017: Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. *Nature Ecology and Evolution*, **1(9)**, 1240-1249, doi:10.1038/s41559-017-0258-8.

Blay-Palmer, A., R. Sonnino, and J. Custot, 2016: A food politics of the possible? Growing sustainable food systems through networks of knowledge. *Agriculture and Human Values*, **33(1)**, 27-43, doi:10.1007/s10460-015-9592-0.

Boardman, B., 2004: New directions for household energy efficiency: evidence from the UK. *Energy Policy*, **32(17)**, 1921-1933, doi:10.1016/j.enpol.2004.03.021.

Bockarjova, M. and L. Steg, 2014: Can Protection Motivation Theory predict pro-environmental behavior? Explaining the adoption of electric vehicles in the Netherlands. *Global Environmental Change*, **28**, 276-288, doi:10.1016/j.gloenvcha.2014.06.010.

Boeckmann, M. and I. Rohn, 2014: Is planned adaptation to heat reducing heat-related mortality and illness? A systematic review. *BMC public health*, **14(1)**, 1112.

Bogale, A., 2015: Weather-indexed insurance: an elusive or achievable adaptation strategy to climate variability and change for smallholder farmers in Ethiopia. *Climate and Development*, **5529(May)**, 37-41, doi:10.1080/17565529.2014.934769.

Bonsch, M. et al., 2016: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11-24, doi:10.1111/gcbb.12226.

Boonstra, W.J. and T.T.H. Hanh, 2015: Adaptation to climate change as social-ecological trap: a case study of fishing and aquaculture in the Tam Giang Lagoon, Vietnam. *Environment, Development and Sustainability*, **17(6)**, 1527-1544, doi:10.1007/s10668-014-9612-z.

Booth, M.S., 2018: Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy. *Environmental Research Letters*, **13(3)**, 035001, doi:10.1088/1748-9326/aaac88.

Boot-Handford, M.E. et al., 2014: Carbon capture and storage update. *Energy Environ. Sci.*, **7(1)**, 130-189, doi:10.1039/C3EE42350F.

Borch, K., N.–E. Clausen, and G. Ellis, 2014: Environmental and social impacts of wind energy. In: *DTU International Energy Report 2014: Wind energy - drivers and barriers for higher shares of wind in the global power generation mix* [Larsen, H.H. and L.S. Petersen (eds.)]. Technical University of Denmark (DTU), Kogens Lyngby, Denmark, pp. 86-90.

Bosello, F. and E. De Cian, 2014: Climate change, sea level rise, and coastal disasters. A review of modeling practices. *Energy Economics*, **46**, 593-605, doi:10.1016/j.eneco.2013.09.002.

Boucher, O. et al., 2014: Rethinking climate engineering categorization in the context of climate change mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **5(1)**, 23-35, doi:10.1002/wcc.261.

Bouf, D. and B. Faivre D'arcier, 2015: The looming crisis in French public transit. *Transport Policy*, **42**, 34-41, doi:10.1016/j.tranpol.2015.04.004.

Boughedir, S., 2015: Case study: disaster risk management and climate change adaptation in Greater Algiers: overview on a study assessing urban vulnerabilities to disaster risk and proposing measures for adaptation. *Current Opinion in Environmental Sustainability*, **13(Supplement C)**, 103-108, doi:https://doi.org/10.1016/j.cosust.2015.03.001.

Bouman, E.A., E. Lindstad, A.I. Rialland, and A.H. Strømman, 2017: State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping - A review. *Transportation Research Part D: Transport and Environment*, **52(Part A)**, 408-421, doi:https://doi.org/10.1016/j.trd.2017.03.022.

Bowen, K.J., K. Ebi, S. Friel, and A.J. McMichael, 2013: A multi-layered governance framework for incorporating social science insights into adapting to the health impacts of climate change. *Global Health Action*, **6(1)**, doi:10.3402/gha.v6i0.21820.

Bows-Larkin, A., 2015: All adrift: aviation, shipping, and climate change policy. *Climate Policy*, **15(6)**, 681-702, doi:10.1080/14693062.2014.965125.

Boysen, L.R., W. Lucht, and D. Gerten, 2017a: Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Global Change Biology*, **23(10)**, 4303-4317, doi:10.1111/gcb.13745.

Boysen, L.R. et al., 2017b: The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, **5(5)**, 463-474, doi:10.1002/2016EF000469.

Branca, G., L. Lipper, N. McCarthy, and M.C. Jolejole, 2013: Food security, climate change, and sustainable land management. A review. *Agronomy for Sustainable Development*, **33(4)**, 635-650, doi:10.1007/s13593-013-0133-1.

Brander, K.M., 2007: Global fish production and climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **104(50)**, 19709-14, doi:10.1073/pnas.0702059104.

Brander, L., R. Brouwer, and A. Wagtendonk, 2013: Economic valuation of regulating services provided by wetlands in agricultural landscapes: A meta-analysis. *Ecological Engineering*, **56**, 89-96, doi:10.1016/J.ECOLENG.2012.12.104.

Brasseur, G.P. and L. Gallardo, 2016: Climate services: Lessons learned and future prospects. *Earth's Future*, **4(3)**, 79-89, doi:10.1002/2015EF000338.

Braun, C., C. Merk, G. Pönitzsch, K. Rehdanz, and U. Schmidt, 2017: Public perception of climate engineering and carbon capture and storage in Germany: survey evidence. *Climate Policy*, **3062(August)**, 1-14, doi:10.1080/14693062.2017.1304888.

Brennan, N., T.M. Van Rensburg, and C. Morris, 2017: Public acceptance of large-scale wind energy generation for export from Ireland to the UK: evidence from Ireland. *Journal of Environmental Planning and Management*, **60(11)**, 1967-1992, doi:10.1080/09640568.2016.1268109.

Bright, R.M., K. Zhao, R.B. Jackson, and F. Cherubini, 2015: Quantifying surface albedo and other direct biogeophysical climate forcings of forestry activities. *Global Change Biology*, **21(9)**, 3246-3266, doi:10.1111/gcb.12951.

Briley, L., D. Brown, and S.E. Kalafatis, 2015: Overcoming barriers during the co-production of climate information for decision-making. *Climate Risk Management*, **9**, 41-49, doi:10.1016/j.crm.2015.04.004.

Brillant, S., 2014: Aquaculture. *Fédération canadienne de la faune*, 33, doi:10.1007/s13398-014-0173-7.2.

Brimont, L., D. Ezzine-de-Blas, A. Karsenty, and A. Toulon, 2015: Achieving Conservation and Equity amidst Extreme Poverty and Climate Risk: The Makira REDD+ Project in Madagascar. *Forests*, **6(12)**, 748-768, doi:10.3390/f6030748.

Briske, D.D. et al., 2015: Climate-change adaptation on rangelands: linking regional exposure with diverse adaptive capacity. *Frontiers in Ecology and the Environment*, **13(5)**, 249-256, doi:10.1890/140266.

Broch, A., S.K. Hoekman, and S. Unnasch, 2013: A review of variability in indirect land use change assessment and modeling in biofuel policy. *Environmental Science & Policy*, **29**, 147-157, doi:10.1016/J.ENVSCI.2013.02.002.

Brockington, D. and D. Wilkie, 2015: Protected areas and poverty. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **370(1681)**, 20140271, doi:10.1098/rstb.2014.0271.

Brockington, J.D., I.M. Harris, and R.M. Brook, 2016: Beyond the project cycle: a medium-term evaluation of agroforestry adoption and diffusion in a south Indian village. *Agroforestry Systems*, **90(3)**, 489-508, doi:10.1007/s10457-015-9872-0.

Broekhoff, D., G. Piggot, and P. Erickson, 2018: Building Thriving, Low-Carbon Cities: An Overview of Policy Options for National Governments. Coalition for Urban Transitions, London and Washington, D.C. 124 pp.

Broitman, B.R. et al., 2017: Dynamic Interactions among Boundaries and the Expansion of Sustainable Aquaculture. *Frontiers in Marine Science*, **4**, doi:10.3389/fmars.2017.00015.

Brooke, J.S. et al., 1992: Coastal Defense - the Retreat Option. *Journal of the Institution of Water and Environmental Management*, **6(2)**, 151-157.

Brooks, S.M., 2015: Social Protection for the Poorest. *Politics & Society*, **43(4)**, 551-582, doi:10.1177/0032329215602894.

Broto, V.C., 2017: Energy landscapes and urban trajectories towards sustainability. *Energy Policy*, **108(December 2016)**, 755-764, doi:10.1016/j.enpol.2017.01.009.

Broto, V.C., E. Boyd, and J. Ensor, 2015: Participatory urban planning for climate change adaptation in coastal cities: Lessons from a pilot experience in Maputo, Mozambique. *Current Opinion in Environmental Sustainability*, **13**, 11-18, doi:10.1016/j.cosust.2014.12.005.

Brouder, S.M. and H. Gomez-Macpherson, 2014: The impact of conservation agriculture on smallholder agricultural yields: A scoping review of the evidence. *Agriculture, Ecosystems & Environment*, **187**, 11-32, doi:10.1016/j.agee.2013.08.010.

Brouwer, A.S., M. van den Broek, A. Seebregts, and A. Faaij, 2015: Operational flexibility and economics of power plants in future low-carbon power systems. *Applied Energy*, **156**, 107-128, doi:10.1016/J.APENERGY.2015.06.065.

Brown, C.J. et al., 2016: Ecological and methodological drivers of species' distribution and phenology responses to climate change. *Global change biology*, **22(4)**, 1548-1560, doi:10.1111/gcb.13184.

Brown, D. and G. McGranahan, 2016: The urban informal economy, local inclusion and achieving a global green transformation. *Habitat International*, **53**, 97-105, doi:10.1016/j.habitatint.2015.11.002.

Brown, S., D. Pyke, and P. Steenhof, 2010: Electric vehicles: The role and importance of standards in an emerging market. *Energy Policy*, **38(7)**, 3797-3806, doi:10.1016/j.enpol.2010.02.059.

Brown, S., J. Sathaye, M. Cannell, and P.E. Kauppi, 1995: Management of forests for mitigation of greenhouse gas emissions. *The Commonwealth Forestry Review*, **75(1)**.

Brown, S. et al., 2018: Quantifying Land and People Exposed to Sea-Level Rise with No Mitigation and 1.5°C and 2.0°C Rise in Global Temperatures to Year 2300. *Earth's Future*, **6(3)**, 583-600, doi:10.1002/2017EF000738.

Brown, T.R., 2015: A techno-economic review of thermochemical cellulosic biofuel pathways. *Bioresource Technology*, **178**, 166-176, doi:10.1016/j.biortech.2014.09.053.

Brown, V., B.Z. Diomedi, M. Moodie, J.L. Veerman, and R. Carter, 2016: A systematic review of economic analyses of active transport interventions that include physical activity benefits. *Transport Policy*, **45**, 190-208, doi:10.1016/j.tranpol.2015.10.003.

Bruckner, T. et al., 2014: Energy Systems. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, United Kingdom and New York, NY, USA.

Brugnach, M., M. Craps, and A. Dewulf, 2017: Including indigenous peoples in climate change mitigation: addressing issues of scale, knowledge and power. *Climatic Change*, **140(1)**, 19-32, doi:10.1007/s10584-014-1280-3.

Brundiers, K., 2018: Educating for post-disaster sustainability efforts. *International Journal of Disaster Risk Reduction*, **27**, 406-414, doi:10.1016/j.ijdrr.2017.11.002.

Brunke, J.–C., M. Johansson, and P. Thollander, 2014: Empirical investigation of barriers and drivers to the adoption of energy conservation measures, energy management practices and energy services in the Swedish iron and steel industry. *Journal of Cleaner Production*, **84**, 509-525, doi:https://doi.org/10.1016/j.jclepro.2014.04.078.

Brzoska, M. and C. Fröhlich, 2016: Climate change, migration and violent conflict: vulnerabilities, pathways and adaptation strategies. *Migration and Development*, **5(2)**, 190-210, doi:10.1080/21632324.2015.1022973.

Buchholz, T., M.D. Hurteau, J. Gunn, and D. Saah, 2016: A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies. *GCB Bioenergy*, **8(2)**, 281-289, doi:10.1111/gcbb.12245.

Buchholz, T., S. Prisley, G. Marland, C. Canham, and N. Sampson, 2014: Uncertainty in projecting GHG emissions from bioenergy. *Nature Climate Change*, **4(12)**, 1045-1047, doi:10.1038/nclimate2418.

Buck, H.J., 2016: Rapid scale-up of negative emissions technologies: social barriers and social implications. *Climatic Change*, **139(2)**, 155-167, doi:10.1007/s10584-016-1770-6.

Buckeridge, M., 2015: Árvores urbanas em São Paulo: planejamento, economia e água. *Estudos Avançados*, **29(84)**, 85-101, doi:10.1590/S0103-40142015000200006.

Buckeridge, M.S., A.P. de Souza, R.A. Arundale, K.J. Anderson-Teixeira, and E. Delucia, 2012: Ethanol from sugarcane in Brazil: A 'midway' strategy for increasing ethanol production while maximizing environmental benefits. *GCB Bioenergy*, **4(2)**, 119-126, doi:10.1111/j.1757-1707.2011.01122.x.

Bui, M. et al., 2018: Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science* (in press), doi:10.1039/C7EE02342A.

Bulkeley, H., P.M. McGuirk, and R. Dowling, 2016: Making a smart city for the smart grid? The urban material politics of actualising smart electricity networks. *Environment and Planning A: Economy and Space*, **48(9)**, 1709-1726, doi:10.1177/0308518X16648152.

Bullock, J.M., J. Aronson, A.C. Newton, R.F. Pywell, and J.M. Rey-Benayas, 2011: Restoration of ecosystem services and biodiversity: conflicts and opportunities. *Trends in Ecology & Evolution*, **26(10)**, 541-549, doi:10.1016/J.TREE.2011.06.011.

Burch, S., A. Shaw, A. Dale, and J. Robinson, 2014: Triggering transformative change: a development path approach to climate change response in communities. *Climate Policy*, **14(4)**, 467-487, doi:10.1080/14693062.2014.876342.

Burney, J. et al., 2014: Climate change adaptation strategies for smallholder farmers in the Brazilian Sertão. *Climatic Change*, **126(1-2)**, 45-59, doi:10.1007/s10584-014-1186-0.

Burney, J.A. and R.L. Naylor, 2012: Smallholder Irrigation as a Poverty Alleviation Tool in Sub-Saharan Africa. *World Development*, **40(1)**, 110-123, doi:10.1016/j.worlddev.2011.05.007.

Burns, W. and S. Nicholson, 2017: Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *Journal of Environmental Studies and Sciences*, **15(2)**, doi:10.1007/s13412-017-0445-6.

Burton, A.J., H.J. Bambrick, and S. Friel, 2014: Is enough attention given to climate change in health service planning? An Australian perspective. *Global Health Action*, **7(1)**, doi:10.3402/gha.v7.23903.

Butler, C. and J. Adamowski, 2015: Empowering marginalized communities in water resources management: Addressing inequitable practices in Participatory Model Building. *Journal of Environmental Management*, **153**, 153-162, doi:10.1016/j.jenvman.2015.02.010.

Butler, J.R.A. et al., 2015: Integrating Top-Down and Bottom-Up Adaptation Planning to Build Adaptive Capacity: A Structured Learning Approach. *Coastal Management*, **43(4)**, 346-364, doi:10.1080/08920753.2015.1046802.

Butler, J.R.A. et al., 2016a: Scenario planning to leap-frog the Sustainable Development Goals: An adaptation pathways approach. *Climate Risk Management*, **12**, 83-99, doi:10.1016/j.crm.2015.11.003.

Butler, J.R.A. et al., 2016b: Priming adaptation pathways through adaptive co-management: Design and evaluation for developing countries. *Climate Risk Management*, **12**, 1-16, doi:10.1016/j.crm.2016.01.001.

Cagno, E., E. Worrell, A. Trianni, and G. Pugliese, 2013: A novel approach for barriers to industrial energy efficiency. *Renewable and Sustainable Energy Reviews*, **19**, 290-308, doi:https://doi.org/10.1016/j.rser.2012.11.007.

Caldecott, B., G. Lomax, and M. Workman, 2015: Stranded Carbon Assets and Negative Emissions Technologies. Smith School of Enterprise and the Environment, University of Oxford, Oxford, UK, UK, 37 pp.

Calvin, K. et al., 2016: Implications of uncertain future fossil energy resources on bioenergy use and terrestrial carbon emissions. *Climatic Change*, **136(1)**, 57-68, doi:10.1007/s10584-013-0923-0.

Cambridge Econometrics, 2015: *Assessing the Employment and Social Impact of Energy Efficiency*.

Cames, M., J. Graichen, A. Siemons, and V. Cook, 2015a: Emission Reduction Targets for International Aviation and Shipping. , 52.

Cames, M., V. Graichen, J. Faber, and D. Nelissen, 2015b: *Greenhouse gas emission reduction targets for international shipping: Discussion paper*. Prepared by Öko-Institut and CE Deflt on behalf of the German Federal Environment Agency (UBA), Berlin, Germany, 21 pp.

Campos, I.S. et al., 2016: Climate adaptation, transitions, and socially innovative action-research approaches. *Ecology and Society*, **21(1)**, art13, doi:10.5751/ES-08059-210113.

Camps-Calvet, M., J. Langemeyer, L. Calvet-Mir, and E. Gómez-Baggethun, 2016: Ecosystem services provided by urban gardens in Barcelona, Spain: Insights for policy and planning. *Environmental Science & Policy*, **62**, 14-23, doi:10.1016/j.envsci.2016.01.007.

Canadell, J.G. and M.R. Raupach, 2008: Managing Forests for Climate Change Mitigation. *Science*, **320(5882)**, 1456-1457, doi:10.1126/science.1155458.

Canadell, J.G. and E.D. Schulze, 2014: Global potential of biospheric carbon management for climate mitigation. *Nature Communications*, **5**, 1-12, doi:10.1038/ncomms6282.

Cannell, M.G.R., 2003: Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. *Biomass and Bioenergy*, **24(2)**, 97-116, doi:10.1016/S0961-9534(02)00103-4.

Cannon, S. and L. Summers, 2014: How Uber and the Sharing Economy Can Win Over Regulators. *Harvard Business Review*, **13(10)**, 24-28.

Caplow, S., P. Jagger, K. Lawlor, and E. Sills, 2011: Evaluating land use and livelihood impacts of early forest carbon projects: Lessons for learning about REDD+. *Environmental Science & Policy*, **14(2)**, 152-167, doi:10.1016/J.ENVSCI.2010.10.003.

Carbo, M.C., R. Smit, B. Van Der Drift, and D. Jansen, 2011: Bio energy with CCS (BECCS): Large potential for BioSNG at low CO_2 avoidance cost. *Energy Procedia*, **4**, 2950-2954, doi:10.1016/j.egypro.2011.02.203.

Carey, M., 2005: Living and dying with glaciers: People's historical vulnerability to avalanches and outburst floods in Peru. *Global and Planetary Change*, **47(2-4 SPEC. ISS.)**, 122-134, doi:10.1016/j.gloplacha.2004.10.007.

Carey, M., 2008: Disasters, Development, and Glacial Lake Control in Twentieth-Century Peru. In: *Mountains: Sources of Water, Sources of Knowledge* [Wiegandt, E. (ed.)]. Springer Netherlands, Dordrecht, pp. 181-196.

Carlson, K. and D.K.D. Pressnail, 2018: Value impacts of energy efficiency retrofits on commercial office buildings in Toronto, Canada. *Energy and Buildings*, **162**, 154-162, doi:10.1016/j.enbuild.2017.12.013.

Carr, E.R. and S.N. Onzere, 2017: Really effective (for 15% of the men): lessons in understanding and addressing user needs in climate services from Mali. *Climate Risk Management*, doi:10.1016/j.crm.2017.03.002.

Carter, J.G. et al., 2015: Climate change and the city: Building capacity for urban adaptation. *Progress in Planning*, **95**, 1-66, doi:10.1016/j.progress.2013.08.001.

Carwardine, J. et al., 2015: Spatial Priorities for Restoring Biodiverse Carbon Forests. *BioScience*, **65(4)**, 372-382, doi:10.1093/biosci/biv008.

Cashman, A. and M.R. Nagdee, 2017: *Impacts of Climate Change on Settlements and Infrastructure in the Coastal and Marine Environments of Caribbean Small Island Developing States (SIDS)*. Caribbean Marine Climate Change Report Card: Science Review 2017, 153-173 pp.

Castrejón, D., A.M. Zavala, J.A. Flores, M.P. Flores, and D. Barrón, 2018: Analysis of the contribution of CCS to achieve the objectives of Mexico to reduce GHG emissions. *International Journal of Greenhouse Gas Control*, **71**, 184-193, doi:https://doi.org/10.1016/j.ijggc.2018.02.019.

Cattaneo, C. and G. Peri, 2016: The migration response to increasing temperatures. *Journal of Development Economics*, **122**, 127-146.

CCRIF, 2017: *Annual Report 2016-2017*. CCRIF SPC, Grand Cayman, 107 pp.

Cengiz, M.S. and M.S. Mamiş, 2015: Price-Efficiency Relationship for Photovoltaic Systems on a Global Basis. *International Journal of Photoenergy*, **2015(256101)**, 1-12, doi:10.1155/2015/256101.

Challinor, A.J. et al., 2014: A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change*, **4(4)**, 287-291, doi:10.1038/nclimate2153.

Challinor, A.J. et al., 2018: Improving the use of crop models for risk assessment and climate change adaptation. *Agricultural Systems*, **159**, 296-306, doi:10.1016/j.agsy.2017.07.010.

Chambers, L.E. et al., 2017: A database for traditional knowledge of weather and climate in the Pacific. *Meteorological Applications*, **24(3)**, 491-502, doi:10.1002/met.1648.

Chandel, S.S., A. Sharma, and B.M. Marwaha, 2016: Review of energy efficiency initiatives and regulations for residential buildings in India. *Renewable and Sustainable Energy Reviews*, **54**, 1443-1458, doi:10.1016/j.rser.2015.10.060.

Chandra, A., P. Dargusch, and K.E. McNamara, 2016: How might adaptation to climate change by smallholder farming communities contribute to climate change mitigation outcomes? A case study from Timor-Leste, Southeast Asia. *Sustainability Science*, **11(3)**, 477-492, doi:10.1007/s11625-016-0361-9.

Chang, C.–C., 1999: Carbon sequestration cost by afforestation in Taiwan. *Environmental Economics and Policy Studies*, **2(3)**, 199-213, doi:10.1007/BF03353911.

Chang, Y., S. Wilkinson, R. Potangaroa, and E. Seville, 2010: Resources and capacity: lessons learned from post-disaster reconstruction resourcing in Indonesia, China and Australia. In: *The Construction, Building and Real Estate Research Conference of the Royal Institution of Chartered Surveyors*.

Chant, S., M. Klett-davies, and J. Ramalho, 2017: *Challenges and potential solutions for adolescent girls in urban settings: a rapid evidence review*.

Chaturvedi, V. and P.R. Shukla, 2014: Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Climatic Change*, **123(3-4)**, 597-609, doi:10.1007/s10584-013-0898-x.

Chaturvedi, V. et al., 2015: Climate mitigation policy implications for global irrigation water demand. *Mitigation and Adaptation Strategies for Global Change*, **20(3)**, 389-407, doi:10.1007/s11027-013-9497-4.

Chau, K.W., L.H.T. Choy, and C.J. Webster, 2018: Institutional innovations in land development and planning in the 20th and 21st centuries. *Habitat International*, **75**, 90-95, doi:10.1016/j.habitatint.2018.03.011.

Chaudhury, M., J. Vervoort, P. Kristjanson, P. Ericksen, and A. Ainslie, 2013: Participatory scenarios as a tool to link science and policy on food security under climate change in East Africa. *Regional Environmental Change*, **13(2)**, 389-398, doi:10.1007/s10113-012-0350-1.

Chava, J. and P. Newman, 2016: Stakeholder Deliberation on Developing Affordable Housing Strategies: Towards Inclusive and Sustainable Transit-Oriented Developments. *Sustainability*, **8(10)**, 1024, doi:10.3390/su8101024.

Chava, J., P. Newman, and R. Tiwari, 2018a: Gentrification in new-build and old-build transit-oriented developments: the case of Bengaluru. *Urban Research & Practice*, 1-17, doi:10.1080/17535069.2018.1437214.

Chava, J., P. Newman, and R. Tiwari, 2018b: Gentrification of station areas and its impact on transit ridership. *Case Studies on Transport Policy*, **6(1)**, 1-10, doi:10.1016/j.cstp.2018.01.007.

Chen, S. and B. Chen, 2016: Urban energy-water nexus: A network perspective. *Applied Energy*, **184**, 905-914, doi:10.1016/j.apenergy.2016.03.042.

Cheng, V.K.M. and G.P. Hammond, 2017: Life-cycle energy densities and land-take requirements of various power generators: A UK perspective. *Journal of the Energy Institute*, **90(2)**, 201-213, doi:10.1016/J.JOEI.2016.02.003.

Cherubin, M.R. et al., 2015: Sugarcane expansion in Brazilian tropical soils-Effects of land use change on soil chemical attributes. *Agriculture, Ecosystems & Environment*, **211**, 173-184, doi:https://doi.org/10.1016/j.agee.2015.06.006.

Cheyne, C. and M. Imran, 2016: Shared transport: Reducing energy demand and enhancing transport options for residents of small towns. *Energy Research & Social Science*, **18**, 139-150, doi:10.1016/j.erss.2016.04.012.

Chu, E., I. Anguelovski, and J.A. Carmin, 2016: Inclusive approaches to urban climate adaptation planning and implementation in the Global South. *Climate Policy*, **16(3)**, 372-392, doi:10.1080/14693062.2015.1019822.

Chu, E., I. Anguelovski, and D. Roberts, 2017: Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities*, **60**, 378-387, doi:10.1016/j.cities.2016.10.016.

Chu, E., T. Schenk, and J. Patterson, 2018: The Dilemmas of Citizen Inclusion in Urban Planning and Governance to Enable a 1.5 °C Climate Change Scenario. *Urban Planning*, **3(2)**, 128-140, doi:http://dx.doi.org/10.17645/up.v3i2.1292.

Chung Tiam Fook, T., 2017: Transformational processes for community-focused adaptation and social change: a synthesis. *Climate and Development*, **9(1)**, 5-21, doi:10.1080/17565529.2015.1086294.

Cinner, J.E. et al., 2018: Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*, **8(2)**, 117-123, doi:10.1038/s41558-017-0065-x.

Clark, D.G., J.D. Ford, T. Pearce, and L. Berrang-Ford, 2016: Vulnerability to unintentional injuries associated with land-use activities and search and rescue in Nunavut, Canada. *Social Science and Medicine*, **169**, 18-26, doi:10.1016/j.socscimed.2016.09.026.

Clark, M. and D. Tilman, 2017: Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, **12(6)**, 064016, doi:https://doi.org/10.1088/1748-9326/aa6cd5.

Clarke, L. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413-510.

Clemens, M., J. Rijke, A. Pathirana, J. Evers, and N. Hong Quan, 2015: Social learning for adaptation to climate change in developing countries: insights from Vietnam. *Journal of Water and Climate Change*, **8(4)**, doi:10.2166/wcc.2015.004.

Clements, J., A. Ray, and G. Anderson, 2013: *The Value of Climate Services Across Economic and Public Sectors: A Review of Relevant Literature*. United States Agency for International Development (USAID).

Clerici, A., B. Cova, and G. Callegari, 2015: Decarbonization of the Electrical Power Sector in Europe: An Asset, An Opportunity or a Problem? *Energy & Environment*, **26(1-2)**, 127-142, doi:10.1260/0958-305X.26.1-2.127.

Climate Council, 2017: *Energy Storage: Poll of Australians August 2017*. 10 pp.

Cloutier, G. et al., 2015: Planning adaptation based on local actors' knowledge and participation: a climate governance experiment. *Climate Policy*, **15(4)**, 458-474, doi:10.1080/14693062.2014.937388.

Cochrane, L. et al., 2017: A reflection on collaborative adaptation research in Africa and Asia. *Regional Environmental Change*, **17(5)**, 1553-1561, doi:10.1007/s10113-017-1140-6.

Cogley, J.G., 2017: Climate science: The future of Asia's glaciers. *Nature*, **549(7671)**, 166-167, doi:10.1038/549166a.

Colenbrander, S., A. Gouldson, A.H. Sudmant, and E. Papargyropoulou, 2015: The economic case for low-carbon development in rapidly growing developing world cities: A case study of Palembang, Indonesia. *Energy Policy*, **80**, 24-35, doi:10.1016/j.enpol.2015.01.020.

Colenbrander, S. et al., 2017: Can low-carbon urban development be pro-poor? The case of Kolkata, India. *Environment and Urbanization*, **29(1)**, 139-158, doi:10.1177/0956247816677775.

Collas, L., R.E. Green, A. Ross, J.H. Wastell, and A. Balmford, 2017: Urban development, land sharing and land sparing: the importance of considering restoration. *Journal of Applied Ecology*, **54(6)**, 1865-1873, doi:10.1111/1365-2664.12908.

Comello, S.D., S.J. Reichelstein, A. Sahoo, and T.S. Schmidt, 2017: Enabling Mini-Grid Development in Rural India. *World Development*, **93**, 94-107, doi:10.1016/j.worlddev.2016.12.029.

Conant, R.T., 2011: Sequestration through forestry and agriculture. *Wiley Interdisciplinary Reviews: Climate Change*, **2(2)**, 238-254, doi:10.1002/wcc.101.

Confalonieri, U.E.C., J.A. Menezes, and C.M. de Souza, 2015: Climate change and adaptation of the health sector: the case of infectious diseases. *Virulence*, **6(6)**, 554-557, doi:10.1080/21505594.2015.1023985.

Connor, P.M. et al., 2014: Policy and regulation for smart grids in the United Kingdom. *Renewable and Sustainable Energy Reviews*, **40**, 269-286, doi:10.1016/j.rser.2014.07.065.

Cook, C.L. and H. Dowlatabadi, 2011: Learning adaptation: Climate-related risk management in the insurance industry. *Climate Change Adaptation in Developed Nations: From Theory to Practice*, 255-266.

Cooney, G., J. Littlefield, J. Marriott, and T.J. Skone, 2015: Evaluating the Climate Benefits of CO_2-Enhanced Oil Recovery Using Life Cycle Analysis. *Environmental Science & Technology*, **49(12)**, 7491-7500, doi:10.1021/acs.est.5b00700.

Cooper, J.A.G., M.C. O'Connor, and S. McIvor, 2016: Coastal defences versus coastal ecosystems: A regional appraisal. *Marine Policy* (in press), doi:10.1016/j.marpol.2016.02.021.

Coq-Huelva, D., A. Higuchi, R. Alfalla-Luque, R. Burgos-Morán, and R. Arias-Gutiérrez, 2017: Co-Evolution and Bio-Social Construction: The Kichwa Agroforestry Systems (Chakras) in the Ecuadorian Amazonia. *Sustainability*, **9(11)**, 1920, doi:10.3390/su9101920.

Corbett, J.J., H. Wang, and J.J. Winebrake, 2009: The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment*, **14(8)**, 593-598, doi:10.1016/j.trd.2009.08.005.

Corfee-Morlot, J. et al., 2012: Towards a Green Investment Policy Framework:The Case Of Low-Carbon, Climate- Resilient Infrastructure. , 60, doi:10.1787/5k8zth7s6s6d-en.

Cornelissen, S., M. Koper, and Y.Y. Deng, 2012: The role of bioenergy in a fully sustainable global energy system. *Biomass and Bioenergy*, **41**, 21-33, doi:10.1016/j.biombioe.2011.12.049.

Corsatea, T.D., 2014: Technological capabilities for innovation activities across Europe: Evidence from wind, solar and bioenergy technologies. *Renewable and Sustainable Energy Reviews***, 37**, 469-479, doi:10.1016/J.RSER.2014.04.067.

Corsten, M., A. Ramírez, L. Shen, J. Koornneef, and A. Faaij, 2013: Environmental impact assessment of CCS chains - Lessons learned and limitations from LCA literature. *International Journal of Greenhouse Gas Control***, 13**, 59-71, doi:10.1016/j.ijggc.2012.12.003.

Cortekar, J. and M. Groth, 2015: Adapting energy infrastructure to climate change - Is there a need for government interventions and legal obligations within the German "energiewende"? *Energy Procedia***, 73**, 12-17, doi:10.1016/j.egypro.2015.07.552.

Cortekar, J., S. Bender, M. Brune, and M. Groth, 2016: Why climate change adaptation in cities needs customised and flexible climate services. *Climate Services***, 4**, 42-51, doi:10.1016/j.cliser.2016.11.002.

Costa, D., P. Burlando, and C. Priadi, 2016: The importance of integrated solutions to flooding and water quality problems in the tropical megacity of Jakarta. *Sustainable Cities and Society***, 20(Supplement C)**, 199-209, doi:10.1016/j.scs.2015.09.009.

Coulibaly, J.Y., B. Chiputwa, T. Nakelse, and G. Kundhlande, 2017: Adoption of agroforestry and the impact on household food security among farmers in Malawi. *Agricultural Systems***, 155**, 52-69, doi:10.1016/j.agsy.2017.03.017.

Coulibaly, Y.J., G. Kundhlande, A. Tall, H. Kaur, and J. Hansen, 2015: Which climate services do farmers and pastoralists need in Malawi? Baseline Study for the GFCS Adaptation Program in Africa. CCAFS Working Paper, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)., Copenhagen, Denmark.

Council, C., 2016: *Renewable Energy Jobs: Future Growth in Australia*. Climate Council, Potts Point, NSW, 60 pp.

Council, C., 2017: *State of Solar 2016: Globally and in Australia*. Climate Council, Potts Point, NSW, 24 pp.

Council, C.E., 2012: *Wind Farm Investment and Employment And Carbon Abatement in Australia*. Clean Energy Council, Melbourne, VIC, 45 pp.

Crate, S. et al., 2017: Permafrost livelihoods: A transdisciplinary review and analysis of thermokarst-based systems of indigenous land use. *Anthropocene***, 18**, 89-104, doi:10.1016/j.ancene.2017.06.001.

Creutzig, F., E. Corbera, S. Bolwig, and C. Hunsberger, 2013: Integrating place-specific livelihood and equity outcomes into global assessments of bioenergy deployment. *Environmental Research Letters***, 8(3)**, 035047, doi:10.1088/1748-9326/8/3/035047.

Creutzig, F. et al., 2015: Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy***, 7(5)**, 916-944, doi:10.1111/gcbb.12205.

Crispim, J., J. Braz, R. Castro, and J. Esteves, 2014: Smart Grids in the EU with smart regulation: Experiences from the UK, Italy and Portugal. *Utilities Policy***, 31**, 85-93, doi:10.1016/j.jup.2014.09.006.

Crnčević, T. and V. Orlović Lovren, 2018: Displacement and climate change: improving planning policy and increasing community resilience. *International Journal of Climate Change Strategies and Management***, 10(1)**, 105-120.

Cronin, T. et al., 2016: Moving consensus and managing expectations: media and REDD+ in Indonesia. *Climatic Change***, 137(1-2)**, 57-70, doi:10.1007/s10584-015-1563-3.

Cuéllar-Franca, R.M. and A. Azapagic, 2015: Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of* CO_2 *Utilization***, 9**, 82-102, doi:10.1016/j.jcou.2014.12.001.

Cui, Z. et al., 2018: Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, doi:10.1038/nature25785.

Culwick, C. and K. Bobbins, 2016: *A Framework for a Green Infrastructure Planning Approach in the Gauteng City-Region*. GCRO, Johannesburg, 132 pp.

Cunningham, S.C. et al., 2015: Balancing the environmental benefits of reforestation in agricultural regions. *Perspectives in Plant Ecology, Evolution and Systematics***, 17(4)**, 301-317, doi:10.1016/j.ppees.2015.06.001.

Cunsolo Willox, A., S.L. Harper, and V.L. Edge, 2013: Storytelling in a digital age: digital storytelling as an emerging narrative method for preserving and promoting indigenous oral wisdom. *Qualitative Research***, 13(2)**, 127-147, doi:10.1177/1468794112446105.

Cunsolo Willox, A. et al., 2012: "From this place and of this place:" Climate change, sense of place, and health in Nunatsiavut, Canada. *Social Science and Medicine*, **75(3)**, 538-547, doi:10.1016/j.socscimed.2012.03.043.

Cunsolo Willox, A. et al., 2015: Examining relationships between climate change and mental health in the Circumpolar North. *Regional Environmental Change*, **15(1)**, 169-182, doi:10.1007/s10113-014-0630-z.

Dagnachew, A.G., P.L. Lucas, A.F. Hof, and D.P. van Vuuren, 2018: Trade-offs and synergies between universal electricity access and climate change mitigation in Sub-Saharan Africa. *Energy Policy*, **114**, 355-366, doi:10.1016/j.enpol.2017.12.023.

Daioglou, V. et al., 2017: Greenhouse gas emission curves for advanced biofuel supply chains. *Nature Climate Change*, **7(12)**, 920-924, doi:10.1038/s41558-017-0006-8.

Dale, V.H., E.S. Parish, and K.L. Kline, 2015: Risks to global biodiversity from fossil-fuel production exceed those from biofuel production. *Biofuels, Bioproducts and Biorefining*, **9(2)**, 177-189, doi:10.1002/bbb.1528.

Dallimer, M. and N. Strange, 2015: Why socio-political borders and boundaries matter in conservation. *Trends in Ecology and Evolution*, **30(3)**, 132-139, doi:10.1016/j.tree.2014.12.004.

Daly, P. et al., 2017: Rehabilitating coastal agriculture and aquaculture after inundation events: Spatial analysis of livelihood recovery in post-tsunami Aceh, Indonesia. *Ocean and Coastal Management*, **142**, 218-232, doi:10.1016/j.ocecoaman.2017.03.027.

DaMatta, F.M., A. Grandis, B.C. Arenque, and M.S. Buckeridge, 2010: Impacts of climate changes on crop physiology and food quality. *Food Research International*, **43(7)**, 1814-1823, doi:10.1016/j.foodres.2009.11.001.

Dang Phan, T.–H., R. Brouwer, and M. Davidson, 2014: The economic costs of avoided deforestation in the developing world: A meta-analysis. *Journal of Forest Economics*, **20(1)**, 1-16, doi:10.1016/j.jfe.2013.06.004.

David, G.S., E.D. Carvalho, D. Lemos, A.N. Silveira, and M. Dall'Aglio-Sobrinho, 2015: Ecological carrying capacity for intensive tilapia (Oreochromis niloticus) cage aquaculture in a large hydroelectrical reservoir in Southeastern Brazil. *Aquacultural Engineering*, **66**, 30-40, doi:10.1016/j.aquaeng.2015.02.003.

Davidse, B.J., M. Othengrafen, and S. Deppisch, 2015: Spatial planning practices of adapting to climate change. *European Journal of Spatial Development*, **57(57)**, 1-21.

Davies, M., C. Béné, A. Arnall, A. Newsham, and C. Coirolo, 2013: Promoting Resilient Livelihoods through Adaptive Social Protection: Lessons from 124 programmes in South Asia. *Development Policy Review*, **31(1)**, 27-58.

de Besi, M. and K. McCormick, 2015: Towards a Bioeconomy in Europe: National, Regional and Industrial Strategies. *Sustainability*, **7(8)**, 10461-10478, doi:10.3390/su70810461.

de Coninck, H.C. and S.M. Benson, 2014: Carbon Dioxide Capture and Storage: Issues and Prospects. *Annual Review of Environment and Resources*, **39**, 243-70, doi:10.1146/annurev-environ-032112-095222.

de Groot, J. and L. Steg, 2007: General Beliefs and the Theory of Planned Behavior: The Role of Environmental Concerns in the TPB. *Journal of Applied Social Psychology*, **37(8)**, 1817-1836, doi:10.1111/j.1559-1816.2007.00239.x.

de Jong, S. et al., 2017: Life-cycle analysis of greenhouse gas emissions from renewable jet fuel production. *Biotechnology for Biofuels*, **10(1)**, 64, doi:10.1186/s13068-017-0739-7.

de Leon, E.G. and J. Pittock, 2017: Integrating climate change adaptation and climate-related disaster risk-reduction policy in developing countries: A case study in the Philippines. *Climate and Development*, **9(5)**, 471-478, doi:10.1080/17565529.2016.1174659.

De Silva, S.S. and F.B. Davy, 2010: Success stories in asian aquaculture. *Success Stories in Asian Aquaculture*, 1-214, doi:10.1007/978-90-481-3087-0.

De Souza, A.P., J.–C. Cocuron, A.C. Garcia, A.P. Alonso, and M.S. Buckeridge, 2015: Changes in Whole-Plant Metabolism during the Grain-Filling Stage in Sorghum Grown under Elevated CO_2 and Drought. *Plant physiology*, **169(3)**, 1755-65, doi:10.1104/pp.15.01054.

De Visser, E. et al., 2011: PlantaCap: A ligno-cellulose bio-ethanol plant with CCS. *Energy Procedia*, **4**, 2941-2949, doi:10.1016/j.egypro.2011.02.202.

DeCicco, J.M. et al., 2016: Carbon balance effects of U.S. biofuel production and use. *Climatic Change*, **138(3-4)**, 667-680, doi:10.1007/s10584-016-1764-4.

Deenihan, G. and B. Caulfield, 2014: Estimating the health economic benefits of cycling. *Journal of Transport & Health*, **1(2)**, 141-149, doi:10.1016/j.jth.2014.02.001.

del Ninno, C., S. Coll-Black, and P. Fallavier, 2016: Social Protection: Building Resilience Among the Poor and Protecting the Most Vulnerable. In: *Confronting Drought in Africa's Drylands: Opportunities for Enhancing Resilience*. Africa Development Forum, The World Bank, pp. 165-184.

Delshad, A. and L. Raymond, 2013: Media Framing and Public Attitudes Toward Biofuels. *Review of Policy Research*, **30(2)**, 190-210, doi:10.1111/ropr.12009.

Demirbas, A.H. and I. Demirbas, 2007: Importance of rural bioenergy for developing countries. *Energy Conversion and Management*, **48(8)**, 2386-2398, doi:10.1016/j.enconman.2007.03.005.

Demuzere, M. et al., 2014: Mitigating and adapting to climate change: Multi-functional and multi-scale assessment of green urban infrastructure. *Journal of Environmental Management*, **146**, 107-115, doi:10.1016/j.jenvman.2014.07.025.

Deng, Q. et al., 2017: A global meta-analysis of soil phosphorus dynamics after afforestation. *New Phytologist*, **213(1)**, 181-192, doi:10.1111/nph.14119.

Deng, X. and C. Zhao, 2015: Identification of Water Scarcity and Providing Solutions for Adapting to Climate Changes in the Heihe River Basin of China. *Advances in Meteorology*, **2015**, 1-13, doi:10.1155/2015/279173.

Deng, Y.Y., M. Koper, M. Haigh, and V. Dornburg, 2015: Country-level assessment of long-term global bioenergy potential. *Biomass and Bioenergy*, **74**, 253-267, doi:10.1016/J.BIOMBIOE.2014.12.003.

DeNooyer, T.A., J.M. Peschel, Z. Zhang, and A.S. Stillwell, 2016: Integrating water resources and power generation: The energy-water nexus in Illinois. *Applied Energy*, **162**, 363-371, doi:10.1016/j.apenergy.2015.10.071.

Derakhshan, G., H.A. Shayanfar, and A. Kazemi, 2016: The optimization of demand response programs in smart grids. *Energy Policy*, **94**, 295-306, doi:10.1016/j.enpol.2016.04.009.

Descheemaeker, K. et al., 2016: Climate change adaptation and mitigation in smallholder crop--livestock systems in sub-Saharan Africa: a call for integrated impact assessments. *Regional Environmental Change*, **16(8)**, 2331-2343.

Despotou, E., 2012: Vision for Photovoltaics in the Future. *Comprehensive Renewable Energy*, **1(10)**, 179-198, doi:10.1016/B978-0-08-087872-0.00109-8.

Dessens, O., A. Anger, T. Barker, and J. Pyle, 2014: Effects of decarbonising international shipping and aviation on climate mitigation and air pollution. *Environmental Science & Policy*, **44**, 1-10, doi:10.1016/j.envsci.2014.07.007.

Devereux, S., 2016: Social protection for enhanced food security in sub-Saharan Africa. *Food Policy*, **60**, 52-62, doi:10.1016/j.foodpol.2015.03.009.

Devereux, S. et al., 2015: Evaluating the targeting effectiveness of social transfers: A literature review. Institute of Development Studies.

Dhar, S., M. Pathak, and P.R. Shukla, 2017: Electric vehicles and India's low carbon passenger transport: a long-term co-benefits assessment. *Journal of Cleaner Production*, **146(Supplement C)**, 139-148, doi:10.1016/j.jclepro.2016.05.111.

Dhar, S., M. Pathak, and P.R. Shukla, 2018: Transformation of India's transport sector under global warming of 2 °C and 1.5 °C scenario. *Journal of Cleaner Production*, **172**, 417-427, doi:10.1016/j.jclepro.2017.10.076.

Dhar, T.K. and L. Khirfan, 2017: Climate change adaptation in the urban planning and design research: missing links and research agenda. *Journal of Environmental Planning and Management*, **60(4)**, 602-627, doi:10.1080/09640568.2016.1178107.

Di Gregorio, M., C.T. Gallemore, M. Brockhaus, L. Fatorelli, and E. Muharrom, 2017a: How institutions and beliefs affect environmental discourse: Evidence from an eight-country survey on REDD+. *Global Environmental Change*, **45**, 133-150, doi:10.1016/J.GLOENVCHA.2017.05.006.

Di Gregorio, M. et al., 2017b: Climate policy integration in the land use sector: Mitigation, adaptation and sustainable development linkages. *Environmental Science & Policy*, **67**, 35-43, doi:10.1016/J.ENVSCI.2016.11.004.

Diaz, D.B., 2016: Estimating global damages from sea level rise with the Coastal Impact and Adaptation Model (CIAM). *Climatic Change*, **137(1)**, 143-156, doi:10.1007/s10584-016-1675-4.

Díaz, S., D.A. Wardle, and A. Hector, 2009: Incorporating biodiversity in climate change mitigation initiatives. In: *Biodiversity, Ecosystem Functioning, and Human Wellbeing*. Oxford University Press, Oxford.

Diaz-Maurin, F. and Z. Kovacic, 2015: The unresolved controversy over nuclear power: A new approach from complexity theory. *Global Environmental Change*, **31**, 207-216, doi:10.1016/j.gloenvcha.2015.01.014.

Diczfalusy, B. and P. Taylor, 2011: *Technology roadmap, energy-efficient buildings: heating and cooling equipment*.

Dilling, L. and E. Failey, 2013: Managing carbon in a multiple use world: The implications of land-use decision context for carbon management. *Global Environmental Change*, **23(1)**, 291-300, doi:10.1016/J.GLOENVCHA.2012.10.012.

Dinku, T. et al., 2014: Bridging critical gaps in climate services and applications in africa. *Earth Perspectives*, **1(1)**, 15, doi:10.1186/2194-6434-1-15.

Dixon, R.K., J.K. Winjum, and P.E. Schroeder, 1993: Conservation and sequestration of carbon: The potential of forest and agroforest management practices. *Global Environmental Change*, **3(2)**, 159-173, doi:https://doi.org/10.1016/0959-3780(93)90004-5.

Dixon, R.K., J.K. Winjum, K.J. Andrasko, J.J. Lee, and P.E. Schroeder, 1994: Integrated land-use systems: Assessment of promising agroforest and alternative land-use practices to enhance carbon conservation and sequestration. *Climatic Change*, **27(1)**, 71-92, doi:10.1007/BF01098474.

Dixon, T., S.T. McCoy, and I. Havercroft, 2015: Legal and Regulatory Developments on CCS. *International Journal of Greenhouse Gas Control*, **40**, 431-448, doi:https://doi.org/10.1016/j.ijggc.2015.05.024.

Dodman, D., S. Colenbrander, and D. Archer, 2017a: Conclusion. In: *Responding to climate change in Asian cities: Governance for a more resilient urban future* [Archer, D., S. Colenbrander, and D. Dodman (eds.)]. Routledge Earthscan, Abingdon, UK.

Dodman, D., H. Leck, M. Rusca, and S. Colenbrander, 2017b: African Urbanisation and Urbanism: Implications for risk accumulation and reduction. *International Journal of Disaster Risk Reduction*, **26(June)**, 7-15, doi:10.1016/j.ijdrr.2017.06.029.

Dominy, S.W.J. et al., 2010: A retrospective and lessons learned from Natural Resources Canada's Forest 2020 afforestation initiative. *The Forestry Chronicle*, **86(3)**, 339-347, doi:10.5558/tfc86339-3.

Dong, S., 2017: Himalayan Grasslands: Indigenous Knowledge and Institutions for Social Innovation BT - Environmental Sustainability from the Himalayas to the Oceans: Struggles and Innovations in China and India. In: [Dong, S., J. Bandyopadhyay, and S. Chaturvedi (eds.)]. Springer International Publishing, Cham, pp. 99-126.

Dooley, J.J.J., 2013: Estimating the supply and demand for deep geologic CO_2 storage capacity over the course of the 21st century: A meta-analysis of the literature. *Energy Procedia*, **37**, 5141-5150, doi:10.1016/j.egypro.2013.06.429.

Dornburg, V. et al., 2010: Bioenergy revisited: Key factors in global potentials of bioenergy. *Energy & Environmental Science*, **3(3)**, 258, doi:10.1039/b922422j.

Dorward, P., G. Clarkson, and R. Stern, 2015: *Participatory integrated climate services for agriculture (PICSA): Field manual*. 65 pp.

Dougill, A.J. et al., 2017: Mainstreaming conservation agriculture in Malawi: Knowledge gaps and institutional barriers. *Journal of Environmental Management*, **195**, 25-34, doi:10.1016/j.jenvman.2016.09.076.

Dowd, A.–M., M. Rodriguez, and T. Jeanneret, 2015: Social Science Insights for the BioCCS Industry. *Energies*, **8(5)**, 4024-4042, doi:10.3390/en8054024.

Downie, A., D. Lau, A. Cowie, and P. Munroe, 2014: Approaches to greenhouse gas accounting methods for biomass carbon. *Biomass and Bioenergy*, **60**, 18-31, doi:10.1016/J.BIOMBIOE.2013.11.009.

Dragojlovic, N. and E. Einsiedel, 2015: What drives public acceptance of second-generation biofuels? Evidence from Canada. *Biomass and Bioenergy*, **75**, 201-212, doi:10.1016/J.BIOMBIOE.2015.02.020.

Drielsma, M.J. et al., 2017: Bridging the gap between climate science and regional-scale biodiversity conservation in south-eastern Australia. *Ecological Modelling*, **360**, 343-362, doi:10.1016/j.ecolmodel.2017.06.022.

Duarte, C.M., I.J. Losada, I.E. Hendriks, I. Mazarrasa, and N. Marbà, 2013: The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, **3(11)**, 961-968, doi:10.1038/nclimate1970.

Duguma, L.A., P.A. Minang, and M. Van Noordwijk, 2014: Climate change mitigation and adaptation in the land use sector: From complementarity to synergy. *Environmental Management***, 54(3)**, 420-432, doi:10.1007/s00267-014-0331-x.

Durkalec, A., C. Furgal, M.W. Skinner, and T. Sheldon, 2015: Climate change influences on environment as a determinant of Indigenous health: Relationships to place, sea ice, and health in anInuit community. *Social Science and Medicine***, 136-137**, 17-26, doi:10.1016/j.socscimed.2015.04.026.

Duvat, V., 2013: Coastal protection structures in Tarawa Atoll, Republic of Kiribati. *Sustainability Science***, 8(3)**, 363-379, doi:10.1007/s11625-013-0205-9.

Eakin, H.C.C., M.C.C. Lemos, and D.R.R. Nelson, 2014: Differentiating capacities as a means to sustainable climate change adaptation. *Global Environmental Change***, 27(1)**, 1-8, doi:10.1016/j.gloenvcha.2014.04.013.

Eberhard, A., J. Kolker, and J. Leigland, 2014: *South Africa's Renewable Energy IPP Procurement Program: Success Factors and Lessons*. Public-Private Infrastructure Advisory Facility (PPIAF), Washington, DC, 1-56 pp.

Eberhard, A., O. Rosnes, M. Shkaratan, and H. Vennemo, 2011: *Africa's Power Infrastructure: Investment, Integration, Efficiency*. 352 pp.

Eberhard, A., K. Gratwick, E. Morella, and P. Antmann, 2016: *Independent Power Projects in Sub-Saharan Africa: Lessons from Five Key Countries*. The World Bank, Washington, DC, 382 pp.

Ebi, K.L. and M.O. del Barrio, 2017: Lessons Learned on Health Adaptation to Climate Variability and Change: Experiences Across Low- and Middle-Income Countries. *Environmental Health Perspectives***, 125(7)**, doi:10.1289/EHP405.

Ebi, K.L. and J.J. Hess, 2017: The past and future in understanding the health risks of and responses to climate variability and change. *International Journal of Biometeorology***, 61**, 71-80, doi:10.1007/s00484-017-1406-1.

Ebi, K.L., J.C. Semenza, and J. Rocklöv, 2016: Current medical research funding and frameworks are insufficient to address the health risks of global environmental change. *Environmental Health***, 15(1)**, 108, doi:10.1186/s12940-016-0183-3.

Ebi, K.L., T.J. Teisberg, L.S. Kalkstein, L. Robinson, and R.F. Weiher, 2004: Heat watch/warning systems save lives: Estimated costs and benefits for Philadelphia 1995-98. *Bulletin of the American Meteorological Society*, doi:10.1175/BAMS-85-8-1067.

Edwards, D.P. et al., 2017: Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture.. *Biology letters***, 13(4)**, 20160715, doi:10.1098/rsbl.2016.0715.

Edwards, P., 2015: Aquaculture environment interactions: Past, present and likely future trends. *Aquaculture***, 447**, 2-14, doi:10.1016/j.aquaculture.2015.02.001.

EEA, 2017: *Aviation and shipping - impacts on Europe's environment: TERM 2017: Transport and Environment Reporting Mechanism (TERM) report*. European Environment Agency (EEA), Copenhagen, 70 pp.

Eisenack, K. and R. Stecker, 2012: A framework for analyzing climate change adaptations as actions. *Mitigation and Adaptation Strategies for Global Change***, 17(3)**, 243-260, doi:10.1007/s11027-011-9323-9.

Eisenberg, D.A., 2016: Transforming building regulatory systems to address climate change. *Building Research & Information***, 44(5-6)**, 468-473, doi:10.1080/09613218.2016.1126943.

Elliott, J. et al., 2014: Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences***, 111(9)**, 3239-3244, doi:10.1073/pnas.1222474110.

Elliott, M. and E. Wolanski, 2015: Editorial - Climate change impacts on rural poverty in low-elevation coastal zones, Edward B. Barbier. *Estuarine, Coastal and Shelf Science***, 165**, ii-iii, doi:10.1016/S0272-7714(15)00287-5.

Ellison, D. et al., 2017: Trees, forests and water: Cool insights for a hot world. *Global Environmental Change***, 43**, 51-61, doi:10.1016/j.gloenvcha.2017.01.002.

Elmqvist, T. et al., 2013a: *The world's first global assessment of the effects of urbanization on biodiversity and ecosystem services*.

Elmqvist, T. et al., 2013b: *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities A Global Assessment*. Springer, Dordrecht Heidelberg New York London, 755 pp.

Elmqvist, T. et al., 2015: Benefits of restoring ecosystem services in urban areas. *Current Opinion in Environmental Sustainability*, **14(Supplement C)**, 101-108, doi:10.1016/j.cosust.2015.05.001.

Emmer, A., J. Klimeš, M. Mergili, V. Vilímek, and A. Cochachin, 2016: 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods. *CATENA*, **147(Supplement C)**, 269-279, doi:https://doi.org/10.1016/j.catena.2016.07.032.

Endo, I. et al., 2017: Participatory land-use approach for integrating climate change adaptation and mitigation into basin-scale local planning. *Sustainable Cities and Society*, **35**, 47-56, doi:10.1016/j.scs.2017.07.014.

Endo, S. et al., 2012: Measurement of soil contamination by radionuclides due to the Fukushima Dai-ichi Nuclear Power Plant accident and associated estimated cumulative external dose estimation. *Journal of Environmental Radioactivity*, **111**, 18-27, doi:10.1016/j.jenvrad.2011.11.006.

Ensor, J. and B. Harvey, 2015: Social learning and climate change adaptation: evidence for international development practice. *Wiley Interdisciplinary Reviews: Climate Change*, **6(5)**, 509-522, doi:10.1002/wcc.348.

Ensor, J.E., S.E. Park, S.J. Attwood, A.M. Kaminski, and J.E. Johnson, 2016: Can community-based adaptation increase resilience? *Climate and Development*, 1-18, doi:10.1080/17565529.2016.1223595.

Ensor, J.E. et al., 2018: Variation in perception of environmental change in nine Solomon Islands communities: implications for securing fairness in community-based adaptation. *Regional Environmental Change*, **18(4)**, 1131-1143, doi:10.1007/s10113-017-1242-1.

Erb, K.–H., H. Haberl, and C. Plutzar, 2012: Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy*, **47**, 260-269, doi:10.1016/j.enpol.2012.04.066.

Erb, K.–H. et al., 2016: Exploring the biophysical option space for feeding the world without deforestation. *Nature Communications*, **7**, 11382, doi:10.1038/NCOMMS11382.

Erb, K.–H. et al., 2017: Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature*, **553(7686)**, 73-76, doi:10.1038/nature25138.

Ertör, I. and M. Ortega-Cerdà, 2017: Unpacking the objectives and assumptions underpinning European aquaculture. *Environmental Politics*, **26(5)**, 893-914, doi:10.1080/09644016.2017.1306908.

Essl, I. and V. Mauerhofer, 2018: Opportunities for mutual implementation of nature conservation and climate change policies: A multilevel case study based on local stakeholder perceptions. *Journal of Cleaner Production*, **183**, 898-907, doi:10.1016/j.jclepro.2018.01.210.

Esteban, M. and J. Portugal-Pereira, 2014: Post-disaster resilience of a 100% renewable energy system in Japan. *Energy*, **68**, 756-764, doi:10.1016/j.energy.2014.02.045.

Esteve, P., C. Varela-Ortega, I. Blanco-Gutiérrez, and T.E. Downing, 2015: A hydro-economic model for the assessment of climate change impacts and adaptation in irrigated agriculture. *Ecological Economics*, **120**, 49-58, doi:10.1016/j.ecolecon.2015.09.017.

Estrada, F., R. Tol, and W. Botzen, 2017: A global economic assessment of city policies to reduce climate change impacts. *Nature Climate Change*, **7(June 2017)**, 403-406, doi:10.1038/nclimate3301.

Evans, M.C. et al., 2015: Carbon farming via assisted natural regeneration as a cost-effective mechanism for restoring biodiversity in agricultural landscapes. *Environmental Science & Policy*, **50**, 114-129, doi:10.1016/J.ENVSCI.2015.02.003.

Ewing, M. and S. Msangi, 2009: Biofuels production in developing countries: assessing tradeoffs in welfare and food security. *Environmental Science & Policy*, **12(4)**, 520-528, doi:10.1016/J.ENVSCI.2008.10.002.

Ewing, R., S. Hamidi, and J.B. Grace, 2016: Compact development and VMT-Environmental determinism, self-selection, or some of both? *Environment and Planning B: Planning and Design*, **43(4)**, 737-755, doi:10.1177/0265813515594811.

Fabbri, A. et al., 2011: From geology to economics: Technico-economic feasibility of a biofuel-CCS system. *Energy Procedia*, **4**, 2901-2908, doi:10.1016/j.egypro.2011.02.197.

Fabian, N., 2015: Economics: Support low-carbon investment. *Nature*, **519(7541)**, 27-29, doi:10.1038/519027a.

Fader, M., S. Shi, W. von Bloh, A. Bondeau, and W. Cramer, 2016: Mediterranean irrigation under climate change: more efficient irrigation needed to compensate for increases in irrigation water requirements. *Hydrology and Earth System Sciences*, **20(2)**, 953-973, doi:10.5194/hess-20-953-2016.

Falco, S., F. Adinolfi, M. Bozzola, and F. Capitanio, 2014: Crop insurance as a strategy for adapting to climate change. *Journal of Agricultural Economics*, **65(2)**, 485-504.

Falconnier, G.N., K. Descheemaeker, B. Traore, A. Bayoko, and K.E. Giller, 2018: Agricultural intensification and policy interventions: Exploring plausible futures for smallholder farmers in Southern Mali. *Land Use Policy*, **70**, 623-634, doi:10.1016/j.landusepol.2017.10.044.

FAO, 2013a: *Food wastage footprint. Impacts on natural resources. Summary Report*. Food and Agriculture Organisation of the United Nations, Rome, Italy, 63 pp.

FAO, 2013b: *The state of Food and Agriculture: Food systems for better nutrition*. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO, 2016: *The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all*. 200 pp.

FAO, IFAD, UNICEF, WFP, and WHO, 2017: The state of food security and nutrition in the world. Building resilience for peace and food security.. 117 pp.

FAO & NZAGRC, 2017: *Options for low emission development in the Kenya dairy sector - reducing enteric methane for food security and livelihoods*. FAO & New Zealand Agricultural Greenhouse Gas Research Centre, Rome, Italy, 43 pp.

Färe, R., S. Grosskopf, C.A. Pasurka, and R. Shadbegian, 2018: Pollution abatement and employment. *Empirical Economics*, **54(1)**, 259-285, doi:10.1007/s00181-016-1205-2.

Farzaneh, M., M.S. Allahyari, C.A. Damalas, and A. Seidavi, 2017: Crop insurance as a risk management tool in agriculture: The case of silk farmers in northern Iran. *Land Use Policy*, **64**, 225-232.

Favretto, N., L.C. Stringer, M.S. Buckeridge, and S. Afionis, 2017: Policy and Diplomacy in the Production of Second Generation Ethanol in Brazil: International Relations with the EU, the USA and Africa BT - Advances of Basic Science for Second Generation Bioethanol from Sugarcane. In: *Advances of Basic Science for Second Generation from Sugarcane* [Buckeridge, M.S. and A.P. De Souza (eds.)]. Springer International Publishing, New York, pp. 197-212.

Feeley, K.J. and M.R. Silman, 2016: Disappearing climates will limit the efficacy of Amazonian protected areas. *Diversity and Distributions*, **22(11)**, 1081-1084, doi:10.1111/ddi.12475.

Felton, A. et al., 2016: How climate change adaptation and mitigation strategies can threaten or enhance the biodiversity of production forests: Insights from Sweden. *Biological Conservation*, **194**, 11-20, doi:10.1016/j.biocon.2015.11.030.

FEMA, 2014: *Building Science Support and Code Changes Aiding Sandy Recovery. Hurricane Sandy Recovery Fact Sheet No. 3*. 4 pp.

Fenger, A.N., A. Skovmand Bosselmann, R. Asare, and A. de Neergaard, 2017: The impact of certification on the natural and financial capitals of Ghanaian cocoa farmers. *Agroecology and Sustainable Food Systems*, **41(2)**, 143-166, doi:10.1080/21683565.2016.1258606.

Fernández-Giménez, M.E., B. Batkhishig, B. Batbuyan, and T. Ulambayar, 2015: Lessons from the Dzud: Community-Based Rangeland Management Increases the Adaptive Capacity of Mongolian Herders to Winter Disasters. *World Development*, **68**, 48-65, doi:10.1016/j.worlddev.2014.11.015.

Fernández-Llamazares et al., 2017: An empirically tested overlap between indigenous and scientific knowledge of a changing climate in Bolivian Amazonia. *Regional Environmental Change*, **17(6)**, 1673-1685, doi:10.1007/s10113-017-1125-5.

Fernández-Viñé, M.B., T. Gómez-Navarro, and S.F. Capuz-Rizo, 2010: Eco-efficiency in the SMEs of Venezuela. Current status and future perspectives. *Journal of Cleaner Production*, **18(8)**, 736-746, doi:https://doi.org/10.1016/j.jclepro.2009.12.005.

Ferrario, F. et al., 2014: The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications*, **5(May)**, 1-9, doi:10.1038/ncomms4794.

Few, R., A. Martin, and N. Gross-Camp, 2017: Trade-offs in linking adaptation and mitigation in the forests of the Congo Basin. *Regional Environmental Change*, **17(3)**, 851-863, doi:10.1007/s10113-016-1080-6.

Fidelman, P., T. Van Tuyen, K. Nong, and M. Nursey-Bray, 2017: The institutions-adaptive capacity nexus: Insights from coastal resources co-management in Cambodia and Vietnam. *Environmental Science and Policy*, **76**, 103-112, doi:10.1016/j.envsci.2017.06.018.

Figueres, C. et al., 2017: Three years to safeguard our climate. *Nature*, **546(7660)**, 593-595.

Figueroa, P., 2016: Nuclear Risk Governance in Japan and the Fukushima Triple Disaster: Lessons Unlearned. In: *Disaster Governance in Urbanising Asia* [Miller, M.A. and M. Douglass (eds.)]. Springer Singapore, Singapore, pp. 263-282.

Figus, G., K. Turner, P. McGregor, and A. Katris, 2017: Making the case for supporting broad energy efficiency programmes: Impacts on household incomes and other economic benefits. *Energy Policy*, **111**, 157-165, doi:10.1016/j.enpol.2017.09.028.

Finon, D. and F.A. Roques, 2013: European Electricity Market Reforms: The "Visible Hand" of Public Coordination. *Economics of Energy & Environmental Policy*.

Fiorese, G., M. Catenacci, V. Bosetti, and E. Verdolini, 2014: The power of biomass: Experts disclose the potential for success of bioenergy technologies. *Energy Policy*, **65**, 94-114, doi:10.1016/j.enpol.2013.10.015.

Firth, L.B. et al., 2014: Between a rock and a hard place: Environmental and engineering considerations when designing coastal defence structures. *Coastal Engineering*, **87**, 122-135, doi:10.1016/j.coastaleng.2013.10.015.

Fischedick, M. et al., 2014: Industry. In: *Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, P.E. K. Seyboth, A. Adler, I. Baum, S. Brunner, and T.Z.J.C.M. B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 739-810.

Fischer, G. and L. Schrattenholzer, 2001: Global bioenergy potentials through 2050. *Biomass and Bioenergy*, **20(3)**, 151-159, doi:10.1016/S0961-9534(00)00074-X.

Fishman, R., N. Devineni, and S. Raman, 2015: Can improved agricultural water use efficiency save India's groundwater? *Environmental Research Letters*, **10(8)**, 84022.

Flynn, M., J. Ford, T. Pearce, S. Harper, and IHACC Research Team, 2018: Participatory scenario planning and climate change impacts, adaptation, and vulnerability research in the Arctic. *Environmental Science & Policy*, **79**, 45-53.

Foley, J.A. et al., 2011: Solutions for a cultivated planet. *Nature*, doi:10.1038/nature10452.

Forbes, B.C. et al., 2009: High resilience in the Yamal-Nenets social-ecological system, West Siberian Arctic, Russia. *Proceedings of the National Academy of Sciences*, **106(52)**, 22041-22048, doi:10.1073/pnas.0908286106.

Ford, J.D., 2012: Indigenous health and climate change. *American Journal of Public Health*, **102(7)**, 1260-1266, doi:10.2105/AJPH.2012.300752.

Ford, J.D., G. McDowell, and T. Pearce, 2015: The adaptation challenge in the Arctic. *Nature Climate Change*, **5(12)**, 1046-1053, doi:10.1038/nclimate2723.

Ford, J.D., T. Pearce, F. Duerden, C. Furgal, and B. Smit, 2010: Climate change policy responses for Canada's Inuit population: The importance of and opportunities for adaptation. *Global Environmental Change-Human and Policy Dimensions*, **20(1)**, 177-191, doi:10.1016/j.gloenvcha.2009.10.008.

Ford, J.D. et al., 2014: Adapting to the effects of climate change on inuit health. *American Journal of Public Health*, **104(SUPPL. 3)**, e9-e17, doi:10.2105/AJPH.2013.301724.

Ford, J.D. et al., 2016: Community-based adaptation research in the Canadian Arctic. *Wiley Interdisciplinary Reviews: Climate Change*, **7(2)**, 175-191, doi:10.1002/wcc.376.

Ford, J.D. et al., 2018: Preparing for the health impacts of climate change in Indigenous communities: The role of community-based adaptation. *Global Environmental Change*, **49**, 129-139.

Forman, C., I.K. Muritala, R. Pardemann, and B. Meyer, 2016: Estimating the global waste heat potential. *Renewable and Sustainable Energy Reviews*, **57(Supplement C)**, 1568-1579, doi:https://doi.org/10.1016/j.rser.2015.12.192.

Fornell, R., T. Berntsson, and A. Åsblad, 2013: Techno-economic analysis of a kraft pulp-mill-based biorefinery producing both ethanol and dimethyl ether. *Energy*, **50(1)**, 83-92, doi:10.1016/j.energy.2012.11.041.

Foxon, T. et al., 2015: Low carbon infrastructure investment: extending business models for sustainability. *Infrastructure Complexity*, **2(1)**, 1-13, doi:10.1186/s40551-015-0009-4.

Francesch-Huidobro, M., M. Dabrowski, Y. Tai, F. Chan, and D. Stead, 2017: Governance challenges of flood-prone delta cities: Integrating flood risk management and climate change in spatial planning. *Progress in Planning*, **114**, 1-27, doi:10.1016/j.progress.2015.11.001.

Frank, S. et al., 2013: How effective are the sustainability criteria accompanying the European Union 2020 biofuel targets? *GCB Bioenergy*, **5(3)**, 306-314, doi:10.1111/j.1757-1707.2012.01188.x.

Franke, A.C., G.J. van den Brand, and K.E. Giller, 2014: Which farmers benefit most from sustainable intensification? An ex-ante impact assessment of expanding grain legume production in Malawi. *European Journal of Agronomy*, **58**, 28-38, doi:10.1016/j.eja.2014.04.002.

Frankenberg, E., B. Sikoki, C. Sumantri, W. Suriastini, and D. Thomas, 2013: Education, Vulnerability, and Resilience after a Natural Disaster. *Ecology and Society*, **18(2)**, doi:10.5751/ES-05377-180216.

Fraser, E. et al., 2016: Biotechnology or organic? Extensive or intensive? Global or local? A critical review of potential pathways to resolve the global food crisis. *Trends in Food Science & Technology*, **48**, 78-87, doi:10.1016/j.tifs.2015.11.006.

Fricko, O. et al., 2016: Energy sector water use implications of a 2°C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.

Fridahl, M., 2017: Socio-political prioritization of bioenergy with carbon capture and storage. *Energy Policy*, **104**, 89-99, doi:10.1016/J.ENPOL.2017.01.050.

Fridman, M., A.K.– Lam, and O. Krasko, 2016: Characteristics of young adults of Belarus with post-Chernobyl papillary thyroid carcinoma: a long-term follow-up of patients with early exposure to radiation at the 30th anniversary of the accident. *Clinical Endocrinology*, **85(6)**, 971-978, doi:10.1111/cen.13137.

Fu, X. and J. Song, 2017: Assessing the economic costs of sea level rise and benefits of coastal protection: A spatiotemporal approach. *Sustainability*, **9(8)**, doi:10.3390/su9081495.

Fuentes-Saguar, P.D., A.J. Mainar-Causapé, and E. Ferrari, 2017: The Role of Bioeconomy Sectors and Natural Resources in EU Economies: A Social Accounting Matrix-Based Analysis Approach. *Sustainability*, **9(12)**.

Furtado, A.T. and R. Perrot, 2015: Innovation dynamics of the wind energy industry in South Africa and Brazil: technological and institutional lock-ins. *Innovation and Development*, **5(2)**, 263-278, doi:10.1080/2157930X.2015.1057978.

Fuso Nerini, F. et al., 2018: Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nature Energy*, **3(1)**, 10-15, doi:10.1038/s41560-017-0036-5.

Fuss, S. et al., 2014: Betting on negative emissions. *Nature Climate Change*, **4(10)**, 850-853, doi:10.1038/nclimate2392.

Fuss, S. et al., 2018: Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Letters* (in press), doi:https://doi.org/10.1088/1748-9326/aabf9f.

Fytili, D. and A. Zabaniotou, 2017: Social acceptance of bioenergy in the context of climate change and sustainability - A review. *Current Opinion in Green and Sustainable Chemistry*, **8**, 5-9, doi:10.1016/J.COGSC.2017.07.006.

Gajjar, S.P., C. Singh, and T. Deshpande, 2018: Tracing back to move ahead: a review of development pathways that constrain adaptation futures. *Climate and Development*, doi:10.1080/17565529.2018.1442793.

Gamborg, C., H.T. Anker, and P. Sandøe, 2014: Ethical and legal challenges in bioenergy governance: Coping with value disagreement and regulatory complexity. *Energy Policy*, **69**, 326-333, doi:10.1016/J.ENPOL.2014.02.013.

Gao, Y. and P. Newman, 2018: Beijing's Peak Car Transition: Hope for Emerging Cities in the 1.5 °C Agenda. *Urban Planning*, **3(2)**, 82, doi:10.17645/up.v3i2.1246.

Garcia, O.W., T. Amann, and J. Hartmann, 2018: Biomass demand can affect forests nutrient budgets in wood exportation regions. *Scientific Reports* (in press).

García de Jalón, S., S. Silvestri, and A.P. Barnes, 2017: The potential for adoption of climate smart agricultural practices in Sub-Saharan livestock systems. *Regional Environmental Change*, **17(2)**, 399-410, doi:10.1007/s10113-016-1026-z.

García Romero, H. and A. Molina, 2015: *Agriculture and Adaptation to Climate Change: The Role of Insurance in Risk Management: The Case of Colombia*. Inter-American Development Bank, 49 pp.

Garg, A., J. Maheshwari, P.R. Shukla, and R. Rawal, 2017: Energy appliance transformation in commercial buildings in India under alternate policy scenarios. *Energy*, **140**, 952-965, doi:10.1016/j.energy.2017.09.004.

Garrett-Peltier, H., 2017: Green versus brown: Comparing the employment impacts of energy efficiency, renewable energy, and fossil fuels using an input-output model. *Economic Modelling*, **61**, 439-447, doi:10.1016/j.econmod.2016.11.012.

Garsaball, E.C. and H. Markov, 2017: Climate change: are building codes keeping up? A case study on hurricanes in the Caribbean. *Proceedings of the Institution of Civil Engineers - Forensic Engineering*, **170(2)**, 67-71, doi:10.1680/jfoen.16.00034.

Gasc, F., D. Guerrier, S. Barrett, and S. Anderson, 2014: *Assessing the effectiveness of investments in climate information services*. IIED, London.

Gatersleben, B. and D. Uzzell, 2007: Affective Appraisals of the Daily Commute. *Environment and Behavior*, **39(3)**, 416-431, doi:10.1177/0013916506294032.

Gaüzère, P., F. Jiguet, and V. Devictor, 2016: Can protected areas mitigate the impacts of climate change on bird's species and communities? *Diversity and Distributions*, **22(6)**, 625-637, doi:10.1111/ddi.12426.

Gebru, B., P. Kibaya, T. Ramahaleo, K. Kwena, and P. Mapfumo, 2015: *Improving access to climate-related information for adaptation*. IDRC, Canada, 1-4 pp.

Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**, 1242-1244, doi:10.1126/science.aao3760.

Gemenne, F. and J. Blocher, 2017: How can migration serve adaptation to climate change? Challenges to fleshing out a policy ideal. *Geographical Journal*, doi:10.1111/geoj.12205.

Gencsü, I. and M. Hino, 2015: *Raising Ambition to Reduce International Aviation and Maritime Emissions. Contributing paper for Seizing the Global Opportunity: Partnerships for Better Growth and a Better Climate*. New Climate Economy, London, United Kingdom and Washington DC, 24 pp.

Geneletti, D., D. La Rosa, M. Spyra, and C. Cortinovis, 2017: A review of approaches and challenges for sustainable planning in urban peripheries. *Landscape and Urban Planning*, **165**, 231-243, doi:10.1016/j.landurbplan.2017.01.013.

Genesio, L., F.P. Vaccari, and F. Miglietta, 2016: Black carbon aerosol from biochar threats its negative emission potential. *Global Change Biology*, **22(7)**, 2313-2314, doi:10.1111/gcb.13254.

Geng, Y. et al., 2016: Cost analysis of air capture driven by wind energy under different scenarios. *Journal of Modern Power Systems and Clean Energy*, **4(2)**, 275-281, doi:10.1007/s40565-015-0150-y.

Gentile, N. et al., 2015: Monitoring Protocol to Assess the Overall Performance of Lighting and Daylighting Retrofit Projects. *Energy Procedia*, **78**, 2681-2686, doi:10.1016/j.egypro.2015.11.347.

Georgescu, M. et al., 2015: Prioritizing urban sustainability solutions: Coordinated approaches must incorporate scale-dependent built environment induced effects. *Environmental Research Letters*, **10(6)**, doi:10.1088/1748-9326/10/6/061001.

Geraint, E. and F. Gianluca, 2016: *The social acceptance of wind energy: JRC Science for Policy Report*. European Commission, Joint Research Centre (JRC), Brussels, Belgium, 77 pp.

Gerbens-Leenes, W., A.Y. Hoekstra, and T.H. van der Meer, 2009: The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, **106(25)**, 10219-10223, doi:10.1073/pnas.0812619106.

Gerber, P.J. et al., 2013: *Tackling climate change through livestock - A global assessment of emissions and mitigation opportunities*. Food and Agriculture Organization, Rome, 133 pp.

Gerke, B.F., M.A. McNeil, and T. Tu, 2017: The International Database of Efficient Appliances (IDEA): A new tool to support appliance energy-efficiency deployment. *Applied Energy*, **205**, 453-464, doi:10.1016/j.apenergy.2017.07.093.

German, L. and G. Schoneveld, 2012: A review of social sustainability considerations among EU-approved voluntary schemes for biofuels, with implications for rural livelihoods. *Energy Policy*, **51**, 765-778, doi:10.1016/J.ENPOL.2012.09.022.

Ghahramani, A. and D. Bowran, 2018: Transformative and systemic climate change adaptations in mixed crop-livestock farming systems. *Agricultural Systems*, **164**, 236-251, doi:10.1016/j.agsy.2018.04.011.

Gheewala, S.H., G. Berndes, and G. Jewitt, 2011: The bioenergy and water nexus. *Biofuels, Bioproducts and Biorefining*, **5(4)**, 353-360, doi:10.1002/bbb.295.

Gi, K., F. Sano, A. Hayashi, and K. Akimoto, 2018: A model-based analysis on energy systems transition for climate change mitigation and ambient particulate matter 2.5 concentration reduction. *Mitigation and Adaptation Strategies for Global Change*, doi:10.1007/s11027-018-9806-z.

Giannantoni, C., 2014: The Relevance of Emerging Solutions for Thinking, Decision Making and Acting. The case of Smart Grids. *Ecological Modelling*, **271(C)**, 62-71, doi:10.1016/j.ecolmodel.2013.04.001.

Gibbs, M.T., 2016: Why is coastal retreat so hard to implement? Understanding the political risk of coastal adaptation pathways. *Ocean and Coastal Management*, **130**, 107-114, doi:10.1016/j.ocecoaman.2016.06.002.

Gibon, T., A. Arvesen, and E.G. Hertwich, 2017: Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renewable and Sustainable Energy Reviews*, **76(July 2016)**, 1283-1290, doi:10.1016/j.rser.2017.03.078.

Gil, J., M. Siebold, and T. Berger, 2015: Adoption and development of integrated crop-livestock-forestry systems in Mato Grosso, Brazil. *Agriculture, Ecosystems & Environment*, **199**, 394-406, doi:10.1016/j.agee.2014.10.008.

Gilderbloom, J.I., W.W. Riggs, and W.L. Meares, 2015: Does walkability matter? An examination of walkability's impact on housing values, foreclosures and crime. *Cities*, **42**, 13-24, doi:10.1016/j.cities.2014.08.001.

Giles-Corti, B. et al., 2016: City planning and population health: a global challenge. *The Lancet*, **388(10062)**, 2912-2924, doi:10.1016/S0140-6736(16)30066-6.

Gilfillan, D., T.T. Nguyen, and H.T. Pham, 2017: Coordination and health sector adaptation to climate change in the Vietnamese Mekong Delta. *Ecology and Society*, **22(3)**, 14, doi:10.5751/ES-09235-220314.

Giller, K.E. et al., 2015: Beyond conservation agriculture. *Frontiers in Plant Science*, **6**, doi:10.3389/fpls.2015.00870.

Gillingham, P.K. et al., 2015: The effectiveness of protected areas in the conservation of species with changing geographical ranges. *Biological Journal of the Linnean Society*, **115(3)**, 707-717, doi:10.1111/bij.12506.

Gioli, G., G. Hugo, M.M. Costa, and J. Scheffran, 2016: Human mobility, climate adaptation, and development. *Migration and Development*, **5(2)**, 165-170, doi:10.1080/21632324.2015.1096590.

Girard, C., M. Pulido-Velazquez, J.–D. Rinaudo, C. Pagé, and Y. Caballero, 2015: Integrating top-down and bottom-up approaches to design global change adaptation at the river basin scale. *Global Environmental Change*, **34**, 132-146, doi:10.1016/j.gloenvcha.2015.07.002.

Girvetz, E.H., E. Gray, T.H. Tear, and M.A. Brown, 2014: Bridging climate science to adaptation action in data sparse Tanzania. *Environmental Conservation*, **41(02)**, 229-238, doi:10.1017/S0376892914000010.

Giuliano, G. and S. Hanson (eds.), 2017: *The Geography of Urban Transportation*. Guilford Press, New York, USA, 400 pp.

Glaas, E., E.C.H. Keskitalo, and M. Hjerpe, 2017: Insurance sector management of climate change adaptation in three Nordic countries: the influence of policy and market factors. *Journal of Environmental Planning and Management*, **60(9)**, 1601-1621, doi:10.1080/09640568.2016.1245654.

Glazebrook, G. and P. Newman, 2018: The City of the Future. *Urban Planning*, **3(2)**, 1, doi:10.17645/up.v3i2.1247.

Glenk, K. and S. Colombo, 2011: Designing policies to mitigate the agricultural contribution to climate change: an assessment of soil based carbon sequestration and its ancillary effects. *Climatic Change*, **105(1-2)**, 43-66, doi:10.1007/s10584-010-9885-7.

Global CCS Institute, 2017: *The Global Status of CCS 2016 Summary Report*. 28 pp.

Godfray, H.C.J. and T. Garnett, 2014: Food security and sustainable intensification. *Phil. Trans. R. Soc. B*, **369(1639)**, 20120273.

Godfrey-Wood, R. and B.C.R. Flower, 2017: Does Guaranteed Employment Promote Resilience to Climate Change? The Case of India's Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA). *Development Policy Review*, **38(1)**, 42-49, doi:10.1111/dpr.12309.

Goetz, A., L. German, C. Hunsberger, and O. Schmidt, 2017: Do no harm? Risk perceptions in national bioenergy policies and actual mitigation performance. *Energy Policy*, **108**, 776-790, doi:10.1016/J.ENPOL.2017.03.067.

Goetz, S.J. et al., 2015: Measurement and monitoring needs, capabilities and potential for addressing reduced emissions from deforestation and forest degradation under REDD+. *Environmental Research Letters*, **10(12)**, 123001.

Gohin, A., 2008: Impacts of the European Biofuel Policy on the Farm Sector: A General Equilibrium Assessment. *Review of Agricultural Economics*, **30(4)**, 623-641, doi:10.1111/j.1467-9353.2008.00437.x.

Gomez, L.F. et al., 2015: Urban environment interventions linked to the promotion of physical activity: A mixed methods study applied to the urban context of Latin America. *Social Science & Medicine*, **131**, 18-30, doi:10.1016/j.socscimed.2015.02.042.

Gómez-Aíza, L. et al., 2017: Can wildlife management units reduce land use/land cover change and climate change vulnerability? Conditions to encourage this capacity in Mexican municipalities. *Land Use Policy*, **64**, 317-326, doi:https://doi.org/10.1016/j.landusepol.2017.03.004.

Gong, X. et al., 2013: Sub-tropic degraded red soil restoration: Is soil organic carbon build-up limited by nutrients supply. *Forest Ecology and Management*, **300**, 77-87, doi:10.1016/J.FORECO.2012.12.002.

González, A.G., M.G. Zotano, W. Swan, P. Bouillard, and H. Elkadi, 2017: Maturity Matrix Assessment: Evaluation of Energy Efficiency Strategies in Brussels Historic Residential Stock. *Energy Procedia*, **111**, 407-416, doi:10.1016/j.egypro.2017.03.202.

González, M.F. and T. Ilyina, 2016: Impacts of artificial ocean alkalinization on the carbon cycle and climate in Earth system simulations. *Geophysical Research Letters*, **43(12)**, 6493-6502, doi:10.1002/2016GL068576.

Goodale, M.W. and A. Milman, 2016: Cumulative adverse effects of offshore wind energy development on wildlife. *Journal of Environmental Planning and Management*, **59(1)**, 1-21, doi:10.1080/09640568.2014.973483.

Goodwin, P. and K. Van Dender, 2013: Peak Car' - Themes and Issues. *Transport Reviews*, **33(3)**, 243-254, doi:10.1080/01441647.2013.804133.

Goosen, H. et al., 2013: Climate Adaptation Services for the Netherlands: an operational approach to support spatial adaptation planning. *Regional Environmental Change*, doi:10.1007/s10113-013-0513-8.

Gössling, S. and A.S. Choi, 2015: Transport transitions in Copenhagen: Comparing the cost of cars and bicycles. *Ecological Economics*, **113**, 106-113, doi:10.1016/j.ecolecon.2015.03.006.

Gota, S., C. Huizenga, K. Peet, N. Medimorec, and S. Bakker, 2018: Decarbonising transport to achieve Paris Agreement targets. *Energy Efficiency*, doi:10.1007/s12053-018-9671-3.

Gough, C. and P. Upham, 2011: Biomass energy with carbon capture and storage (BECCS or Bio-CCS). *Greenhouse Gases: Science and Technology*, **1(4)**, 324-334, doi:10.1002/ghg.34.

Gough, C., L. O'Keefe, and S. Mander, 2014: Public perceptions of CO_2 transportation in pipelines. *Energy Policy*, **70**, 106-114, doi:10.1016/J.ENPOL.2014.03.039.

Grabowski, P.P. and J.M. Kerr, 2014: Resource constraints and partial adoption of conservation agriculture by hand-hoe farmers in Mozambique. *International Journal of Agricultural Sustainability*, **12(1)**, 37-53, doi:10.1080/14735903.2013.782703.

Granderson, A.A., 2017: The Role of Traditional Knowledge in Building Adaptive Capacity for Climate Change: Perspectives from Vanuatu. *Weather, Climate, and Society*, **9(3)**, 545-561, doi:10.1175/WCAS-D-16-0094.1.

Grandin, J., H. Haarstad, K. Kjaeras, and S. Bouzarovski, 2018: The politics of rapid urban transformation. *Current opinion in Environmental Sustainability*, **31**, 16-22, doi:10.1016/j.cosust.2017.12.002.

Grau, B., E. Bernat, R. Antoni, R. Jordi-Roger, and P. Rita, 2010: Small-scale production of straight vegetable oil from rapeseed and its use as biofuel in the Spanish territory. *Energy Policy*, **38(1)**, 189-196, doi:10.1016/J.ENPOL.2009.09.004.

Greatrex, H. et al., 2015: *Scaling up index insurance for smallholder farmers: Recent evidence and insights*. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Grecequet, M., J. DeWaard, J.J. Hellmann, and G.J. Abel, 2017: Climate Vulnerability and Human Migration in Global Perspective. *Sustainability*, **9(5)**, 720, doi:10.3390/su9050720.

Green, A.L. et al., 2014: Designing Marine Reserves for Fisheries Management, Biodiversity Conservation, and Climate Change Adaptation. *Coastal Management*, **42(2)**, 143-159, doi:10.1080/08920753.2014.877763.

Green, D. and L. Minchin, 2014: Living on climate-changed country: Indigenous health, well-being and climate change in remote Australian communities. *EcoHealth*, **11(2)**, 263-272, doi:10.1007/s10393-013-0892-9.

Green, D. et al., 2017: Advancing Australia's role in climate change and health research. *Nature Climate Change*, **7(2)**, 103-106, doi:10.1038/nclimate3182.

Green, J. and P. Newman, 2017: Disruptive innovation, stranded assets and forecasting: the rise and rise of renewable energy. *Journal of Sustainable Finance & Investment*, **7(2)**, 169-187, doi:10.1080/20430795.2016.1265410.

Green, O.O. et al., 2016: Adaptive governance to promote ecosystem services in urban green spaces. *Urban Ecosystems*, **19(1)**, 77-93, doi:10.1007/s11252-015-0476-2.

Greene, J.S. and M. Geisken, 2013: Socioeconomic impacts of wind farm development: a case study of Weatherford, Oklahoma. *Energy, Sustainability and Society*, **3(1)**, 2, doi:10.1186/2192-0567-3-2.

Greenwood, O., H.L. Mossman, A.J. Suggitt, R.J. Curtis, and I.M.D. Maclean, 2016: Using in situ management to conserve biodiversity under climate change. *Journal of Applied Ecology*, **53(3)**, 885-894, doi:10.1111/1365-2664.12602.

Gregg, J.S. and S.J. Smith, 2010: Global and regional potential for bioenergy from agricultural and forestry residue biomass. *Mitigation and Adaptation Strategies for Global Change*, **15(3)**, 241-262, doi:10.1007/s11027-010-9215-4.

Greve, M., B. Reyers, A. Mette Lykke, and J.–C. Svenning, 2013: Spatial optimization of carbon-stocking projects across Africa integrating stocking potential with co-benefits and feasibility. *Nature Communications*, **4**, 2975.

Griscom, B.W. et al., 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences*, **114(44)**, 11645-11650, doi:10.1073/pnas.1710465114.

Gu, A., F. Teng, and Y. Wang, 2014: China energy-water nexus: Assessing the water-saving synergy effects of energy-saving policies during the eleventh Five-year Plan. *Energy Conversion and Management*, **85**, 630-637, doi:https://doi.org/10.1016/j.enconman.2014.04.054.

Guarnacci, U., 2012: Governance for sustainable reconstruction after disasters: Lessons from Nias, Indonesia. *Environmental Development*, **2(1)**, 73-85, doi:10.1016/j.envdev.2012.03.010.

Guido, Z. et al., 2018: The stresses and dynamics of smallholder coffee systems in Jamaica's Blue Mountains: a case for the potential role of climate services. *Climatic Change*, **147(1-2)**, 253-266, doi:10.1007/s10584-017-2125-7.

Gunasekara, R., G. Pecnik, M. Girvan, and T. de la Rosa, 2018: Delivering integrated water management benefits: the North West Bicester development, UK. *Proceedings of the Institution of Civil Engineers - Water Management*, **171(2)**, 110-121, doi:10.1680/jwama.16.00119.

Gupta, D.K. et al., 2016: Mitigation of greenhouse gas emission from rice-wheat system of the Indo-Gangetic plains: Through tillage, irrigation and fertilizer management. *Agriculture, Ecosystems & Environment*, **230**, 1-9, doi:10.1016/j.agee.2016.05.023.

Gutiérrez, J.L. et al., 2012: Physical Ecosystem Engineers and the Functioning of Estuaries and Coasts. *Treatise on Estuarine and Coastal Science*, **7**, 53-81, doi:10.1016/B978-0-12-374711-2.00705-1.

Gwedla, N. and C.M. Shackleton, 2015: The development visions and attitudes towards urban forestry of officials responsible for greening in South African towns. *Land Use Policy*, **42**, 17-26, doi:10.1016/j.landusepol.2014.07.004.

Haberl, H. et al., 2011: Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass and Bioenergy*, **35(12)**, 4753-4769, doi:10.1016/j.biombioe.2011.04.035.

Haeberli, W., Y. Schaub, and C. Huggel, 2017: Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges. *Geomorphology*, **293(Part B)**, 405-417, doi:https://doi.org/10.1016/j.geomorph.2016.02.009.

Haeberli, W. et al., 2016: New lakes in deglaciating high-mountain regions - opportunities and risks. *Climatic Change*, **139(2)**, 201-214, doi:10.1007/s10584-016-1771-5.

Haggblade, S. et al., 2015: Journal of Agribusiness in Developing and Emerging Economies. *Journal of Agribusiness in Developing and Emerging Economies*, **5(2)**, 170 - 189.

Haim, D., E.M. White, and R.J. Alig, 2016: Agriculture Afforestation for Carbon Sequestration Under Carbon Markets in the United States: Leakage Behavior from Regional Allowance Programs. *Applied Economic Perspectives and Policy*, **38(1)**, 132-151.

Hakala, K., M. Kontturi, and K. Pahkala, 2008: Field biomass as global energy source. *Agricultural and Food Science*, **18(3-4)**, 347-365.

Hall, J.M., T. Van Holt, A.E. Daniels, V. Balthazar, and E.F. Lambin, 2012: Trade-offs between tree cover, carbon storage and floristic biodiversity in reforesting landscapes. *Landscape Ecology*, **27(8)**, 1135-1147, doi:10.1007/s10980-012-9755-y.

Hall, S. and T.J. Foxon, 2014: Values in the Smart Grid: The co-evolving political economy of smart distribution. *Energy Policy*, **74**, 600-609, doi:10.1016/j.enpol.2014.08.018.

Hallegatte, S., C. Green, R.J. Nicholls, and J. Corfee-Morlot, 2013: Future flood losses in major coastal cities. *Nature Climate Change*, **3(9)**, 802-806, doi:10.1038/nclimate1979.

Hallström, E., A. Carlsson-Kanyama, and P. Börjesson, 2015: Environmental impact of dietary change: A systematic review. *Journal of Cleaner Production*, **91**, 1-11, doi:10.1016/j.jclepro.2014.12.008.

Hallström, E., Q. Gee, P. Scarborough, and D.A. Cleveland, 2017: A healthier US diet could reduce greenhouse gas emissions from both the food and health care systems. *Climatic Change*, **142(1-2)**, 199-212, doi:10.1007/s10584-017-1912-5.

Hamilton, L.C., J. Hartter, M. Lemcke-Stampone, D.W. Moore, and T.G. Safford, 2015: Tracking Public Beliefs About Anthropogenic Climate Change. *PLOS ONE*, **10(9)**, e0138208.

Hamilton, T.L. and C.J. Wichman, 2018: Bicycle infrastructure and traffic congestion: Evidence from DC's Capital Bikeshare. *Journal of Environmental Economics and Management*, **87**, 72-93, doi:10.1016/j.jeem.2017.03.007.

Hammar, T., C.A. Ortiz, J. Stendahl, S. Ahlgren, and P.–A. Hansson, 2015: Time-Dynamic Effects on the Global Temperature When Harvesting Logging Residues for Bioenergy. *BioEnergy Research*, **8(4)**, 1912-1924, doi:10.1007/s12155-015-9649-3.

Hammond, G.P. and B. Li, 2016: Environmental and resource burdens associated with world biofuel production out to 2050: footprint components from carbon emissions and land use to waste arisings and water consumption. *GCB Bioenergy*, **8(5)**, 894-908, doi:10.1111/gcbb.12300.

Hampson, K.J. et al., 2014: Delivering climate services for farmers and pastoralists through interactive radio: scoping report for the GFCS Adaptation Program in Africa. CCAFS Working Paper, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark.

Han, F., R. Xie, Y. Lu, J. Fang, and Y. Liu, 2018: The effects of urban agglomeration economies on carbon emissions: Evidence from Chinese cities. *Journal of Cleaner Production*, **172**, 1096-1110, doi:10.1016/j.jclepro.2017.09.273.

Han, F.X., J.S. Lindner, and C. Wang, 2007: Making carbon sequestration a paying proposition. *Naturwissenschaften*, **94(3)**, 170-182, doi:10.1007/s00114-006-0170-6.

Hangx, S.J.T. and C.J. Spiers, 2009: Coastal spreading of olivine to control atmospheric CO_2 concentrations: A critical analysis of viability. *International Journal of Greenhouse Gas Control*, **3(6)**, 757-767, doi:10.1016/j.ijggc.2009.07.001.

Hansen, J., A. Rose, and J. Hellin, 2017: *Prospects for scaling up the contribution of index insurance to smallholder adaptation to climate risk*.

Hansen, M. and B. Hauge, 2017: Prosumers and smart grid technologies in Denmark: developing user competences in smart grid households. *Energy Efficiency*, **10(5)**, 1215-1234, doi:10.1007/s12053-017-9514-7.

Harjanne, A., 2017: Servitizing climate science-Institutional analysis of climate services discourse and its implications. *Global Environmental Change*, **46(November 2016)**, 1-16, doi:10.1016/j.gloenvcha.2017.06.008.

Harper, S.L. et al., 2015: Climate-sensitive health priorities in Nunatsiavut, Canada. *BMC Public Health*, **15(1)**, 605, doi:10.1186/s12889-015-1874-3.

Harris, Z.M., R. Spake, and G. Taylor, 2015: Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions. *Biomass and Bioenergy*, **82**, 27-39, doi:10.1016/J.BIOMBIOE.2015.05.008.

Harteveld, C. and P. Suarez, 2015: Guest editorial: games for learning and dialogue on humanitarian work. *Journal of Humanitarian Logistics and Supply Chain Management*, **5(1)**, 61-72, doi:10.1108/JHLSCM-01-2015-0005.

Hartmann, J. and S. Kempe, 2008: What is the maximum potential for CO_2 sequestration by "stimulated" weathering on the global scale? *Naturwissenschaften*, **95(12)**, 1159-1164, doi:10.1007/s00114-008-0434-4.

Hartmann, J. et al., 2013: Enhanced chemical weathering as a geoengineering strategy to reduce atmospheric carbon dioxide, supply nutrients, and mitigate ocean acidification: Enhanced weathering. *Reviews of Geophysics*, **51(2)**, 113-149, doi:10.1002/rog.20004.

Hartwig, J., J. Kockat, W. Schade, and S. Braungardt, 2017: The macroeconomic effects of ambitious energy efficiency policy in Germany - Combining bottom-up energy modelling with a non-equilibrium macroeconomic model. *Energy*, **124**, 510-520, doi:10.1016/j.energy.2017.02.077.

Harvey, B., T. Pasanen, A. Pollard, and J. Raybould, 2017: Fostering Learning in Large Programmes and Portfolios: Emerging Lessons from Climate Change and Sustainable Development. *Sustainability*, **9(3)**, 315, doi:10.3390/su9020315.

Harvey, C.A. et al., 2014: Climate-Smart Landscapes: Opportunities and Challenges for Integrating Adaptation and Mitigation in Tropical Agriculture. *Conservation Letters*, **7(2)**, 77-90, doi:10.1111/conl.12066.

Harvey, L.D.D., 2008: Mitigating the atmospheric CO 2 increase and ocean acidification by adding limestone powder to upwelling regions. *Journal of Geophysical Research*, **113(C4)**, C04028, doi:10.1029/2007JC004373.

Hasanbeigi, A., M. Arens, and L. Price, 2014: Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: A technical review. *Renewable and Sustainable Energy Reviews*, **33(Supplement C)**, 645-658, doi:https://doi.org/10.1016/j.rser.2014.02.031.

Hauck, J., P. Köhler, D. Wolf-Gladrow, and C. Völker, 2016: Iron fertilisation and century-scale effects of open ocean dissolution of olivine in a simulated CO_2 removal experiment. *Environmental Research Letters*, **11(2)**, doi:10.1088/1748-9326/11/2/024007.

Hauer, M.E., J.M. Evans, and D.R. Mishra, 2016: Millions projected to be at risk from sea-level rise in the continental United States. *Nature Climate Change*, **6(7)**, 691-695, doi:10.1038/nclimate2961.

Havet, A. et al., 2014: Review of livestock farmer adaptations to increase forages in crop rotations in western France. *Agriculture, ecosystems & environment*, **190**, 120-127.

Havlik, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, **111(10)**, 3709-3714, doi:10.1073/pnas.1308044111.

Hawkins, T.R., B. Singh, G. Majeau-Bettez, and A.H. Strømman, 2013: Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. *Journal of Industrial Ecology*, **17(1)**, 53-64, doi:10.1111/j.1530-9290.2012.00532.x.

Hayman, P., L. Rickards, R. Eckard, and D. Lemerle, 2012: Climate change through the farming systems lens: challenges and opportunities for farming in Australia. *Crop and Pasture Science*, **63(3)**, 203, doi:10.1071/CP11196.

Hazledine, T., S. Donovan, and C. Mak, 2017: Urban agglomeration benefits from public transit improvements: Extending and implementing the Venables model. *Research in Transportation Economics*, **66**, 36-45, doi:10.1016/j.retrec.2017.09.002.

He, F., Q. Zhang, J. Lei, W. Fu, and X. Xu, 2013: Energy efficiency and productivity change of China's iron and steel industry: Accounting for undesirable outputs. *Energy Policy*, **54**, 204-213, doi:https://doi.org/10.1016/j.enpol.2012.11.020.

Hebrok, M. and C. Boks, 2017: Household food waste: Drivers and potential intervention points for design - An extensive review. *Journal of Cleaner Production*, **151**, 380-392, doi:10.1016/j.jclepro.2017.03.069.

Heck, V., D. Gerten, W. Lucht, and A. Popp, 2018: Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, **8(2)**, 151-155, doi:10.1038/s41558-017-0064-y.

Hedenus, F. and C. Azar, 2009: Bioenergy plantations or long-term carbon sinks? - A model based analysis. *Biomass and Bioenergy*, **33(12)**, 1693-1702, doi:10.1016/J.BIOMBIOE.2009.09.003.

Heidari, M., D. Majcen, N. van der Lans, I. Floret, and M.K. Patel, 2018: Analysis of the energy efficiency potential of household lighting in Switzerland using a stock model. *Energy and Buildings*, **158**, 536-548, doi:10.1016/j.enbuild.2017.08.091.

Heidenreich, S., 2015: Sublime technology and object of fear: offshore wind scientists assessing publics. *Environment and Planning A*, **47(5)**, 1047-1062, doi:10.1177/0308518X15592311.

Henderson, B.B. et al., 2015: Greenhouse gas mitigation potential of the world's grazing lands: Modeling soil carbon and nitrogen fluxes of mitigation practices. *Agriculture, Ecosystems and Environment*, **207**, 91-100, doi:10.1016/j.agee.2015.03.029.

Henly-Shepard, S., S.A. Gray, and L.J. Cox, 2015: The use of participatory modeling to promote social learning and facilitate community disaster planning. *Environmental Science & Policy*, **45**, 109-122, doi:10.1016/j.envsci.2014.10.004.

Hennessey, R., J. Pittman, A. Morand, and A. Douglas, 2017: Co-benefits of integrating climate change adaptation and mitigation in the Canadian energy sector. *Energy Policy*, **111**, 214-221, doi:10.1016/j.enpol.2017.09.025.

Henriques, J. and J. Catarino, 2016: Motivating towards energy efficiency in small and medium enterprises. *Journal of Cleaner Production*, **139**, 42-50, doi:https://doi.org/10.1016/j.jclepro.2016.08.026.

Henry, R.C. et al., 2018: Food supply and bioenergy production within the global cropland planetary boundary. *PLOS ONE*, **13(3)**, e0194695, doi:10.1371/journal.pone.0194695.

Henry, R.K., Z. Yongsheng, and D. Jun, 2006: Municipal solid waste management challenges in developing countries - Kenyan case study. *Waste Management*, **26(1)**, 92-100, doi:10.1016/j.wasman.2005.03.007.

Hernández-Morcillo, M., P. Burgess, J. Mirck, A. Pantera, and T. Plieninger, 2018: Scanning agroforestry-based solutions for climate change mitigation and adaptation in Europe. *Environmental Science and Policy*, **80**, 44-52, doi:10.1016/j.envsci.2017.11.013.

Herrero, M. et al., 2015: Livestock and the Environment: What Have We Learned in the Past Decade? *Annual Review of Environment and Resources*, **40(1)**, 177-202, doi:10.1146/annurev-environ-031113-093503.

Herwehe, L. and C.A. Scott, 2017: Drought adaptation and development: small-scale irrigated agriculture in northeast Brazil. *Climate and Development*, 1-10, doi:10.1080/17565529.2017.1301862.

Hess, J. and I. Kelman, 2017: Tourism Industry Financing of Climate Change Adaptation: Exploring the Potential in Small Island Developing States. *Climate, Disaster and Development Journal*, **2(2)**, 34-45, doi:10.18783/cddj.v002.i02.a04.

Hess, J.J. and K.L. Ebi, 2016: Iterative management of heat early warning systems in a changing climate. *Annals of the New York Academy of Sciences*, **1382(1)**, 21-30, doi:10.1111/nyas.13258.

Hess, J.J., J.Z. McDowell, and G. Luber, 2012: Integrating climate change adaptation into public health practice: Using adaptive management to increase adaptive capacity and build resilience. *Environmental Health Perspectives*, **120(2)**, 171-179, doi:10.1289/ehp.1103515.

Hetz, K., 2016: Contesting adaptation synergies: political realities in reconciling climate change adaptation with urban development in Johannesburg, South Africa. *Regional Environmental Change*, **16(4)**, 1171-1182, doi:10.1007/s10113-015-0840-z.

Hewitson, B., K. Waagsaether, J. Wohland, K. Kloppers, and T. Kara, 2017: Climate information websites: an evolving landscape. *Wiley Interdisciplinary Reviews: Climate Change*, **8(5)**, 1-22, doi:10.1002/wcc.470.

Hiç, C., P. Pradhan, D. Rybski, and J.P. Kropp, 2016: Food Surplus and Its Climate Burdens. *Environmental Science and Technology*, doi:10.1021/acs.est.5b05088.

Hidayat, N.K., P. Glasbergen, and A. Offermans, 2015: Sustainability certification and palm oil smallholders' livelihood: A Comparison between Scheme Smallholders and Independent Smallholders in Indonesia. *International Food and Agribusiness Management Review*, **18(3)**, 25-48.

Hill Clarvis, M. and N.L. Engle, 2015: Adaptive capacity of water governance arrangements: a comparative study of barriers and opportunities in Swiss and US states. *Regional Environmental Change*, **15(3)**, 517-527, doi:10.1007/s10113-013-0547-y.

Hinkel, J. et al., 2014: Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, **111(9)**, 3292-3297, doi:10.1073/pnas.1222469111.

Hino, M., C.B. Field, and K.J. Mach, 2017: Managed retreat as a response to natural hazard risk. *Nature Climate Change*, **7(5)**, 364-370, doi:10.1038/nclimate3252.

Hirschberg, S. et al., 2016: Health effects of technologies for power generation: Contributions from normal operation, severe accidents and terrorist threat. *Reliability Engineering and System Safety*, **145**, 373-387, doi:10.1016/j.ress.2015.09.013.

Hiwasaki, L., E. Luna, Syamsidik, and R. Shaw, 2014: Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities. *International Journal of Disaster Risk Reduction*, **10**, 15-27, doi:10.1016/j.ijdrr.2014.07.007.

Hiwasaki, L., E. Luna, Syamsidik, and J.A. Marçal, 2015: Local and indigenous knowledge on climate-related hazards of coastal and small island communities in Southeast Asia. *Climatic Change*, **128(1-2)**, 35-56, doi:10.1007/s10584-014-1288-8.

Ho, S.S. et al., 2018: Science Literacy or Value Predisposition? A Meta-Analysis of Factors Predicting Public Perceptions of Benefits, Risks, and Acceptance of Nuclear Energy. *Environmental Communication*, 1-15, doi:10.1080/17524032.2017.1394891.

Hoffmann, R. and R. Muttarak, 2017: Learn from the past, prepare for the future: Impacts of education and experience on disaster preparedness in the Philippines and Thailand. *World Development*, **96**, 32-51.

Högy, P. et al., 2009: Effects of elevated CO_2 on grain yield and quality of wheat: results from a 3-year free-air CO_2 enrichment experiment. *Plant Biology*, **11(s1)**, 60-69, doi:10.1111/j.1438-8677.2009.00230.x.

Holland, R.A. et al., 2015: A synthesis of the ecosystem services impact of second generation bioenergy crop production. *Renewable and Sustainable Energy Reviews*, **46**, 30-40, doi:10.1016/J.RSER.2015.02.003.

Holmes, G. and D.W. Keith, 2012: An air-liquid contactor for large-scale capture of CO_2 from air. *Philosophical transactions. Series A, Mathematical, Physical, and Engineering sciences*, **370(1974)**, 4380-403, doi:10.1098/rsta.2012.0137.

Holmes, G. et al., 2013: Outdoor prototype results for direct atmospheric capture of carbon dioxide. *Energy Procedia*, **37**, 6079-6095.

Holmlund, C.M. and M. Hammer, 1999: Ecosystem services generated by fish populations. *Ecological Economics*, **29(2)**, 253-268, doi:10.1016/S0921-8009(99)00015-4.

Honegger, M. and D. Reiner, 2018: The political economy of negative emissions technologies: consequences for international policy design. *Climate Policy*, **18(3)**, 306-321, doi:10.1080/14693062.2017.1413322.

Hong, N.B. and M. Yabe, 2017: Improvement in irrigation water use efficiency: a strategy for climate change adaptation and sustainable development of Vietnamese tea production. *Environment, Development and Sustainability*, **19(4)**, 1247-1263, doi:10.1007/s10668-016-9793-8.

Hoogwijk, M., A. Faaij, B. de Vries, and W. Turkenburg, 2009: Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, **33(1)**, 26-43, doi:10.1016/j.biombioe.2008.04.005.

Hoogwijk, M., A. Faaij, B. Eickhout, B. De Vries, and W. Turkenburg, 2005: Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, **29(4)**, 225-257, doi:10.1016/j.biombioe.2005.05.002.

Hooli, L.J., 2016: Resilience of the poorest: coping strategies and indigenous knowledge of living with the floods in Northern Namibia. *Regional Environmental Change*, **16(3)**, 695-707, doi:10.1007/s10113-015-0782-5.

Hosking, J. and D. Campbell-Lendrum, 2012: How well does climate change and human health research match the demands of policymakers? A scoping review. *Environmental Health Perspectives*, **120(8)**, 1076-1082, doi:10.1289/ehp.1104093.

Hou, C.– et al., 2017: Integrated direct air capture and CO_2 utilization of gas fertilizer based on moisture swing adsorption. *Journal of Zhejiang University-SCIENCE A*, **18(10)**, 819-830, doi:10.1631/jzus.A1700351.

Houghton, A., 2011: Health Impact Assessments A Tool for Designing Climate Change Resilience Into Green Building and Planning Projects. *Journal of Green Building*, **6(2)**, 66-87, doi:10.3992/jgb.6.2.66.

Houghton, R.A. and A.A. Nassikas, 2018: Negative emissions from stopping deforestation and forest degradation, globally. *Global Change Biology*, **24(1)**, 350-359, doi:10.1111/gcb.13876.

Houghton, R.A., B. Byers, and A.A. Nassikas, 2015: A role for tropical forests in stabilizing atmospheric CO_2. *Nature Clim. Change*, **5(12)**, 1022-1023.

House, K.Z., C.H. House, D.P. Schrag, and M.J. Aziz, 2007: Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change. *Environmental Science & Technology*, **41(24)**, 8464-8470, doi:10.1021/es0701816.

House, K.Z. et al., 2011: Economic and energetic analysis of capturing CO_2 from ambient air. *Proceedings of the National Academy of Sciences*, **108(51)**, 20428-20433, doi:10.1073/pnas.1012253108.

Howes, M. et al., 2015: Towards networked governance: improving interagency communication and collaboration for disaster risk management and climate change adaptation in Australia. *Journal of Environmental Planning and Management*, **58(5)**, 757-776, doi:10.1080/09640568.2014.891974.

Howson, P. and S. Kindon, 2015: Analysing access to the local REDD+ benefits of Sungai Lamandau, Central Kalimantan, Indonesia. *Asia Pacific Viewpoint*, **56(1)**, 96-110, doi:10.1111/apv.12089.

Hoy, D. et al., 2014: Adapting to the health impacts of climate change in a sustainable manner. *Globalization and Health*, **10(1)**, 82, doi:10.1186/s12992-014-0082-8.

Hsieh, S. et al., 2017: Defining density and land uses under energy performance targets at the early stage of urban planning processes. *Energy Procedia*, **122**, 301-306, doi:10.1016/j.egypro.2017.07.326.

Huang, C.–W., R.I. McDonald, and K.C. Seto, 2018: The importance of land governance for biodiversity conservation in an era of global urban expansion. *Landscape and Urban Planning*, **173**, 44-50, doi:10.1016/j.landurbplan.2018.01.011.

Huhtala, A. and P. Remes, 2017: Quantifying the social costs of nuclear energy: Perceived risk of accident at nuclear power plants. *Energy Policy*, **105**, 320-331, doi:10.1016/j.enpol.2017.02.052.

Humpenöder, F. et al., 2014: Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environmental Research Letters*, **9(6)**, 64029, doi:10.1088/1748-9326/9/6/064029.

Humpenöder, F. et al., 2015: Land-Use and Carbon Cycle Responses to Moderate Climate Change: Implications for Land-Based Mitigation? *Environmental Science & Technology*, **49(11)**, 6731-6739, doi:10.1021/es506201r.

Humpenöder, F. et al., 2017: Large-scale bioenergy production: How to resolve sustainability trade-offs? *Environmental Research Letters*, **13(2)**, 024011, doi:10.1088/1748-9326/aa9e3b.

Hung, H.–C., Y.–T. Lu, and C.–H. Hung, 2018: The determinants of integrating policy-based and community-based adaptation into coastal hazard risk management: a resilience approach. *Journal of Risk Research*, 1-19, doi:10.1080/13669877.2018.1454496.

Hunsberger, C., S. Bolwig, E. Corbera, and F. Creutzig, 2014: Livelihood impacts of biofuel crop production: Implications for governance. *Geoforum*, **54**, 248-260, doi:10.1016/j.geoforum.2013.09.022.

Hunt, A., J. Ferguson, M. Baccini, P. Watkiss, and V. Kendrovski, 2017: Climate and weather service provision: Economic appraisal of adaptation to health impacts. *Climate Services*, **7**, 78-86, doi:10.1016/j.cliser.2016.10.004.

Huntington, H.P. et al., 2018: Staying in place during times of change in Arctic Alaska: the implications of attachment, alternatives, and buffering. *Regional Environmental Change*, **18(2)**, 489-499, doi:10.1007/s10113-017-1221-6.

Hurlimann, A.C. and A.P. March, 2012: The role of spatial planning in adapting to climate change. *Wiley Interdisciplinary Reviews: Climate Change***, 3(5)**, 477-488, doi:10.1002/wcc.183.

Hylkema, H. and A. Rand, 2014: Reduction of freshwater usage of a coal fired power plant with CCS by applying a high level of integration of all water streams. *Energy Procedia***, 63**, 7187 - 7197.

IAEA, 2017: *Nuclear Technology Review 2017*. IAEA.

IAEA, 2018: Power Reactor Information System - Country Statistics: France. https://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=FR (Accessed: 12 April 2018).

Ickowitz, A., E. Sills, and C. de Sassi, 2017: Estimating Smallholder Opportunity Costs of REDD+: A Pantropical Analysis from Households to Carbon and Back. *World Development***, 95**, 15-26, doi:10.1016/J.WORLDDEV.2017.02.022.

IEA, 2017a: *Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations*. IEA, Paris, France, 443 pp.

IEA, 2017b: *Global EV Outlook 2017: Two Million and Counting*. International Energy Agency (IEA), Paris, France, 71 pp.

IEA, 2017c: *World Energy Outlook 2017*. International Energy Agency, Paris, France, 748 pp.

IEA, 2017d: *World Energy Outlook 2017 - Executive Summary*. IEA, Paris, France, 13 pp.

IEA GHG, 2012: *Barriers to implementation of CCS: Capacity constraints*. 106 pp.

Iiyama, M. et al., 2017: Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. *Agroforestry Systems***, 91(2)**, 271-293, doi:10.1007/s10457-016-9926-y.

Immerzeel, D.J., P.A. Verweij, F. van der Hilst, and A.P.C. Faaij, 2014: Biodiversity impacts of bioenergy crop production: a state-of-the-art review. *GCB Bioenergy***, 6(3)**, 183-209, doi:10.1111/gcbb.12067.

Inamara, A. and V. Thomas, 2017: Pacific climate change adaptation: The use of participatory media to promote indigenous knowledge. *Pacific Journalism Review***, 23(1)**, 113-132.

Inderberg, T.H. and L.A. Løchen, 2012: Adaptation to climate change among electricity distribution companies in Norway and Sweden: lessons from the field. *Local Environment***, 17(6-7)**, 663-678, doi:10.1080/13549839.2011.646971.

Ingalls, M.L. and M.B. Dwyer, 2016: Missing the forest for the trees? Navigating the trade-offs between mitigation and adaptation under REDD. *Climatic Change***, 136(2)**, 353-366, doi:10.1007/s10584-016-1612-6.

Ingty, T., 2017: High mountain communities and climate change: adaptation, traditional ecological knowledge, and institutions. *Climatic Change***, 145(1-2)**, 41-55, doi:10.1007/s10584-017-2080-3.

Ionesco, D., D. Mokhnacheva, and F. Gemenne, 2016: *The Atlas of Environmental Migration*. Taylor & Francis.

IPCC, 2005: Special Report on Carbon Dioxide Capture and Storage. [Metz, B., O. Davidson, H.C. de Coninck, M. Loos, and L.A. Meyer (eds.)]. Cambridge University Press, Cambridge, UK, Cambridge, United Kingdom and New York, NY, USA, UK and New York, NY, USA, 442 pp.

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of IPCC Intergovernmental Panel on Climate Change. [Field, C.B., V. Barros, T.F. Stocker, Q. Dahe, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.–K. Plattner, S.K. Allen, and Others (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 594 pp.

IRENA, 2013: *Smart Grids and Renewables - A Guide for Effective Deployment*. International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, 47 pp.

IRENA, 2015: *Renewable power generation costs in 2014*. IRENA, Abu Dhabi, United Arab Emirates, 164 pp.

IRENA, 2016: *The Power to Change: Solar and Wind Cost Reduction Potential to 2025*. IRENAs Innovation and Technology Centre (IITC), Bonn, Germany, 112 pp.

IRENA, 2017a: *Adapting Market Design to High Shares of Variable Renewable Energy*. International Renewable Energy Agency (IRENA), Abu Dhabi, UAE, 166 pp.

IRENA, 2017b: *Renewable Energy and Jobs: Annual Review 2017*. International Renewable Energy Agency (IRENA), Abu Dhabi, United Arab Emirates, 24 pp.

Irlam, L., 2017: *Global costs of carbon capture and storage - 2017 Update*. Global CCS Institute, Canberra, Australia, 16 pp.

Ishikawa, T., 2014: A Brief Review of Dose Estimation Studies Conducted after the Fukushima Daiichi Nuclear Power Plant Accident. *Periodical Title Radiation emergency medicine*, 21-27.

Ishimoto, Y. et al., 2017: Putting Costs of Direct Air Capture in Context. FCEA Working Paper Series: 002, Forum for Climate Engineering Assessment, Washington DC, USA, 21 pp.

Ivy, S.L., C.N. Patson, N. Joyce, M. Wilkson, and T. Christian, 2017: Medium-term effects of conservation agriculture on soil quality. *African Journal of Agricultural Research*, **12(29)**, 2412-2420, doi:10.5897/AJAR2016.11092.

Jackson, R.B. et al., 2005: Trading water for carbon with biological carbon sequestration. *Science*, **310(5756)**, 1944-1947, doi:10.1126/science.1119282.

Jacobi, J., S. Rist, and M.A. Altieri, 2017: Incentives and disincentives for diversified agroforestry systems from different actors' perspectives in Bolivia. *International Journal of Agricultural Sustainability*, **15(4)**, 365-379, doi:10.1080/14735903.2017.1332140.

Jacobson, M.Z. and M.A. Delucchi, 2009: A Path to Sustainable Energy by 2030. *Scientific American*, **301(5)**, 58-65 pp.

Jägermeyr, J. et al., 2015: Water savings potentials of irrigation systems: global simulation of processes and linkages. *Hydrology and Earth System Sciences*, **19(7)**, 3073-3091, doi:10.5194/hess-19-3073-2015.

Jagger, P. et al., 2014: Multi-Level Policy Dialogues, Processes, and Actions: Challenges and Opportunities for National REDD+ Safeguards Measurement, Reporting, and Verification (MRV). *Forests*, **5(9)**, 2136-2162, doi:10.3390/f5092136.

Jaglin, S., 2014: Regulating Service Delivery in Southern Cities: Rethinking urban heterogeneity. In: *The Routledge Handbook on Cities of the Global South* [Parnell, S. and S. Oldfield (eds.)]. Routledge, Abingdon, UK, pp. 636.

Jahandideh-Tehrani, M., O. Bozorg Haddad, and H.A. Loáiciga, 2014: Hydropower Reservoir Management Under Climate Change: The Karoon Reservoir System. *Water Resources Management*, **29(3)**, 749-770, doi:10.1007/s11269-014-0840-7.

Jain, M., T. Hoppe, and H. Bressers, 2017a: A Governance Perspective on Net Zero Energy Building Niche Development in India: The Case of New Delhi. *Energies*, **10(8)**, 1144, doi:10.3390/en10081144.

Jain, M., T. Hoppe, and H. Bressers, 2017b: Analyzing sectoral niche formation: The case of net-zero energy buildings in India. *Environmental Innovation and Societal Transitions*, **25**, 47-63, doi:10.1016/j.eist.2016.11.004.

Jain, M., A.B. Rao, and A. Patwardhan, 2018: Consumer preference for labels in the purchase decisions of air conditioners in India. *Energy for Sustainable Development*, **42**, 24-31, doi:10.1016/j.esd.2017.09.008.

Jancloes, M. et al., 2014: Climate Services to Improve Public Health. *International Journal of Environmental Research and Public Health*, **11(5)**, 4555-4559, doi:10.3390/ijerph110504555.

Jandl, R. et al., 2014: Current status, uncertainty and future needs in soil organic carbon monitoring. *Science of The Total Environment*, **468-469**, 376-383, doi:10.1016/J.SCITOTENV.2013.08.026.

Janif, S.Z. et al., 2016: Value of traditional oral narratives in building climate-change resilience: insights from rural communities in Fiji. *Ecology and Society*, **21(2)**, doi:10.5751/ES-08100-210207.

Jantke, K., J. Müller, N. Trapp, and B. Blanz, 2016: Is climate-smart conservation feasible in Europe? Spatial relations of protected areas, soil carbon, and land values. *Environmental Science & Policy*, **57(Supplement C)**, 40-49, doi:10.1016/j.envsci.2015.11.013.

Jantz, P., S. Goetz, and N. Laporte, 2014: Carbon stock corridors to mitigate climate change and promote biodiversity in the tropics. *Nature Climate Change*, **4(2)**, 138-142, doi:10.1038/nclimate2105.

Jarvis, D.I. et al., 2008: A global perspective of the richness and evenness of traditional crop-variety diversity maintained by farming communities. *Proceedings of the National Academy of Sciences*, **105(14)**, 5326-5331, doi:10.1073/pnas.0800607105.

Jat, R.K. et al., 2014: Seven years of conservation agriculture in a rice-wheat rotation of Eastern Gangetic Plains of South Asia: Yield trends and economic profitability. *Field Crops Research*, **164**, 199-210, doi:10.1016/j.fcr.2014.04.015.

Jeffery, S., F.G.A. Verheijen, M. van der Velde, and A.C. Bastos, 2011: A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, **144(1)**, 175-187, doi:10.1016/j.agee.2011.08.015.

Jena, P.R., T. Stellmacher, and U. Grote, 2017: Can coffee certification schemes increase incomes of smallholder farmers? Evidence from Jinotega, Nicaragua. *Environment, Development and Sustainability*, **19(1)**, 45-66, doi:10.1007/s10668-015-9732-0.

Jenkins, K., S. Surminski, J. Hall, and F. Crick, 2017: Assessing surface water flood risk and management strategies under future climate change: Insights from an Agent-Based Model. *Science of the Total Environment*, **595**, 159-168, doi:10.1016/j.scitotenv.2017.03.242.

Jennings, S. et al., 2016: Aquatic food security: insights into challenges and solutions from an analysis of interactions between fisheries, aquaculture, food safety, human health, fish and human welfare, economy and environment. *Fish and Fisheries*, **17(4)**, 893-938, doi:10.1111/faf.12152.

Jensen, N. and C. Barrett, 2017: Agricultural index insurance for development. *Applied Economic Perspectives and Policy*, **39(2)**, 199-219, doi:10.1093/aepp/ppw022.

Jensen, W., T. Stump, B. Brown, C. Werner, and K. Smith, 2017: Walkability, complete streets, and gender: Who benefits most? *Health & Place*, **48**, 80, doi:10.1016/j.healthplace.2017.09.007.

Jha, C.K., V. Gupta, U. Chattopadhyay, and B. Amarayil Sreeraman, 2017: Migration as adaptation strategy to cope with climate change: A study of farmers' migration in rural India. *International Journal of Climate Change Strategies and Management*, IJCCSM-03-2017-0059, doi:10.1108/IJCCSM-03-2017-0059.

Jiang, G. et al., 2014: Soil organic carbon sequestration in upland soils of northern China under variable fertilizer management and climate change scenarios. *Global Biogeochemical Cycles*, **28(3)**, 319-333, doi:10.1002/2013GB004746.

Jillella, S., A. Matan, and P. Newman, 2015: Participatory Sustainability Approach to Value Capture-Based Urban Rail Financing in India through Deliberated Stakeholder Engagement. *Sustainability*, **7(7)**, 8091-8115, doi:10.3390/su7078091.

Jin, J., W. Wang, and X. Wang, 2016: Farmers' Risk Preferences and Agricultural Weather Index Insurance Uptake in Rural China. *International Journal of Disaster Risk Science*, **7(4)**, 366-373, doi:10.1007/s13753-016-0108-3.

Jirka, S., D. Woolf, D. Solomon, and J. Lehmann, 2015: *Climate finance and carbon markets for Ethiopia's Productive Safety Net Programme (PSNP): Executive Summary for Policymakers*. A World Bank Climate Smart Initiative (CSI) Report, Cornell University, 12 pp.

Joffre, O.M. et al., 2015: What drives the adoption of integrated shrimp mangrove aquaculture in Vietnam? *Ocean and Coastal Management*, **114**, 53-63, doi:10.1016/j.ocecoaman.2015.06.015.

Johnson, D.A.K. and Y. Abe, 2015: Global Overview on the Role of the Private Sector in Disaster Risk Reduction: Scopes, Challenges, and Potentials. In: *Disaster Management and Private Sectors: Challenges and Potentials* [Izumi, T. and R. Shaw (eds.)]. Springer Japan, Tokyo, pp. 11-29.

Johnson, J.A., C.F. Runge, B. Senauer, J. Foley, and S. Polasky, 2014: Global agriculture and carbon trade-offs. *Proceedings of the National Academy of Sciences of the United States of America*, **111(34)**, 12342-12347, doi:10.1073/pnas.1412835111.

Johnson, N., N. Parker, and J. Ogden, 2014: How negative can biofuels with CCS take us and at what cost? Refining the economic potential of biofuel production with CCS using spatially-explicit modeling. *Energy Procedia*, **63**, 6770-6791, doi:10.1016/j.egypro.2014.11.712.

Johnson, N. et al., 2015: The contributions of Community-Based monitoring and traditional knowledge to Arctic observing networks: Reflections on the state of the field. *Arctic*, **68(5)**, 1-13, doi:10.14430/arctic4447.

Jones, H.P., D.G. Hole, and E.S. Zavaleta, 2012: Harnessing nature to help people adapt to climate change. *Nature Climate Change*, **2(7)**, 504-509, doi:10.1038/nclimate1463.

Jones, K.R., J.E.M. Watson, H.P. Possingham, and C.J. Klein, 2016: Incorporating climate change into spatial conservation prioritisation: A review. *Biological Conservation*, **194**, 121-130, doi:10.1016/j.biocon.2015.12.008.

Jones, L., B. Harvey, and R. Godfrey-Wood, 2016: *The changing role of NGOs in supporting climate services*. 24 pp.

Jones, L. et al., 2010: Responding to a changing climate:Exploring how disaster risk reduction , social protection and livelihoods approaches promote features of adaptive capacity.

Jørgensen, S.L. and M. Termansen, 2016: Linking climate change perceptions to adaptation and mitigation action. *Climatic Change*, **138(1-2)**, 283-296, doi:10.1007/s10584-016-1718-x.

Joyette, A.R.T., L.A. Nurse, and R.S. Pulwarty, 2015: Disaster risk insurance and catastrophe models in risk-prone small Caribbean islands. *Disasters*, **39(3)**, 467-492, doi:10.1111/disa.12118.

K Murthy, I., 2013: Carbon Sequestration Potential of Agroforestry Systems in India. *Journal of Earth Science & Climatic Change*, **04(01)**, 1-7, doi:10.4172/2157-7617.1000131.

K.C., S., 2013: Community Vulnerability to Floods and Landslides in Nepal. *Ecology and Society*, **18(1)**, doi:10.5751/ES-05095-180108.

Kadi, M., L.N. Njau, J. Mwikya, and A. Kamga, 2011: The State of Climate Information Services for Agriculture and Food Security in East African Countries.

Kahil, M.T., J.D. Connor, and J. Albiac, 2015: Efficient water management policies for irrigation adaptation to climate change in Southern Europe. *Ecological Economics*, **120**, 226-233, doi:10.1016/j.ecolecon.2015.11.004.

Kammann, C. et al., 2017: Biochar as a tool to reduce the agricultural greenhouse-gas burden - knowns, unknowns and future research needs. *Journal of Environmental Engineering and Landscape Management*, **25(2)**, 114-139, doi:10.3846/16486897.2017.1319375.

Kantola, I.B., M.D. Masters, D.J. Beerling, S.P. Long, and E.H. DeLucia, 2017: Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biology letters*, **13(4)**, 20160714, doi:10.1098/rsbl.2016.0714.

Kar, A. et al., 2012: Real-Time Assessment of Black Carbon Pollution in Indian Households Due to Traditional and Improved Biomass Cookstoves. *Environmental Science & Technology*, **46(5)**, 2993-3000, doi:10.1021/es203388g.

Kar, S.K. and A. Sharma, 2015: Wind power developments in India. *Renewable and Sustainable Energy Reviews*, **48**, 264-275, doi:10.1016/j.rser.2015.03.095.

Kärki, J., E. Tsupari, and A. Arasto, 2013: CCS feasibility improvement in industrial and municipal applications by heat utilization. *Energy Procedia*, **37**, 2611-2621, doi:10.1016/j.egypro.2013.06.145.

Kassam, A. et al., 2014: The spread of conservation agriculture: Policy and institutional support for adoption and uptake. *Field Actions Science Reports. The journal of field actions*, **7**.

Kato, H., Y. Onda, and M. Teramage, 2012: Depth distribution of 137Cs, 134Cs, and 131I in soil profile after Fukushima Dai-ichi Nuclear Power Plant Accident. *Journal of Environmental Radioactivity*, **111**, 59-64, doi:10.1016/j.jenvrad.2011.10.003.

Kawaguchi, D. and N. Yukutake, 2017: Estimating the residential land damage of the Fukushima nuclear accident. *Journal of Urban Economics*, **99**, 148-160, doi:10.1016/j.jue.2017.02.005.

Kaya, H.O., M. Koitsiwe, and G.M. Nkondo, 2016: African Indigenous Knowledge Systems and Natural Disaster Management in North West Province, South Africa. *Journal of Human Ecology*, **53(2)**, 101-105.

Keith, D.W., 2009: Why Capture CO_2 from the Atmosphere? *Science*, **325(5948)**, 1654-1655.

Keith, D.W., M. Ha-Duong, and J.K. Stolaroff, 2006: Climate Strategy with CO_2 Capture from the Air. *Climatic Change*, **74(1-3)**, 17-45, doi:10.1007/s10584-005-9026-x.

Kelman, I., 2015: Difficult decisions: Migration from Small Island Developing States under climate change. *Earth's Future*, **3(4)**, 133-142, doi:10.1002/2014EF000278.

Kelman, I., 2017: Linking disaster risk reduction, climate change, and the sustainable development goals. *Disaster Prevention and Management: An International Journal*, **26(3)**, 254-258, doi:10.1108/DPM-02-2017-0043.

Kelman, I., J.C. Gaillard, and J. Mercer, 2015: Climate Change's Role in Disaster Risk Reduction's Future: Beyond Vulnerability and Resilience. *International Journal of Disaster Risk Science*, **6(1)**, 21-27, doi:10.1007/s13753-015-0038-5.

Kelman, I. et al., 2017: Here and now: perceptions of Indian Ocean islanders on the climate change and migration nexus. *Geografiska Annaler: Series B, Human Geography*, **99(3)**, 284-303, doi:10.1080/04353684.2017.1353888.

Kemper, J., 2015: Biomass and carbon dioxide capture and storage: A review. *International Journal of Greenhouse Gas Control*, **40**, 401-430, doi:10.1016/j.ijggc.2015.06.012.

Kenley, C.R. et al., 2009: Job creation due to nuclear power resurgence in the United States. *Energy Policy*, **37(11)**, 4894-4900, doi:10.1016/j.enpol.2009.06.045.

Kent, J.L. and R. Dowling, 2016: The Future of Paratransit and DRT: Introducing Cars on Demand. *Paratransit: Shaping the Flexible Transport Future (Transport and Sustainability)*, **8**, 391-412.

Kenworthy, J. and P.L. Schiller, 2018: *An Introduction to Sustainable Transportortation: Policy, Planning and Implementation*. Routledge, Abingdon, Oxon; New York, NY, 442 pp.

Kettle, N.P. et al., 2014: Integrating scientific and local knowledge to inform risk-based management approaches for climate adaptation. *Climate Risk Management*, **4**, 17-31.

Khanal, S.K. et al., 2010: *Bioenergy and Biofuel from Biowaste and Biomass*. American Society of Civil Engineers (ASCE), Reston, VA, USA, 505 pp.

Kheshgi, H.S., 1995: Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy*, **20(9)**, 915-922, doi:10.1016/0360-5442(95)00035-F.

Khoury, C.K. et al., 2014: Increasing homogeneity in global food supplies and the implications for food security. *Proceedings of the National Academy of Sciences*, **111(11)**, 4001-4006, doi:10.1073/pnas.1313490111.

Kihila, J.M., 2017: Indigenous coping and adaptation strategies to climate change of local communities in Tanzania: a review. *Climate and Development*, 1-11, doi:10.1080/17565529.2017.1318739.

Kilpeläinen, A. et al., 2017: Effects of Initial Age Structure of Managed Norway Spruce Forest Area on Net Climate Impact of Using Forest Biomass for Energy. *BioEnergy Research*, **10(2)**, 499-508, doi:10.1007/s12155-017-9821-z.

Kim, E. and J. Yoo, 2015: Conditional Cash Transfer in the Philippines: How to Overcome Institutional Constraints for Implementing Social Protection. *Asia & the Pacific Policy Studies*, **2(1)**, 75-89, doi:10.1002/app5.72.

Kim, S.C. and Y. Chung, 2018: Dynamics of Nuclear Power Policy in the Post-Fukushima Era: Interest Structure and Politicisation in Japan, Taiwan and Korea. *Asian Studies Review*, **42(1)**, 107-124, doi:10.1080/10357823.2017.1408569.

Kim, Y., W. Kim, and M. Kim, 2014: An international comparative analysis of public acceptance of nuclear energy. *Energy Policy*, **66**, 475-483, doi:10.1016/j.enpol.2013.11.039.

Kindermann, G. et al., 2008: Global cost estimates of reducing carbon emissions through avoided deforestation. *Proceedings of the National Academy of Sciences of the United States of America*, **105(30)**, 10302-7, doi:10.1073/pnas.0710616105.

King, D., Y. Gurtner, A. Firdaus, S. Harwood, and A. Cottrell, 2016: Land use planning for disaster risk reduction and climate change adaptation: Operationalizing policy and legislation at local levels. *International Journal of Disaster Resilience in the Built Environment*, **7(2)**, 158-172, doi:10.1108/IJDRBE-03-2015-0009.

Kirby, M., R. Bark, J. Connor, M.E. Qureshi, and S. Keyworth, 2014: Sustainable irrigation: How did irrigated agriculture in Australia's Murray-Darling Basin adapt in the Millennium Drought? *Agricultural Water Management*, **145**, 154-162, doi:10.1016/j.agwat.2014.02.013.

Kirchhoff, C.J., M.C. Lemos, and S. Dessai, 2013: Actionable Knowledge for Environmental Decision Making: Broadening the Usability of Climate Science. *Annual Review of Environment and Resources*, **38(1)**, 393-414, doi:10.1146/annurev-environ-022112-112828.

Kirkegaard, J.A. et al., 2014: Sense and nonsense in conservation agriculture: Principles, pragmatism and productivity in Australian mixed farming systems. *Agriculture, Ecosystems & Environment*, **187**, 133-145, doi:10.1016/j.agee.2013.08.011.

Kita, S.M., 2017: "Government Doesn't Have the Muscle": State, NGOs, Local Politics, and Disaster Risk Governance in Malawi. *Risk, Hazards & Crisis in Public Policy*, **8(3)**, 244-267, doi:10.1002/rhc3.12118.

Kiunsi, R., 2013: The constraints on climate change adaptation in a city with a large development deficit: the case of Dar es Salaam. *Environment and Urbanization*, **25(2)**, 321-337, doi:10.1177/0956247813489617.

Klein, D. et al., 2014: The global economic long-term potential of modern biomass in a climate-constrained world. *Environmental Research Letters*, **9(7)**, 074017, doi:10.1088/1748-9326/9/7/074017.

Kline, K.L. et al., 2015: Bioenergy and Biodiversity: Key Lessons from the Pan American Region. *Environmental Management*, **56(6)**, 1377-1396, doi:10.1007/s00267-015-0559-0.

Kline, K.L. et al., 2017: Reconciling food security and bioenergy: priorities for action. *GCB Bioenergy*, **9(3)**, 557-576, doi:10.1111/gcbb.12366.

Knoblauch, A. et al., 2014: Changing Patterns of Health in Communities Impacted by a Bioenergy Project in Northern Sierra Leone. *International Journal of Environmental Research and Public Health*, **11(12)**, 12997-13016, doi:10.3390/ijerph111212997.

Knowlton, K. et al., 2014: Development and Implementation of South Asia's First Heat-Health Action Plan in Ahmedabad (Gujarat, India). *International Journal of Environmental Research and Public Health*, **11(4)**, doi:10.3390/ijerph110403473.

Knowlton, N. et al., 2010: Coral Reef Biodiversity. In: *Life in the World's Oceans: Diversity, Distribution, and Abundance*. pp. 65-78.

Koch, H. and S. Vögele, 2009: Dynamic modelling of water demand, water availability and adaptation strategies for power plants to global change. *Ecological Economics*, **68(7)**, 2031-2039, doi:10.1016/J.ECOLECON.2009.02.015.

Koelbl, B.S. et al., 2016: Socio-economic impacts of low-carbon power generation portfolios: Strategies with and without CCS for the Netherlands. *Applied Energy*, **183**, 257-277, doi:https://doi.org/10.1016/j.apenergy.2016.08.068.

Köhler, P., J. Hartmann, and D.A. Wolf-Gladrow, 2010: Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proc Natl Acad Sci U S A*, **107(47)**, 20228-20233, doi:10.1073/pnas.1000545107.

Köhler, P., J.F. Abrams, C. Volker, J. Hauck, and D.A. Wolf-Gladrow, 2013: Geoengineering impact of open ocean dissolution of olivine on atmospheric CO_2, surface ocean pH and marine biology. *Environmental Research Letters*, **8(1)**, doi:Artn 014009 10.1088/1748-9326/8/1/014009.

Kondili, E. and J.K. Kaldellis, 2012: Environmental-Social Benefits/Impacts of Wind Power. *Comprehensive Renewable Energy*, **2**, 503-539, doi:10.1016/B978-0-08-087872-0.00219-5.

Kongsager, R., B. Locatelli, and F. Chazarin, 2016: Addressing climate change mitigation and adaptation together: a global assessment of agriculture and forestry projects. *Environmental Management*, **57(2)**, 271-282, doi:10.1007/s00267-015-0605-y.

Koning, F. et al., 2005: The Ecological and Economic Potential of Carbon Sequestration in Forests: Examples from South America. *AMBIO: A Journal of the Human Environment*, **34(3)**, 224-229, doi:10.1579/0044-7447-34.3.224.

Koomey, J., N.E. Hultman, and A. Grubler, 2017: A reply to "Historical construction costs of global nuclear power reactors". *Energy Policy*, **102**, 640-643, doi:https://doi.org/10.1016/j.enpol.2016.03.052.

Koornneef, J., T. van Keulen, A. Faaij, and W. Turkenburg, 2008: Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2. *International Journal of Greenhouse Gas Control*, **2(4)**, 448-467, doi:10.1016/j.ijggc.2008.06.008.

Koornneef, J., A. Ramírez, W. Turkenburg, and A. Faaij, 2012a: The environmental impact and risk assessment of CO_2 capture, transport and storage - An evaluation of the knowledge base. *Progress in Energy and Combustion Science*, **38(1)**, 62-86, doi:https://doi.org/10.1016/j.pecs.2011.05.002.

Koornneef, J. et al., 2012b: Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. *International Journal of Greenhouse Gas Control*, **11**, 117-132, doi:10.1016/j.ijggc.2012.07.027.

Kooten, G.C., 2000: Economic Dynamics of Tree Planting for Carbon Uptake on Marginal Agricultural Lands. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, **48(1)**, 51-65, doi:10.1111/j.1744-7976.2000.tb00265.x.

Kopytko, N. and J. Perkins, 2011: Climate change, nuclear power, and the adaptation-mitigation dilemma. *Energy Policy*, **39(1)**, 318-333, doi:10.1016/J.ENPOL.2010.09.046.

Korre, A., Z. Nie, and S. Durucan, 2010: Life cycle modelling of fossil fuel power generation with post-combustion CO_2 capture. *International Journal of Greenhouse Gas Control*, **4(2)**, 289-300, doi:10.1016/j.ijggc.2009.08.005.

Kothari, U., 2014: Political discourses of climate change and migration: resettlement policies in the Maldives. *The Geographical Journal*, **180(2)**, 130-140, doi:10.1111/geoj.12032.

Kraaijenbrink, P.D.A., M.F.P. Bierkens, A.F. Lutz, and W.W. Immerzeel, 2017: Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature*, **549(7671)**, 257-260, doi:10.1038/nature23878.

Kragt, M.E., F.L. Gibson, F. Maseyk, and K.A. Wilson, 2016: Public willingness to pay for carbon farming and its co-benefits. *Ecological Economics*, **126**, 125-131, doi:10.1016/j.ecolecon.2016.02.018.

Krarti, M. and K. Dubey, 2018: Review analysis of economic and environmental benefits of improving energy efficiency for UAE building stock. *Renewable and Sustainable Energy Reviews*, **82**, 14-24, doi:10.1016/j.rser.2017.09.013.

Krarti, M., F. Ali, A. Alaidroos, and M. Houchati, 2017: Macro-economic benefit analysis of large scale building energy efficiency programs in Qatar. *International Journal of Sustainable Built Environment*, **6(2)**, 597-609, doi:10.1016/j.ijsbe.2017.12.006.

Kraxner, F. and E.–M. Nordström, 2015: Bioenergy Futures: A Global Outlook on the Implications of Land Use for Forest-Based Feedstock Production. In: *The Future Use of Nordic Forests*. Springer International Publishing, Cham, pp. 63-81.

Kreidenweis, U. et al., 2016: Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environmental Research Letters*, **11(8)**, 085001, doi:10.1088/1748-9326/11/8/085001.

Kubule, A., L. Zogla, and M. Rosa, 2016: Resource and Energy Efficiency in Small and Medium Breweries. *Energy Procedia*, **95**, 223-229, doi:https://doi.org/10.1016/j.egypro.2016.09.055.

Kulkarni, A.R. and D.S. Sholl, 2012: Analysis of equilibrium-based TSA processes for direct capture of CO_2 from air. *Industrial & Engineering Chemistry Research*, **51(25)**, 8631-8645.

Kull, D. et al., 2016: Building Resilience: World Bank Group Experience in Climate and Disaster Resilient Development. *Climate Change Adaptation Strategies -- An Upstream-downstream Perspective*, 255-270, doi:10.1007/978-3-319-40773-9_14.

Kuramochi, T., A. Ramírez, W. Turkenburg, and A. Faaij, 2012: Comparative assessment of CO_2 capture technologies for carbon-intensive industrial processes. *Progress in Energy and Combustion Science*, **38(1)**, 87-112, doi:https://doi.org/10.1016/j.pecs.2011.05.001.

Kuramochi, T. et al., 2017: Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, **18(3)**, 287-305, doi:10.1080/14693062.2017.1397495.

Kuruppu, N. and R. Willie, 2015: Barriers to reducing climate enhanced disaster risks in Least Developed Country-Small Islands through anticipatory adaptation. *Weather and Climate Extremes*, **7**, 72-83, doi:10.1016/j.wace.2014.06.001.

Lackner, K.S., 2009: Capture of carbon dioxide from ambient air. *The European physical journal-special topics*, **176(1)**, 93-106.

Lackner, K.S. and S. Brennan, 2009: Envisioning carbon capture and storage: expanded possibilities due to air capture, leakage insurance, and C-14 monitoring. *Climatic Change*, **96(3)**, 357-378, doi:10.1007/s10584-009-9632-0.

Lackner, K.S. et al., 2012: The urgency of the development of CO_2 capture from ambient air. *Proceedings of the National Academy of Sciences*, **109(33)**, 13156-13162, doi:10.1073/pnas.1108765109.

Lacoue-Labarthe, T. et al., 2016: Impacts of ocean acidification in a warming Mediterranean Sea: An overview. *Regional Studies in Marine Science*, **5**, 1-11, doi:10.1016/j.rsma.2015.12.005.

Lah, O., 2017: Sustainable development synergies and their ability to create coalitions for low-carbon transport measures. *Transportation Research Procedia*, **25**, 5083-5093, doi:10.1016/j.trpro.2017.05.495.

Laird, D.A., R.C. Brown, J.E. Amonette, and J. Lehmann, 2009: Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels, Bioproducts and Biorefining*, **3(5)**, 547-562, doi:10.1002/bbb.169.

Laitner, J.A., 2013: An overview of the energy efficiency potential. *Environmental Innovation and Societal Transitions*, **9**, 38-42, doi:10.1016/j.eist.2013.09.005.

Lakyda, P.I., I.F. Buksha, and V.P. Pasternak, 2005: Opportunities for fulfilling Joint Implementation projects in forestry in Ukraine. *UNASYLVA-FAO-*, **56(3)**, 32.

Lal, R., 2003a: Global Potential of Soil Carbon Sequestration to Mitigate the Greenhouse Effect. *Critical Reviews in Plant Sciences*, **22(2)**, 151-184, doi:10.1080/713610854.

Lal, R., 2003b: Offsetting global CO_2 emissions by restoration of degraded soils and intensification of world agriculture and forestry. *Land Degradation and Development*, **14(3)**, 309-322, doi:10.1002/ldr.562.

Lal, R., 2004a: Carbon Sequestration in Dryland Ecosystems. *Environmental Management*, **33(4)**, 528-544, doi:10.1007/s00267-003-9110-9.

Lal, R., 2004b: Soil carbon sequestration impacts on global climate change and food security. *Science*, **304(5677)**, 1623-7, doi:10.1126/science.1097396.

Lal, R., 2004c: Soil carbon sequestration to mitigate climate change. *Geoderma*, **123(1-2)**, 1-22, doi:10.1016/j.geoderma.2004.01.032.

Lal, R., 2010: Beyond Copenhagen: mitigating climate change and achieving food security through soil carbon sequestration. *Food security*, **2(2)**, 169-177.

Lal, R., 2011: Sequestering carbon in soils of agro-ecosystems. *Food Policy*, **36(SUPPL. 1)**, S33-S39, doi:10.1016/j.foodpol.2010.12.001.

Lal, R., 2013: Intensive Agriculture and the Soil Carbon Pool. *Journal of Crop Improvement*, **27(6)**, 735-751, doi:10.1080/15427528.2013.845053.

Lal, R., R.F. Follett, B.A. Stewart, and J.M. Kimble, 2007: Soil Carbon Sequestration to Mitigate Climate Change and Advance Food Security. *Soil Science*, **172(12)**, 943-956, doi:10.1097/ss.0b013e31815cc498.

Lamond, J.E., C.B. Rose, and C.A. Booth, 2015: Evidence for improved urban flood resilience by sustainable drainage retrofit. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning*, **168(2)**, 101-111, doi:10.1680/udap.13.00022.

Lampert, D.J., H. Cai, and A. Elgowainy, 2016: Wells to wheels: water consumption for transportation fuels in the United States. *Energy & Environmental Science*, **9(3)**, 787-802, doi:10.1039/C5EE03254G.

Landauer, M., S. Juhola, and M. Söderholm, 2015: Inter-relationships between adaptation and mitigation: a systematic literature review. *Climatic Change*, **131(4)**, 505-517, doi:10.1007/s10584-015-1395-1.

Lasco, R.D., R.J.P. Delfino, and M.L.O. Espaldon, 2014: Agroforestry systems: helping smallholders adapt to climate risks while mitigating climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **5(6)**, 825-833, doi:10.1002/wcc.301.

Lashley, J.G. and K. Warner, 2015: Evidence of demand for microinsurance for coping and adaptation to weather extremes in the Caribbean. *Climatic Change*, **133(1)**, 101-112, doi:10.1007/s10584-013-0922-1.

Lassaletta, L. and E. Aguilera, 2015: Soil carbon sequestration is a climate stabilization wedge: Comments on Sommer and Bossio (2014). *Journal of Environmental Management*, **153**, 48-49, doi:10.1016/j.jenvman.2015.01.038.

Laude, A. and O. Ricci, 2011: Can carbon capture and storage on small sources be profitable? An application to the ethanol sector. *Energy Procedia*, **4**, 2909-2917, doi:10.1016/J.EGYPRO.2011.02.198.

Laude, A., O. Ricci, G. Bureau, J. Royer-Adnot, and A. Fabbri, 2011: CO_2 capture and storage from a bioethanol plant: Carbon and energy footprint and economic assessment. *International Journal of Greenhouse Gas Control*, **5(5)**, 1220-1231, doi:10.1016/j.ijggc.2011.06.004.

Lauri, P. et al., 2014: Woody biomass energy potential in 2050. *Energy Policy*, **66**, 19-31, doi:10.1016/j.enpol.2013.11.033.

Le Vine, S., A. Zolfaghari, and J. Polak, 2014: *Carsharing: Evolution, Challenges and Opportunities - 22th ACEA Scientific Advisory Group Report*. European Automoble Manufacturers Association (ACEA), Brussels, Belgium.

Lechthaler, F. and A. Vinogradova, 2017: The climate challenge for agriculture and the value of climate services: Application to coffee-farming in Peru. *European Economic Review*, **94**, 45-70, doi:10.1016/j.euroecorev.2017.02.002.

Leck, H., D. Conway, M. Bradshaw, and J. Rees, 2015: Tracing the Water-Energy-Food Nexus: Description, Theory and Practice. *Geography Compass***, 9(8)**, 445-460, doi:10.1111/gec3.12222.

Lee, C.M. and P. Erickson, 2017: How does local economic development in cities affect global GHG emissions? *Sustainable Cities and Society***, 35**, 626-636, doi:10.1016/j.scs.2017.08.027.

Lee, H.–C., B.A. McCarl, and D. Gillig, 2005: The Dynamic Competitiveness of U.S. Agricultural and Forest Carbon Sequestration. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie***, 53(4)**, 343-357, doi:10.1111/j.1744-7976.2005.00023.x.

Lee, J.W., B. Hawkins, D.M. Day, and D.C. Reicosky, 2010: Sustainability: the capacity of smokeless biomass pyrolysis for energy production, global carbon capture and sequestration. *Energy & Environmental Science***, 3(11)**, 1695, doi:10.1039/c004561f.

Lehmann, J., J. Gaunt, and M. Rondon, 2006: Bio-char Sequestration in Terrestrial Ecosystems - A Review. *Mitigation and Adaptation Strategies for Global Change***, 11(2)**, 403-427, doi:10.1007/s11027-005-9006-5.

Leichenko, R. and J.A. Silva, 2014: Climate change and poverty: vulnerability, impacts, and alleviation strategies. *Wiley Interdisciplinary Reviews: Climate Change***, 5(4)**, 539-556, doi:10.1002/wcc.287.

Lemaire, G., A. Franzluebbers, P.C. de Faccio Carvalho, and B. Dedieu, 2014: Integrated crop--livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agriculture, Ecosystems & Environment***, 190**, 4-8.

Lemos, M.C., 2015: Usable climate knowledge for adaptive and co-managed water governance. *Current Opinion in Environmental Sustainability***, 12**, 48-52, doi:10.1016/j.cosust.2014.09.005.

Lemos, M.C., Y.J. Lo, D.R. Nelson, H. Eakin, and A.M. Bedran-Martins, 2016: Linking development to climate adaptation: Leveraging generic and specific capacities to reduce vulnerability to drought in NE Brazil. *Global Environmental Change***, 39**, 170-179, doi:10.1016/j.gloenvcha.2016.05.001.

Lenton, T.M., 2010: The potential for land-based biological CO_2 removal to lower future atmospheric CO_2 concentration. *Carbon Management***, 1(1)**, 145-160, doi:10.4155/cmt.10.12.

Lenton, T.M., 2014: The Global Potential for Carbon Dioxide Removal. *Geoengineering of the Climate System*, 52-79, doi:10.1039/9781782621225-00052.

Leonard, S., M. Parsons, K. Olawsky, and F. Kofod, 2013: The role of culture and traditional knowledge in climate change adaptation: Insights from East Kimberley, Australia. *Global Environmental Change***, 23(3)**, 623-632, doi:10.1016/j.gloenvcha.2013.02.012.

Lesnikowski, A.C. et al., 2013: National-level factors affecting planned, public adaptation to health impacts of climate change. *Global Environmental Change***, 23(5)**, 1153-1163, doi:10.1016/j.gloenvcha.2013.04.008.

Levidow, L. et al., 2014: Improving water-efficient irrigation: Prospects and difficulties of innovative practices. *Agricultural Water Management***, 146**, 84-94, doi:10.1016/j.agwat.2014.07.012.

Lewandowski, I., 2015: Securing a sustainable biomass supply in a growing bioeconomy. *Global Food Security***, 6**, 34-42, doi:https://doi.org/10.1016/j.gfs.2015.10.001.

Lewandowski, M., 2016: Designing the Business Models for Circular Economy-Towards the Conceptual Framework. *Sustainability***, 8(1)**, 43, doi:10.3390/su8010043.

Ley, D., 2017: Sustainable Development, Climate Change, and Renewable Energy in Rural Central America. In: *Evaluating Climate Change Action for Sustainable Development*. Springer International Publishing, Cham, pp. 187-212.

Li, F. et al., 2017: Urban ecological infrastructure: an integrated network for ecosystem services and sustainable urban systems. *Journal of Cleaner Production***, 163(S1)**, S12-S18, doi:10.1016/j.jclepro.2016.02.079.

Li, H., J. He, Z.P. Bharucha, R. Lal, and J. Pretty, 2016: Improving China's food and environmental security with conservation agriculture. *International Journal of Agricultural Sustainability***, 14(4)**, 377-391, doi:10.1080/14735903.2016.1170330.

Liao, C. and D.G. Brown, 2018: Assessments of synergistic outcomes from sustainable intensification of agriculture need to include smallholder livelihoods with food production and ecosystem services. *Current Opinion in Environmental Sustainability*, **32**, 53-59, doi:10.1016/j.cosust.2018.04.013.

Liao, F., E. Molin, and B. Van Wee, 2017: Consumer preferences for electric vehicles: a literature review. *Transport Reviews*, **37(3)**, 252-275, doi:10.1080/01441647.2016.1230794.

Lilford, R.J. et al., 2017: Improving the health and welfare of people who live in slums. *Lancet*, **389(10068)**, 559-570.

Lin, B. and Z. Du, 2017: Can urban rail transit curb automobile energy consumption? *Energy Policy*, **105**, 120-127, doi:10.1016/j.enpol.2017.02.038.

Lin, B.B. et al., 2017: How green is your garden?: Urban form and socio-demographic factors influence yard vegetation, visitation, and ecosystem service benefits. *Landscape and Urban Planning*, **157**, 239-246, doi:10.1016/j.landurbplan.2016.07.007.

Lin, C.S.K. et al., 2013: Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective. *Energy & Environmental Science*, doi:10.1039/c2ee23440h.

Lin, J.–C., C.–S. Wu, W.–Y. Liu, and C.–C. Lee, 2012: Behavioral intentions toward afforestation and carbon reduction by the Taiwanese public. *Forest Policy and Economics*, **14(1)**, 119-126, doi:10.1016/J.FORPOL.2011.07.016.

Lindenmayer, D.B. and R.J. Hobbs, 2004: Fauna conservation in Australian plantation forests - a review. *Biological Conservation*, **119(2)**, 151-168, doi:10.1016/J.BIOCON.2003.10.028.

Linnerooth-Bayer, J. and S. Hochrainer-Stigler, 2015: Financial instruments for disaster risk management and climate change adaptation. *Climatic Change*, **133(1)**, 85-100, doi:10.1007/s10584-013-1035-6.

Linovski, O., D.M. Baker, and K. Manaugh, 2018: Equity in practice? Evaluations of equity in planning for bus rapid transit. *Transportation Research Part A*, **113**, 75-87, doi:10.1016/j.tra.2018.03.030.

Litman, T.A., 2017: *Economic Value of Walkability*. Victoria Transport Policy Institute, Victoria, Canada.

Litman, T.A., 2018: *Evaluating Active Transport Benefits and Costs: Guide to valuing Walking and Cycling Improvements and Encouragement Programs*. Victoria Transport Policy Institute, Victoria, Canada.

Liu, W., W. Chen, and C. Peng, 2014: Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study. *Ecological Modelling*, **291(Supplement C)**, 6-14, doi:https://doi.org/10.1016/j.ecolmodel.2014.07.012.

Liu, W., Z. Yu, X. Xie, K. von Gadow, and C. Peng, 2018: A critical analysis of the carbon neutrality assumption in life cycle assessment of forest bioenergy systems. *Environmental Reviews*, **26(1)**, 93-101, doi:10.1139/er-2017-0060.

Liu, X. et al., 2017: Microgrids for Enhancing the Power Grid Resilience in Extreme Conditions. *IEEE Transactions on Smart Grid*, **8(2)**, 589-597, doi:10.1109/TSG.2016.2579999.

Lobell, D.B., U.L.C. Baldos, and T.W. Hertel, 2013: Climate adaptation as mitigation: the case of agricultural investments. *Environmental Research Letters*, **8(1)**, 015012, doi:10.1088/1748-9326/8/1/015012.

Lobo, C., N. Chattopadhyay, and K. Rao, 2017: Making smallholder farming climate-smart. *Economic and Political Weekly, LII*, **52(1)**, 53-58.

Locatelli, B., C. Pavageau, E. Pramova, and M. Di Gregorio, 2015a: Integrating climate change mitigation and adaptation in agriculture and forestry: opportunities and trade-offs. *Wiley Interdisciplinary Reviews: Climate Change*, **6(6)**, 585-598, doi:10.1002/wcc.357.

Locatelli, B. et al., 2015b: Tropical reforestation and climate change: beyond carbon. *Restoration Ecology*, **23(4)**, 337-343, doi:10.1111/rec.12209.

Löffler, K. et al., 2017: Designing a model for the global energy system-GENeSYS-MOD: An application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies*, **10(10)**, 1-29, doi:10.3390/en10101468.

Lohmann, U. and B. Gasparini, 2017: A cirrus cloud climate dial? *Science*, **357(6348)**, 248-249, doi:10.1126/science.aan3325.

Loiola, C., W. Mary, and L. Pimentel da Silva, 2018: Hydrological performance of modular-tray green roof systems for increasing the resilience of mega-cities to climate change. *Journal of Hydrology*, doi:10.1016/j.jhydrol.2018.01.004.

Lomax, G., M. Workman, T. Lenton, and N. Shah, 2015: Reframing the policy approach to greenhouse gas removal technologies. *Energy Policy*, **78(Supplement C)**, 125-136, doi:https://doi.org/10.1016/j.enpol.2014.10.002.

Longstaff, H., D.M. Secko, G. Capurro, P. Hanney, and T. McIntyre, 2015: Fostering citizen deliberations on the social acceptability of renewable fuels policy: The case of advanced lignocellulosic biofuels in Canada. *Biomass and Bioenergy*, **74**, 103-112, doi:10.1016/J.BIOMBIOE.2015.01.003.

Lorenz, K. and R. Lal, 2014: Soil organic carbon sequestration in agroforestry systems. A review. *Agronomy for Sustainable Development*, **34(2)**, 443-454, doi:10.1007/s13593-014-0212-y.

Lourenço, T.C., R. Swart, H. Goosen, and R. Street, 2016: The rise of demand-driven climate services. *Nature Climate Change*, **6(1)**, 13-14, doi:10.1038/nclimate2836.

Lovering, J.R., A. Yip, and T. Nordhaus, 2016: Historical construction costs of global nuclear power reactors. *Energy Policy*, **91**, 371-382, doi:10.1016/j.enpol.2016.01.011.

Lovins, A.B., T. Palazzi, R. Laemel, and E. Goldfield, 2018: Relative deployment rates of renewable and nuclear power: A cautionary tale of two metrics. *Energy Research & Social Science*, **38**, 188-192, doi:10.1016/J.ERSS.2018.01.005.

Lu, Y., D. Chadwick, D. Norse, D. Powlson, and W. Shi, 2015: Sustainable intensification of China's agriculture: the key role of nutrient management and climate change mitigation and adaptation. *Agriculture, Ecosystems & Environment*, **209**, 1-4, doi:10.1016/j.agee.2015.05.012.

Lucas, J., 2015: Aquaculture. *Current Biology*, **25(22)**, R1064-5, doi:10.1016/j.cub.2015.08.013.

Luckow, P., M.A. Wise, J.J. Dooley, and S.H. Kim, 2010: Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO_2 concentration limit scenarios. *International Journal of Greenhouse Gas Control*, **4(5)**, 865-877, doi:10.1016/j.ijggc.2010.06.002.

Luisetti, T., E.L. Jackson, and R.K. Turner, 2013: Valuing the European 'coastal blue carbon' storage benefit. *Marine Pollution Bulletin*, **71(1-2)**, 101-106, doi:10.1016/j.marpolbul.2013.03.029.

Lusiana, B., M. van Noordwijk, and G. Cadisch, 2012: Land sparing or sharing? Exploring livestock fodder options in combination with land use zoning and consequences for livelihoods and net carbon stocks using the FALLOW model. *Agriculture, Ecosystems & Environment*, **159**, 145-160, doi:10.1016/j.agee.2012.07.006.

Lutz, W. and R. Muttarak, 2017: Forecasting societies' adaptive capacities through a demographic metabolism model. *Nature Climate Change*, **7(3)**, 177-184, doi:10.1038/nclimate3222.

Lutz, W., R. Muttarak, and E. Striessnig, 2014: Universal education is key to enhanced climate adaptation. *Science*, **346(6213)**, 1061-1062, doi:10.1126/science.1257975.

Lwasa, S., 2017: Options for reduction of greenhouse gas emissions in the low-emitting city and metropolitan region of Kampala. *Carbon Management*, **8(3)**, 263-276, doi:10.1080/17583004.2017.1330592.

Lwasa, S. et al., 2015: A meta-analysis of urban and peri-urban agriculture and forestry in mediating climate change. *Current Opinion in Environmental Sustainability*, **13**, 68-73, doi:10.1016/j.cosust.2015.02.003.

Lyons, K. and P. Westoby, 2014: Carbon colonialism and the new land grab: Plantation forestry in Uganda and its livelihood impacts. *Journal of Rural Studies*, **36**, 13-21, doi:10.1016/J.JRURSTUD.2014.06.002.

Mabon, L. et al., 2013: Tell me what you Think about the Geological Storage of Carbon Dioxide': Towards a Fuller Understanding of Public Perceptions of CCS. *Energy Procedia*, **37**, 7444-7453, doi:10.1016/J.EGYPRO.2013.06.687.

MacDonald, J.P., J. Ford, A.C. Willox, C. Mitchell, and K. Productions, 2015a: Youth-led participatory video as a strategy to enhance inuit youth adaptive capacities for dealing with climate change. *Arctic*, **68(4)**, 486-499, doi:10.14430/arctic4527.

MacDonald, J.P. et al., 2015b: Protective factors for mental health and well-being in a changing climate: Perspectives from Inuit youth in Nunatsiavut, Labrador. *Social Science & Medicine*, **141**, 133-141, doi:10.1016/j.socscimed.2015.07.017.

MacDonald Gibson, J. et al., 2015: Predicting urban design effects on physical activity and public health: A case study. *Health & Place*, **35**, 79-84, doi:10.1016/j.healthplace.2015.07.005.

Magneschi, G., T. Zhang, and R. Munson, 2017: The Impact of CO_2 Capture on Water Requirements of Power Plants. *Energy Procedia*, **114**, 6337-6347, doi:https://doi.org/10.1016/j.egypro.2017.03.1770.

Magni, G., 2017: Indigenous knowledge and implications for the sustainable development agenda. *European Journal of Education*, **52(4)**, 437-447, doi:10.1111/ejed.12238.

Mahlkow, N. and J. Donner, 2017: From Planning to Implementation? The Role of Climate Change Adaptation Plans to Tackle Heat Stress: A Case Study of Berlin, Germany. *Journal of Planning Education and Research*, **37(4)**, 385-396, doi:10.1177/0739456X16664787.

Maibach, E., L. Steg, and J. Anable, 2009: Promoting physical activity and reducing climate change: Opportunities to replace short car trips with active transportation. *Preventive Medicine*, **49(4)**, doi:10.1016/j.ypmed.2009.06.028.

Maizlish, N., N.J. Linesch, and J. Woodcock, 2017: Health and greenhouse gas mitigation benefits of ambitious expansion of cycling, walking, and transit in California. *Journal of Transport & Health*, **6**, 490-500, doi:10.1016/j.jth.2017.04.011.

Majzoobi, A. and A. Khodaei, 2017: Application of microgrids in providing ancillary services to the utility grid. *Energy*, **123**, 555-563, doi:10.1016/j.energy.2017.01.113.

Mamais, D., C. Noutsopoulos, A. Dimopoulou, A. Stasinakis, and T.D. Lekkas, 2015: Wastewater treatment process impact on energy savings and greenhouse gas emissions. *Water Science and Technology*, **71(2)**, 303-308, doi:10.2166/wst.2014.521.

Manning, D.A. and P. Renforth, 2013: Passive sequestration of atmospheric CO_2 through coupled plant-mineral reactions in urban soils. *Environ Sci Technol*, **47(1)**, 135-141, doi:10.1021/es301250j.

Mannke, F., 2011: Key themes of local adaptation to climate change: results from mapping community-based initiatives in Africa. In: *Experiences of Climate Change Adaptation in Africa* [Walter Leal Filho (ed.)]. pp. 17-32.

Mansfield, T.J. and J.M. Gibson, 2015: Health Impacts of Increased Physical Activity from Changes in Transportation Infrastructure: Quantitative Estimates for Three Communities. *BioMed Research International*, 1-15, doi:10.1155/2015/812325.

Mantilla, G., C. Thomson, J. Sharoff, A.G. Barnston, and A. Curtis, 2014: Capacity development through the sharing of climate information with diverse user communities. *Earth Perspectives*, **1(1)**, 21, doi:10.1186/2194-6434-1-21.

Mantyka-Pringle, C.S. et al., 2016: Prioritizing management actions for the conservation of freshwater biodiversity under changing climate and land-cover. *Biological Conservation*, **197**, 80-89, doi:10.1016/j.biocon.2016.02.033.

Mapfumo, P., F. Mtambanengwe, and R. Chikowo, 2016: Building on indigenous knowledge to strengthen the capacity of smallholder farming communities to adapt to climate change and variability in southern Africa. *Climate and Development*, **8(1)**, 72-82, doi:10.1080/17565529.2014.998604.

Maragkogianni, A., S. Papaefthimiou, and C. Zopounidis, 2016: *Mitigating Shipping Emissions in European Ports: Social and Environmental Benefits*. Springer International Publishing, Cham, Switzerland, 76 pp.

Maraseni, T.N. and G. Cockfield, 2015: The financial implications of converting farmland to state-supported environmental plantings in the Darling Downs region, Queensland. *Agricultural Systems*, **135**, 57-65, doi:10.1016/J.AGSY.2014.12.004.

Marengo, J.A. et al., 2017: A globally deployable strategy for co-development of adaptation preferences to sea-level rise: the public participation case of Santos, Brazil. *Natural Hazards*, **88(1)**, 39-53, doi:10.1007/s11069-017-2855-x.

Margerum, R.D. and C.J. Robinson, 2015: Collaborative partnerships and the challenges for sustainable water management. *Current Opinion in Environmental Sustainability*, **12**, 53-58, doi:10.1016/j.cosust.2014.09.003.

Marion Suiseeya, K.R. and S. Caplow, 2013: In pursuit of procedural justice: Lessons from an analysis of 56 forest carbon project designs. *Global Environmental Change*, **23(5)**, 968-979, doi:10.1016/J.GLOENVCHA.2013.07.013.

Marques, V., N. Bento, and P.M. Costa, 2014: The "Smart Paradox": Stimulate the deployment of smart grids with effective regulatory instruments. *Energy*, **69**, 96-103, doi:10.1016/j.energy.2014.01.007.

Martin, M. et al., 2014: Climate-related migration in rural Bangladesh: a behavioural model. *Population and Environment*, **36(1)**, 85-110, doi:10.1007/s11111-014-0207-2.

Masiero, S., 2015: Redesigning the Indian Food Security System through E-Governance: The Case of Kerala. *World Development*, **67**, 126-137, doi:10.1016/j.worlddev.2014.10.014.

Masud-All-Kamal, M. and C.K. Saha, 2014: Targeting social policy and poverty reduction: The case of social safety nets in Bangladesh. *Poverty & Public Policy*, **6(2)**, 195-211.

Matan, A. and P. Newman, 2016: *People Cities: The Life and Legacy of Jan Gehl*. Island Press, Washington DC.

Matan, A., P. Newman, R. Trubka, C. Beattie, and L.A. Selvey, 2015: Health, transport and Urban Planning: Quantifying the Links between Urban Assessment Models and Human health. *Urban Policy and Research*, **33(2)**, 146-149, doi:10.1080/08111146.2014.990626.

Mathbor, G.M., 2007: Enhancement of community preparedness for natural disasters. *International Social Work*, **50(3)**, 357-369, doi:10.1177/0020872807076049.

Mathioudakis, V., P.W. Gerbens-Leenes, T.H. Van der Meer, and A.Y. Hoekstra, 2017: The water footprint of second-generation bioenergy: A comparison of biomass feedstocks and conversion techniques. *Journal of Cleaner Production*, **148**, 571-582, doi:10.1016/J.JCLEPRO.2017.02.032.

Matthews, T. and R. Potts, 2018: Planning for climigration: a framework for effective action. *Climatic Change*, doi:10.1007/s10584-018-2205-3.

Mavhura, E., A. Collins, and P.P. Bongo, 2017: Flood vulnerability and relocation readiness in Zimbabwe. *Disaster Prevention and Management: An International Journal*, **26(1)**, 41-54, doi:10.1108/DPM-05-2016-0101.

Mavhura, E., S.B. Manyena, A.E. Collins, and D. Manatsa, 2013: Indigenous knowledge, coping strategies and resilience to floods in Muzarabani, Zimbabwe. *International Journal of Disaster Risk Reduction*, **5(Supplement C)**, 38-48, doi:https://doi.org/10.1016/j.ijdrr.2013.07.001.

Mawere, M. and T.R. Mubaya, 2015: Indigenous Mechanisms for Disaster Risk Reduction: How the Shona of Zimbabwe Managed Drought and Famine? In: *Harnessing Cultural Capital for Sustainability: A Pan Africanist Perspective* [Mawere, M. and S. Awuah-Nyamekye (eds.)]. Langaa Research and Publishing CIG, Mankon, Cameroon, pp. 1.

Mazzotti, M., R. Baciocchi, M.J. Desmond, and R.H. Socolow, 2013: Direct air capture of CO_2 with chemicals: Optimization of a two-loop hydroxide carbonate system using a countercurrent air-liquid contactor. *Climatic Change*, **118(1)**, 119-135, doi:10.1007/s10584-012-0679-y.

Mbow, C., P. Smith, D. Skole, L. Duguma, and M. Bustamante, 2014a: Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in africa. *Current Opinion in Environmental Sustainability*, **6(1)**, 8-14, doi:10.1016/j.cosust.2013.09.002.

Mbow, C. et al., 2014b: Agroforestry solutions to address food security and climate change challenges in Africa. *Current Opinion in Environmental Sustainability*, **6(1)**, 61-67, doi:10.1016/j.cosust.2013.10.014.

McCarl, B.A., C. Peacocke, R. Chrisman, C.–C. Kung, and R.D. Sands, 2009: Economics of biochar production, utilization and greenhouse gas offsets. In: *Biochar for environmental management: Science and technology*. Earthscan: London, UK, pp. 341-358.

McCloud, K. et al., 2014: *Once in a lifetime: city-building after disaster in Christchurch*. Freerange Press.

McCollum, D.L. et al., 2013: Climate policies can help resolve energy security and air pollution challenges. *Climate Change*, **119(2)**, 479-494.

McCormack, G.R. and A. Shiell, 2011: In search of causality: a systematic review of the relationship between the built environment and physical activity among adults. *International Journal of Behavioral Nutrition and Physical Activity*, **8**, doi:Artn 125 10.1186/1479-5868-8-125.

McCosker, A., A. Matan, and D. Marinova, 2018: Implementing Healthy Planning and Active Living Initiatives: A Virtuous Cycle. *Urban Science*, **2(2)**, 30-46, doi:10.3390/urbansci2020030.

Mccubbin, S.G., T. Pearce, J.D. Ford, and B. Smit, 2017: Social - ecological change and implications for food security in Funafuti, Tuvalu. *Ecology and Society*, **22(1)**, 53-65, doi:10.5751/ES-09129-220153.

McElwee, P. et al., 2016: Using REDD+ Policy to Facilitate Climate Adaptation at the Local Level: Synergies and Challenges in Vietnam. *Forests*, **8(1)**, 11, doi:10.3390/f8010011.

McGlashan, N., N. Shah, B. Caldecott, and M. Workman, 2012: High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection*, **90(6)**, 501-510, doi:10.1016/j.psep.2012.10.004.

McInnes, G., 2017: *Understanding the distributional and household effects of the low-carbon transition in g20 countries*. 29 pp.

McKinley, D.C. et al., 2011: A synthesis of current knowledge on forests and carbon storage in the United States. *Ecological Applications*, **21(6)**, 1902-1924, doi:10.1890/10-0697.1.

McLaren, D., 2012: A comparative global assessment of potential negative emissions technologies. *Special Issue: Negative emissions technology*, **90(6)**, 489-500, doi:10.1016/j.psep.2012.10.005.

McNamara, K.E. and S.S. Prasad, 2014: Coping with extreme weather: Communities in Fiji and Vanuatu share their experiences and knowledge. *Climatic Change*, **123(2)**, 121-132, doi:10.1007/s10584-013-1047-2.

McNeil, M.A. and N. Bojda, 2012: Cost-effectiveness of high-efficiency appliances in the U.S. residential sector: A case study. *Energy Policy*, **45**, 33-42, doi:10.1016/j.enpol.2011.12.050.

McPhearson, T. et al., 2016: Scientists must have a say in the future of cities. *Nature*, **538(7624)**, 165-166, doi:10.1038/538165a.

Mdemu, M., N. Mziray, H. Bjornlund, and J.J. Kashaigili, 2017: Barriers to and opportunities for improving productivity and profitability of the Kiwere and Magozi irrigation schemes in Tanzania. *International Journal of Water Resources Development*, **33(5)**, 725-739, doi:10.1080/07900627.2016.1188267.

Meadowcroft, J., J.C. Stephens, E.J. Wilson, and I.H. Rowlands, 2018: Social dimensions of smart grid: Regional analysis in Canada and the United States. Introduction to special issue of Renewable and Sustainable Energy Reviews. *Renewable and Sustainable Energy Reviews*, **82**, 1909-1912, doi:10.1016/j.rser.2017.06.106.

Measham, T.G. et al., 2011: Adapting to climate change through local municipal planning: barriers and challenges. *Mitigation and Adaptation Strategies for Global Change*, **16(8)**, 889-909, doi:10.1007/s11027-011-9301-2.

Melde, S., F. Laczko, and F. Gemenne, 2017: *Making mobility work for adaptation to environmental changes: Results from the MECLEP global research*. International Organization for Migration.

Mesquita, P.S. and M. Bursztyn, 2016: Integration of social protection and climate change adaptation in Brazil. *British Food Journal*, **118(12)**, 3030-3043, doi:10.1108/BFJ-02-2016-0082.

Methmann, C. and A. Oels, 2015: From 'fearing' to 'empowering' climate refugees: Governing climate-induced migration in the name of resilience. *Security Dialogue*, **46(1)**, 51-68, doi:10.1177/0967010614552548.

Metting, F.B., J.L. Smith, J.S. Amthor, and R.C. Izaurralde, 2001: Science needs and new technology for increasing soil carbon sequestration. *Climatic Change*, **51(1)**, 11-34, doi:10.1023/A:1017509224801.

Meyers, S. and S. Kromer, 2008: Measurement and verification strategies for energy savings certificates: meeting the challenges of an uncertain world. *Energy Efficiency*, **1(4)**, 313-321, doi:10.1007/s12053-008-9019-5.

Mguni, P., L. Herslund, and M.B. Jensen, 2016: Sustainable urban drainage systems: examining the potential for green infrastructure-based stormwater management for Sub-Saharan cities. *Natural Hazards*, **82(S2)**, 241-257, doi:10.1007/s11069-016-2309-x.

Mialhe, F. et al., 2016: The development of aquaculture on the northern coast of Manila Bay (Philippines): an analysis of long-term land-use changes and their causes. *Journal of Land Use Science*, **11(2)**, 236-256, doi:10.1080/1747423X.2015.1057245.

Mikunda, T. et al., 2014: Designing policy for deployment of CCS in industry. *Climate Policy*, **14(5)**, 665-676, doi:10.1080/14693062.2014.905441.

Miller, S., H. Shemer, and R. Semiat, 2015: Energy and environmental issues in desalination. *Desalination*, **366(Supplement C)**, 2-8, doi:https://doi.org/10.1016/j.desal.2014.11.034.

Mills, E., 2007: Synergisms between climate change mitigation and adaptation: An insurance perspective. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 809-842, doi:10.1007/s11027-007-9101-x.

Mills, M. et al., 2016: Reconciling Development and Conservation under Coastal Squeeze from Rising Sea Level. *Conservation Letters*, **9(5)**, 361-368, doi:10.1111/conl.12213.

Milman, A. and K. Jagannathan, 2017: Conceptualization and implementation of ecosystems-based adaptation. *Climatic Change*, **142(1-2)**, 113-127, doi:10.1007/s10584-017-1933-0.

Milner, A.M. et al., 2017: Glacier shrinkage driving global changes in downstream systems. *Proceedings of the National Academy of Sciences*, **114(37)**, 9770-9778, doi:10.1073/pnas.1619807114.

Minasny, B. et al., 2017: Soil carbon 4 per mille. *Geoderma*, **292**, 59-86, doi:10.1016/j.geoderma.2017.01.002.

Mingarro, M. and J.M. Lobo, 2018: Environmental representativeness and the role of emitter and recipient areas in the future trajectory of a protected area under climate change. *Animal Biodiversity and Conservation*, **41(2)**.

Minx, J.C. et al., 2017: The fast-growing dependence on negative emissions. (in press).

Mirasgedis, S., C. Tourkolias, E. Pavlakis, and D. Diakoulaki, 2014: A methodological framework for assessing the employment effects associated with energy efficiency interventions in buildings. *Energy and Buildings*, **82**, 275-286, doi:10.1016/j.enbuild.2014.07.027.

Mistry, J. and A. Berardi, 2016: Bridging indigenous and scientific knowledge. *Science*, **352(6291)**, 1274-1275, doi:10.1126/science.aaf1160.

Mistry, J., B.A. Bilbao, and A. Berardi, 2016: Community owned solutions for fire management in tropical ecosystems: case studies from Indigenous communities of South America. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371(1696)**, 20150174, doi:10.1098/rstb.2015.0174.

Mitlin, D. and D. Satterthwaite, 2013: *Urban poverty in the global South: scale and nature*. Routledge, Abingdon, UK and New York, NY, USA.

Mochizuki, J. and S.E. Chang, 2017: Disasters as opportunity for change: Tsunami recovery and energy transition in Japan. *International Journal of Disaster Risk Reduction*, **21(Supplement C)**, 331-339, doi:10.1016/j.ijdrr.2017.01.009.

Modahl, I.S., C. Askham, K.A. Lyng, and A. Brekke, 2012: Weighting of environmental trade-offs in CCS-an LCA case study of electricity from a fossil gas power plant with post-combustion CO_2capture, transport and storage. *International Journal of Life Cycle Assessment*, **17(7)**, 932-943, doi:10.1007/s11367-012-0421-z.

Moffat, C.F., 2017: Aquaculture. *Issues in Environmental Science and Technology*, **2017-Janua**, 128-175, doi:10.1039/9781782626916-00128.

Moglia, M. et al., 2018: Urban transformation stories for the 21st century: Insights from strategic conversations. *Global Environmental Change*, **50**, 222-237, doi:10.1016/j.gloenvcha.2018.04.009.

Mohamed, M., M. Ferguson, and P. Kanaroglou, 2017: What hinders adoption of the electric bus in Canadian transit? Perspectives of transit providers. *Transportation Research Part D*, doi:10.1016/j.trd.2017.09.019.

Mohan, A., 2017: Whose land is it anyway? Energy futures & land use in India. *Energy Policy*, **110**, 257-262, doi:10.1016/j.enpol.2017.08.025.

Möllersten, K., J. Yan, and J. R. Moreira, 2003: Potential market niches for biomass energy with CO_2 capture and storage-Opportunities for energy supply with negative CO_2 emissions. *Biomass and Bioenergy*, **25(3)**, 273-285, doi:https://doi.org/10.1016/S0961-9534(03)00013-8.

Möllersten, K., L. Gao, and J. Yan, 2006: CO_2 Capture in Pulp and Paper Mills: CO_2 Balances and Preliminary Cost Assessment. *Mitigation and Adaptation Strategies for Global Change*, **11(5-6)**, 1129-1150, doi:10.1007/s11027-006-9026-9.

Möllersten, K., L. Gao, J. Yan, and M. Obersteiner, 2004: Efficient energy systems with CO_2 capture and storage from renewable biomass in pulp and paper mills. *Renewable Energy*, **29(9)**, 1583-1598, doi:10.1016/j.renene.2004.01.003.

Monahan, W.B. and D.M. Theobald, 2018: Climate change adaptation benefits of potential conservation partnerships. *PLoS ONE*, **13(2)**, doi:10.1371/journal.pone.0191468.

Montefrio, M.J.F. and D.A. Sonnenfeld, 2013: Global-Local Tensions in Contract Farming of Biofuel Crops Involving Indigenous Communities in the Philippines. *Society & Natural Resources*, **26(3)**, 239-253, doi:10.1080/08941920.2012.682114.

Moore, J.C., S. Jevrejeva, and A. Grinsted, 2010: Efficacy of geoengineering to limit 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, **107(36)**, 15699-15703, doi:10.1073/pnas.1008153107.

Moosdorf, N., P. Renforth, and J. Hartmann, 2014: Carbon Dioxide Efficiency of Terrestrial Enhanced Weathering. *Environmental Science & Technology*, **48(9)**, 4809-4816, doi:10.1021/es4052022.

Morales-Florez, V., A. Santos, A. Lemus, and L. Esquivias, 2011: Artificial weathering pools of calcium-rich industrial waste for CO_2 sequestration. *Chemical Engineering Journal*, **166(1)**, 132-137, doi:10.1016/j.cej.2010.10.039.

Moreira, J.R., 2006: Global Biomass Energy Potential. *Mitigation and Adaptation Strategies for Global Change*, **11(2)**, 313-342, doi:10.1007/s11027-005-9003-8.

Moreira, J.R., V. Romeiro, S. Fuss, F. Kraxner, and S.A. Pacca, 2016: BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues. *Applied Energy*, **179**, 55-63, doi:10.1016/J.APENERGY.2016.06.044.

Morris, R.L., G. Deavin, S. Hemelryk Donald, and R.A. Coleman, 2016: Eco-engineering in urbanised coastal systems: Consideration of social values. *Ecological Management and Restoration*, **17(1)**, 33-39, doi:10.1111/emr.12200.

Moula, M.M.E., J. Nyári, and A. Bartel, 2017: Public acceptance of biofuels in the transport sector in Finland. *International Journal of Sustainable Built Environment*, **6(2)**, 434-441, doi:10.1016/J.IJSBE.2017.07.008.

Mouratiadou, I. et al., 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy*, **64**, 48-58, doi:10.1016/J.ENVSCI.2016.06.007.

Muench, S., S. Thuss, and E. Guenther, 2014: What hampers energy system transformations? The case of smart grids. *Energy Policy*, **73**, 80-92, doi:10.1016/J.ENPOL.2014.05.051.

Mullaney, J., T. Lucke, and S.J. Trueman, 2015: A review of benefits and challenges in growing street trees in paved urban environments. *Landscape and Urban Planning*, **134**, 157-166, doi:10.1016/j.landurbplan.2014.10.013.

Müller, B. and D. Kreuer, 2016: Ecologists Should Care about Insurance, too. *Trends in Ecology and Evolution*, **31(1)**, 1-2, doi:10.1016/j.tree.2015.10.006.

Müller, B., L. Johnson, and D. Kreuer, 2017: Maladaptive outcomes of climate insurance in agriculture. *Global Environmental Change*, **46**, 23-33, doi:10.1016/j.gloenvcha.2017.06.010.

Mungai, L.M. et al., 2016: Smallholder Farms and the Potential for Sustainable Intensification. *Frontiers in Plant Science*, **7**, doi:10.3389/fpls.2016.01720.

Muñoz, R. et al., 2016: Managing Glacier Related Risks Disaster in the Chucchún Catchment, Cordillera Blanca, Peru BT - Climate Change Adaptation Strategies - An Upstream-downstream Perspective. In: [Salzmann, N., C. Huggel, S.U. Nussbaumer, and G. Ziervogel (eds.)]. Springer International Publishing, Cham, pp. 59-78.

Murakami, K., T. Ida, M. Tanaka, and L. Friedman, 2015: Consumers' willingness to pay for renewable and nuclear energy: A comparative analysis between the US and Japan. *Energy Economics*, **50**, 178-189, doi:10.1016/j.eneco.2015.05.002.

Murphy, A.G., J. Hartell, V. Cárdenas, and J.R. Skees, 2012: *Risk Management Instruments for Food Price Volatility and Weather Risk in Latin America and the Caribbean: The Use of Risk Management Instruments*. Discussion Paper, Inter-American Development Bank, 110 pp.

Murrant, D., A. Quinn, and L. Chapman, 2015: The water-energy nexus: Future water resource availability and its implications on UK thermal power generation. *Water and Environment Journal*, **29(3)**, 307-319, doi:10.1111/wej.12126.

Murray, J.P., R. Grenyer, S. Wunder, N. Raes, and J.P.G. Jones, 2015: Spatial patterns of carbon, biodiversity, deforestation threat, and REDD+ projects in Indonesia. *Conservation Biology*, **29(5)**, 1434-1445, doi:10.1111/cobi.12500.

Musah-Surugu, I.J., A. Ahenkan, J.N. Bawole, and S.A. Darkwah, 2018: Migrants' remittances: A complementary source of financing adaptation to climate change at the local level in Ghana. *International Journal of Climate Change Strategies and Management*, **10(1)**, 178-196.

Muttarak, R. and W. Lutz, 2014: Is Education a Key to Reducing Vulnerability to Natural Disasters and hence Unavoidable Climate Change? *Ecology and Society*, doi:10.5751/ES-06476-190142.

Mycoo, M.A., 2017: Beyond 1.5ºC: vulnerabilities and adaptation strategies for Caribbean Small Island Developing States. *Regional Environmental Change*, doi:10.1007/s10113-017-1248-8.

Myers, C.D., T. Ritter, and A. Rockway, 2017: Community Deliberation to Build Local Capacity for Climate Change Adaptation: The Rural Climate Dialogues Program. In: *Climate Change Adaptation in North America: Fostering Resilience and the Regional Capacity to Adapt* [Leal Filho, W. and J.M. Keenan (eds.)]. Springer International Publishing, Cham, pp. 9-26.

Myers, N. and T.J. Goreau, 1991: Tropical forests and the greenhouse effect: A management response. *Climatic Change*, **19(1)**, 215-225, doi:10.1007/BF00142229.

Nabernegg, S. et al., 2017: The Deployment of Low Carbon Technologies in Energy Intensive Industries: A Macroeconomic Analysis for Europe, China and India. *Energies*, **10(3)**, 360, doi:10.3390/en10030360.

Nadeau, C.P., A.K. Fuller, and D.L. Rosenblatt, 2015: Climate-smart management of biodiversity. *Ecosphere*, **6(6)**, doi:10.1890/ES15-00069.1.

Nagataki, S., N. Takamura, K. Kamiya, and M. Akashi, 2013: Measurements of Individual Radiation Doses in Residents Living Around the Fukushima Nuclear Power Plant. *Radiation Research*, **180(5)**, 439-447, doi:10.1667/RR13351.1.

Nahayo, L. et al., 2018: Extent of disaster courses delivery for the risk reduction in Rwanda. *International Journal of Disaster Risk Reduction*, **27**, 127-132, doi:10.1016/j.ijdrr.2017.09.046.

Nahlika, M.J. and M. Chester, 2014: Transit-orientated smart growth can reduce life cycle environmental impacts and household costs in Los Angeles. *Transport Policy*, **35**, 21-30, doi:10.1016/j.tranpol.2014.05.004.

Naiki, Y., 2016: Trade and Bioenergy: Explaining and Assessing the Regime Complex for Sustainable Bioenergy. *European Journal of International Law*, **27(1)**, 129-159, doi:10.1093/ejil/chw004.

Nair, P.K., V.D. Nair, B.M. Kumar, and S.G. Haile, 2009: Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *Environmental Science & Policy*, **12(8)**, 1099-1111.

Nakashima, D.J., K. Galloway McLean, H.D. Thulstrup, A. Ramos Castillo, and J.T. Rubis, 2012: *Weathering Uncertainty: Traditional Knowledge for Climate Change Assessment and Adaptation*. UNESCO, and Darwin, UNU, Paris, 120 pp.

Nakayachi, K., H.M. Yokoyama, and S. Oki, 2015: Public anxiety after the 2011 Tohoku earthquake: fluctuations in hazard perception after catastrophe. *Journal of Risk Research*, **18(2)**, 156-169, doi:10.1080/13669877.2013.875936.

Nantongo, M.G., 2017: Legitimacy of local REDD+ processes. A comparative analysis of pilot projects in Brazil and Tanzania. *Environmental Science & Policy*, **78**, 81-88, doi:https://doi.org/10.1016/j.envsci.2017.09.005.

Napp, T.A., A. Gambhir, T.P. Hills, N. Florin, and P.S. Fennell, 2014: A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. *Renewable and Sustainable Energy Reviews*, **30(Supplement C)**, 616-640, doi:https://doi.org/10.1016/j.rser.2013.10.036.

Narayan, S. et al., 2016: The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS ONE*, **11(5)**, doi:10.1371/journal.pone.0154735.

Natcher, D.C. et al., 2007: Notions of time and sentience: Methodological considerations for Arctic climate change research. *Arctic Anthropology*, **44(2)**, 113-126, doi:10.1353/arc.2011.0099.

Naus, J., G. Spaargaren, B.J.M. van Vliet, and H.M. van Der Horst, 2014: Smart grids, information flows and emerging domestic energy practices. *Energy Policy*, **68**, 436-446, doi:10.1016/j.enpol.2014.01.038.

Nazara, S. and B.P. Resosudarmo, 2007: Aceh-Nias Reconstruction and Rehabilitation: Progress and Challenges at the End of 2006, 2007. *ADB Institute Discussion Paper No. 70*.

Ndah, H.T. et al., 2015: Adoption Potential for Conservation Agriculture in Africa: A Newly Developed Assessment Approach (QAToCA) Applied in Kenya and Tanzania. *Land Degradation & Development*, **26(2)**, 133-141, doi:10.1002/ldr.2191.

NEA, 2016: *Uranium 2016: Resources, Production and Demand*. Nuclear Energy Agency and the International Atomic Energy Agency.

Needhidasan, S., M. Samuel, and R. Chidambaram, 2014: Electronic waste - an emerging threat to the environment of urban India. *Journal of Environmental Health Science and Engineering*, **12(1)**, 36, doi:10.1186/2052-336X-12-36.

Neimark, B., S. Mahanty, and W. Dressler, 2016: Mapping Value in a 'Green' Commodity Frontier: Revisiting Commodity Chain Analysis. *Development and Change*, **47(2)**, 240-265, doi:10.1111/dech.12226.

Nelson, D.R., M.C. Lemos, H. Eakin, and Y.–J. Lo, 2016: The limits of poverty reduction in support of climate change adaptation. *Environmental Research Letters*, **11(9)**, 094011, doi:10.1088/1748-9326/11/9/094011.

Nemet, G.F. and A.R. Brandt, 2012: Willingness to Pay for a Climate Backstop: Liquid Fuel Producers and Direct CO_2 Air Capture. *The Energy Journal*, **33(1)**, 53-81.

Nemet, G.F. et al., 2018: Negative emissions - Part 3: Innovation and upscaling. *Environmental Research Letters* (in press), doi:10.1088/1748-9326/aabff4.

Neroutsou, T.I. and B. Croxford, 2016: Lifecycle costing of low energy housing refurbishment: A case study of a 7 year retrofit in Chester Road, London. *Energy and Buildings*, **128**, 178-189, doi:10.1016/j.enbuild.2016.06.040.

Neumann, B., A.T. Vafeidis, J. Zimmermann, and R.J. Nicholls, 2015: Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. *PLoS ONE*, **10(3)**, doi:10.1371/journal.pone.0118571.

Neureiter, C., 2017: *A Domain-Specific, Model Driven Engineering Approach For Systems Engineering In The Smart Grid*. MBSE4U.

Newbold, T. et al., 2015: Global effects of land use on local terrestrial biodiversity. *Nature*, **520(7545)**, 45-50, doi:10.1038/nature14324.

Newman, P. and J.R. Kenworthy, 2015: *The End of Automobile Dependence: How Cities are Moving Beyond Car-based Planning*. Island Press, Washington DC, USA, 201-226 pp.

Newman, P., A. Matan, and J. McIntosh, 2015: Urban Transport and Sustainable Development. In: *Routledge International Handbook of Sustainable Development* [Redclift, M. and D. Springett (eds.)]. Taylor and Francis, Melbourne, VIC, pp. 337-350.

Newman, P., L. Kosonen, and J. Kenworthy, 2016: Theory of urban fabrics: planning the walking, transit/public transport and automobile/motor car cities for reduced car dependency. *Town Planning Review*, **87(4)**, 429-458, doi:10.3828/tpr.2016.28.

Newman, P., T. Beatley, and H. Boyer, 2017: *Resilient Cities: Overcoming Fossil Fuel Dependence*. Island Press, Washington DC, USA, 264 pp.

Ngendakumana, S. et al., 2017: Implementing REDD+ : learning from forest conservation policy and social safeguards frameworks in Cameroon. *International Forestry Review*, **19(2)**, 209-223, doi:10.1505/146554817821255187.

Nguyen, T.–T., V. Martin, A. Malmquist, and C.A.S. Silva, 2017: A review on technology maturity of small scale energy storage technologies. *Renewable Energy and Environmental Sustainability*, **2(36)**, 8, doi:10.1051/rees/2017039.

Nguyen, T.T.T., P.J. Bowman, M. Haile-Mariam, J.E. Pryce, and B.J. Hayes, 2016: Genomic selection for tolerance to heat stress in Australian dairy cattle. *Journal of Dairy Science*, **99(4)**, 2849-2862, doi:10.3168/jds.2015-9685.

Nicola, F., 2015: The impact of weather insurance on consumption, investment, and welfare. *Quantitative Economics*, **6(3)**, 637-661.

Nie, Z., A. Korre, and S. Durucan, 2011: Life cycle modelling and comparative assessment of the environmental impacts of oxy-fuel and post-combustion CO_2 capture, transport and injection processes. *Energy Procedia*, **4**, 2510-2517, doi:10.1016/j.egypro.2011.02.147.

Nigatu, A.S., B.O. Asamoah, and H. Kloos, 2014: Knowledge and perceptions about the health impact of climate change among health sciences students in Ethiopia: a cross-sectional study. *BMC Public Health*, **14(1)**, 587, doi:10.1186/1471-2458-14-587.

Niggli, U., A. Fließbach, P. Hepperly, and N. Scialabba, 2009: *Low greenhouse gas agriculture: Mitigation and adaptation potential of sustainable farming systems*. 26 pp.

Nijland, H. and J. van Meerkerk, 2017: Mobility and environmental impacts of car sharing in the Netherlands. *Environmental Innovation and Societal Transitions*, **23**, 84-91, doi:10.1016/j.eist.2017.02.001.

Nijnik, M. and P. Halder, 2013: Afforestation and reforestation projects in South and South-East Asia under the Clean Development Mechanism: Trends and development opportunities. *Land Use Policy*, **31**, 504-515, doi:10.1016/J.LANDUSEPOL.2012.08.014.

Nijnik, M., G. Pajot, A.J. Moffat, and B. Slee, 2013: An economic analysis of the establishment of forest plantations in the United Kingdom to mitigate climatic change. *Forest Policy and Economics*, **26**, 34-42, doi:10.1016/J.FORPOL.2012.10.002.

Nikulshina, V., D. Hirsch, M. Mazzotti, and A. Steinfeld, 2006: CO_2 capture from air and co-production of H2 via the Ca(OH)2-CaCO3 cycle using concentrated solar power-Thermodynamic analysis. *Energy*, **31(12)**, 1715-1725, doi:10.1016/J.ENERGY.2005.09.014.

Nilsson, S. and W. Schopfhauser, 1995: The carbon-sequestration potential of a global afforestation program. *Climatic Change*, **30(3)**, 267-293, doi:10.1007/BF01091928.

Nishikawa, M., T. Kato, T. Homma, and S. Takahara, 2016: Changes in risk perceptions before and after nuclear accidents: Evidence from Japan. *Environmental Science & Policy*, **55**, 11-19, doi:10.1016/j.envsci.2015.08.015.

Nitschke, M., A. Krackowizer, L.A. Hansen, P. Bi, and R.G. Tucker, 2017: Heat Health Messages: A Randomized Controlled Trial of a Preventative Messages Tool in the Older Population of South Australia. *International Journal of Environmental Research and Public Health*, **14(9)**, doi:10.3390/ijerph14090992.

Nitschke, M. et al., 2016: Evaluation of a heat warning system in Adelaide, South Australia, using case-series analysis. *BMJ open*, **6(7)**, e012125, doi:10.1136/bmjopen-2016-012125.

Niven, R.J. and D.K. Bardsley, 2013: Planned retreat as a management response to coastal risk: a case study from the Fleurieu Peninsula, South Australia. *Regional Environmental Change*, **13(1)**, 193-209, doi:10.1007/s10113-012-0315-4.

Nordstrom, K.F., 2014: Living with shore protection structures: A review. *Estuarine, Coastal and Shelf Science*, **150**, 11-23, doi:10.1016/j.ecss.2013.11.003.

Norton, B.A. et al., 2015: Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landscape and Urban Planning*, **134**, 127-138, doi:10.1016/j.landurbplan.2014.10.018.

Novak, J.M. et al., 2016: Soil Health, Crop Productivity, Microbial Transport, and Mine Spoil Response to Biochars. *BioEnergy Research*, **9(2)**, 454-464, doi:10.1007/s12155-016-9720-8.

Nowak, D.J., D.E. Crane, and J.C. Stevens, 2006: Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, **4(3-4)**, 115-123, doi:10.1016/j.ufug.2006.01.007.

NRC, 2015: *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. National Reserach Council (NRC). The National Academies Press, Washington DC, USA, 154 pp.

Nunn, P.D., J. Runman, M. Falanruw, and R. Kumar, 2017: Culturally grounded responses to coastal change on islands in the Federated States of Micronesia, northwest Pacific Ocean. *Regional Environmental Change*, **17(4)**, 959-971, doi:10.1007/s10113-016-0950-2.

Nur, I. and K.K. Shrestha, 2017: An Integrative Perspective on Community Vulnerability to Flooding in Cities of Developing Countries. *Procedia Engineering*, **198(Supplement C)**, 958-967, doi:https://doi.org/10.1016/j.proeng.2017.07.141.

Nyong, A., F. Adesina, and B. Osman Elasha, 2007: The value of indigenous knowledge in climate change mitigation and adaptation strategies in the African Sahel. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 787-797, doi:10.1007/s11027-007-9099-0.

Obersteiner, M. et al., 2006: Global supply of biomass for energy and carbon sequestration from afforestation/reforestation activities. *Mitigation and Adaptation Strategies for Global Change*, **11(5-6)**, 1003-1021, doi:10.1007/s11027-006-9031-z.

Odeh, N.A. and T.T. Cockerill, 2008: Life cycle GHG assessment of fossil fuel power plants with carbon capture and storage. *Energy Policy*, **36(1)**, 367-380, doi:10.1016/j.enpol.2007.09.026.

Odemerho, F.O., 2014: Building climate change resilience through bottom-up adaptation to flood risk in Warri, Nigeria. *Environment and Urbanization*, **27(1)**, 139-160, doi:10.1177/0956247814558194.

Oe, M. et al., 2016: Three-year trend survey of psychological distress, post-traumatic stress, and problem drinking among residents in the evacuation zone after the Fukushima Daiichi Nuclear Power Plant accident [The Fukushima Health Management Survey]. *Psychiatry and Clinical Neurosciences*, **70(6)**, 245-252, doi:10.1111/pcn.12387.

O'Hare, P., I. White, and A. Connelly, 2016: Insurance as maladaptation: Resilience and the 'business as usual' paradox. *Environment and Planning C: Government and Policy*, **34(6)**, 1175-1193, doi:10.1177/0263774X15602022.

Oldekop, J.A., G. Holmes, W.E. Harris, and K.L. Evans, 2016: A global assessment of the social and conservation outcomes of protected areas. *Conservation Biology*, **30(1)**, 133-141, doi:10.1111/cobi.12568.

Olmstead, S.M., 2014: Climate change adaptation and water resource management: A review of the literature. *Energy Economics*, **46**, 500-509, doi:10.1016/j.eneco.2013.09.005.

Olschewski, R. and P.C. Benítez, 2005: Secondary forests as temporary carbon sinks? The economic impact of accounting methods on reforestation projects in the tropics. *Ecological Economics*, **55(3)**, 380-394, doi:10.1016/J.ECOLECON.2004.09.021.

Olson, K.R., 2013: Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: Issues paper for protocol development. *Geoderma*, **195-196**, 201-206, doi:10.1016/J.GEODERMA.2012.12.004.

Olson, K.R., M.M. Al-Kaisi, R. Lal, and B. Lowery, 2014: Experimental Consideration, Treatments, and Methods in Determining Soil Organic Carbon Sequestration Rates. *Soil Science Society of America Journal*, **78(2)**, 348, doi:10.2136/sssaj2013.09.0412.

Onaindia, M., B. Fernández de Manuel, I. Madariaga, and G. Rodríguez-Loinaz, 2013: Co-benefits and trade-offs between biodiversity, carbon storage and water flow regulation. *Forest Ecology and Management*, **289**, 1-9, doi:10.1016/j.foreco.2012.10.010.

Onarheim, K., A. Mathisen, and A. Arasto, 2015: Barriers and opportunities for application of CCS in Nordic industry-A sectorial approach. *International Journal of Greenhouse Gas Control*, **36**, 93-105, doi:10.1016/j.ijggc.2015.02.009.

Orchard, S.E., L.C. Stringer, and C.H. Quinn, 2015: Impacts of aquaculture on social networks in the mangrove systems of northern Vietnam. *Ocean and Coastal Management*, **114**, 1-10, doi:10.1016/j.ocecoaman.2015.05.019.

Ossa-Moreno, J., K.M. Smith, and A. Mijic, 2017: Economic analysis of wider benefits to facilitate SuDS uptake in London, UK. *Sustainable Cities and Society*, **28**, 411-419, doi:10.1016/j.scs.2016.10.002.

Oteros-Rozas, E. et al., 2015: Participatory scenario planning in place-based social-ecological research: insights and experiences from 23 case studies. *Ecology and Society*, **20(4)**, doi:10.5751/es-07985-200432.

Otuoze, A.O., M.W. Mustafa, and R.M. Larik, 2018: Smart grids security challenges: Classification by sources of threats. *Journal of Electrical Systems and Information Technology* (in press), doi:10.1016/j.jesit.2018.01.001.

Ouédraogo, M. et al., 2018: Farmers' Willingness to Pay for Climate Information Services: Evidence from Cowpea and Sesame Producers in Northern Burkina Faso. *Sustainability*, **10(3)**.

Overmars, K.P. et al., 2014: Estimating the opportunity costs of reducing carbon dioxide emissions via avoided deforestation, using integrated assessment modelling. *Land Use Policy*, **41(Supplement C)**, 45-60, doi:https://doi.org/10.1016/j.landusepol.2014.04.015.

Oya, C., F. Schaefer, D. Skalidou, C. Mccosker, and L. Langer, 2017: Effects of certification schemes for agricultural production on socio-economic outcomes in low-and middle-income countries.

Paavola, J., 2017: Health impacts of climate change and health and social inequalities in the UK. *Environmental Health*, **16(S1)**, 113, doi:10.1186/s12940-017-0328-z.

Pacheco-Torres, R., J. Roldán, E. Gago, and J. Ordóñez, 2017: Assessing the relationship between urban planning options and carbon emissions at the use stage of new urbanized areas: A case study in a warm climate location. *Energy and Buildings*, **136**, 73-85, doi:10.1016/j.enbuild.2016.11.055.

Padawangi, R. and M. Douglass, 2015: Water, Water Everywhere: Toward Participatory Solutions to Chronic Urban Flooding in Jakarta. *Pacific Affairs*, **88(3)**, 517-550.

Paidakaki, A. and F. Moulaert, 2017: Disaster Resilience into Which Direction(s)? Competing Discursive and Material Practices in Post-Katrina New Orleans. *Housing, Theory and Society*, 1-23, doi:10.1080/14036096.2017.1308434.

Palm, C., H. Blanco-Canqui, F. DeClerck, L. Gatere, and P. Grace, 2014: Conservation agriculture and ecosystem services: An overview. *Agriculture, Ecosystems & Environment*, **187**, 87-105, doi:10.1016/j.agee.2013.10.010.

Pan, G., P. Smith, and W. Pan, 2009: The role of soil organic matter in maintaining the productivity and yield stability of cereals in China. *Agriculture, Ecosystems & Environment*, **129(1)**, 344-348.

Panagopoulos, T., J.A. González Duque, and M. Bostenaru Dan, 2016: Urban planning with respect to environmental quality and human well-being. *Environmental Pollution*, **208**, 137-144, doi:10.1016/j.envpol.2015.07.038.

Panda, A., U. Sharma, K.N. Ninan, and A. Patt, 2013: Adaptive capacity contributing to improved agricultural productivity at the household level: empirical findings highlighting the importance of crop insurance. *Global Environmental Change*, **23(4)**, 782-790.

Pang, M. et al., 2017: Trade-off between carbon reduction benefits and ecological costs of biomass-based power plants with carbon capture and storage (CCS) in China. *Journal of Cleaner Production*, **144**, 279-286, doi:10.1016/J.JCLEPRO.2017.01.034.

Panic, M. and J.D. Ford, 2013: A review of national-level adaptation planning with regards to the risks posed by climate change on infectious diseases in 14 OECD nations. *International Journal of Environmental Research and Public Health*, doi:10.3390/ijerph10127083.

Panteli, M. and P. Mancarella, 2015: Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research*, **127**, 259-270, doi:10.1016/j.epsr.2015.06.012.

Papargyropoulou, E., R. Lozano, J. K. Steinberger, N. Wright, and Z. Ujang, 2014: The food waste hierarchy as a framework for the management of food surplus and food waste. *Journal of Cleaner Production*, **76**, 106-115, doi:10.1016/j.jclepro.2014.04.020.

Paquay, F.S. and R.E. Zeebe, 2013: Assessing possible consequences of ocean liming on ocean pH, atmospheric CO_2 concentration and associated costs. *International Journal of Greenhouse Gas Control*, **17**, 183-188, doi:10.1016/J.IJGGC.2013.05.005.

Parcell, J.L. and P. Westhoff, 2006: Economic Effects of Biofuel Production on States and Rural Communities. *Journal of Agricultural and Applied Economics*, **38(02)**, 377-387, doi:10.1017/S1074070800022422.

Parikh, K.S. and J.K. Parikh, 2016: Realizing potential savings of energy and emissions from efficient household appliances in India. *Energy Policy*, **97**, 102-111, doi:10.1016/j.enpol.2016.07.005.

Parkinson, S.C. and N. Djilali, 2015: Robust response to hydro-climatic change in electricity generation planning. *Climatic Change*, **130(4)**, 475-489, doi:10.1007/s10584-015-1359-5.

Parnell, S., 2015: Fostering Transformative Climate Adaptation and Mitigation in the African City: Opportunities and Constraints of Urban Planning. In: *Urban Vulnerability and Climate Change in Africa: A Multidisciplinary Approach*. Springer, Cham, Switzerland, pp. 349-367.

Pascuala, U., R. Muradian, L.C. Rodríguez, and A. Duraiappah, 2010: Exploring the links between equity and efficiency in payments for environmental services: A conceptual approach. *Ecological Economics*, **69(6)**, 1237-1244, doi:10.1016/J.ECOLECON.2009.11.004.

Patel, M., X. Zhang, and A. Kumar, 2016: Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: A review. *Renewable and Sustainable Energy Reviews*, **53**, 1486-1499, doi:10.1016/J.RSER.2015.09.070.

Patel, R., G. Walker, M. Bhatt, and V. Pathak, 2017: The Demand for Disaster Microinsurance for Small Businesses in Urban Slums: The Results of Surveys in Three Indian Cities. *PLOS Currents Disasters*, **9**, doi:10.1371/currents.dis.83315629ac7cae7e2c4f78c589a3ce1c.

Paterson, J., P. Berry, K. Ebi, and L. Varangu, 2014: Health Care Facilities Resilient to Climate Change Impacts. *International Journal of Environmental Research and Public Health*, **11(12)**, 13097-13116, doi:10.3390/ijerph111213097.

Paterson, S. and B.A. Bryan, 2012: Food-Carbon Trade-offs between Agriculture and Reforestation Land Uses under Alternate Market-based Policies. *Ecology and Society*, **17(3)**, art21, doi:10.5751/ES-04959-170321.

Paul, K.I., A. Reeson, P.J. Polglase, and P. Ritson, 2013: Economic and employment implications of a carbon market for industrial plantation forestry. *Land Use Policy*, **30(1)**, 528-540, doi:10.1016/J.LANDUSEPOL.2012.04.015.

Paul, K.I. et al., 2016: Managing reforestation to sequester carbon, increase biodiversity potential and minimize loss of agricultural land. *Land Use Policy*, **51**, 135-149, doi:https://doi.org/10.1016/j.landusepol.2015.10.027.

Paustian, K. et al., 2016: Climate-smart soils. *Nature*, **532(7597)**, 49-57, doi:10.1038/nature17174.

Payne, J., F. Downy, and D. Weatherall, 2015: *Capturing the "multiple benefits" of energy efficiency in practice: the UK example*.

Paz, S., M. Negev, A. Clermont, and M.S. Green, 2016: Health aspects of climate change in cities with Mediterranean climate, and local adaptation plans. *International Journal of Environmental Research and Public Health*, **13(4)**, doi:10.3390/ijerph13040438.

Pearce, T., J. Ford, A.C. Willox, and B. Smit, 2015: Inuit Traditional Ecological Knowledge (TEK), Subsistence Hunting and Adaptation to Climate Change in the Canadian Arctic. *Arctic*, **68(2)**, 233-245.

Pehnt, M. and J. Henkel, 2009: Life cycle assessment of carbon dioxide capture and storage from lignite power plants. *International Journal of Greenhouse Gas Control*, **3(1)**, 49-66, doi:10.1016/j.ijggc.2008.07.001.

Pereira, G.I. and P.P. da Silva, 2017: Energy efficiency governance in the EU-28: analysis of institutional, human, financial, and political dimensions. *Energy Efficiency*, **10(5)**, 1279-1297, doi:10.1007/s12053-017-9520-9.

Pereira, H.M. et al., 2010: Scenarios for Global Biodiversity in the 21st Century. *Science*, **330(6010)**, 1496-1501, doi:10.1126/science.1196624.

Pérez-Escamilla, R., 2017: Food Security and the 2015-2030 Sustainable Development Goals: From Human to Planetary Health. *Current Developments in Nutrition*, **1(7)**, e000513, doi:10.3945/cdn.117.000513.

Perrels, A., T. Frei, F. Espejo, L. Jamin, and A. Thomalla, 2013: Socio-economic benefits of weather and climate services in Europe. *Advances in Science & Research*, doi:10.5194/asr-1-1-2013.

Persson, U.M., 2015: The impact of biofuel demand on agricultural commodity prices: a systematic review. *Wiley Interdisciplinary Reviews: Energy and Environment*, **4(5)**, 410-428, doi:10.1002/wene.155.

Petersen, B. and S. Snapp, 2015: What is sustainable intensification? Views from experts. *Land Use Policy*, **46**, 1-10, doi:10.1016/j.landusepol.2015.02.002.

Peterson, S.B. and J.J. Michalek, 2013: Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption. *Energy Policy*, **52**, 429-438, doi:10.1016/j.enpol.2012.09.059.

Pfau, S.F., J.E. Hagens, B. Dankbaar, and A.J.M. Smits, 2014: Visions of Sustainability in Bioeconomy Research. *Sustainability*, **6(3)**, 1222-1249, doi:10.3390/su6031222.

Pfeiffer, L. and C.–Y.C. Lin, 2014: Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. *Journal of Environmental Economics and Management*, **67(2)**, 189-208, doi:10.1016/j.jeem.2013.12.002.

Pham, T.T., M. Moeliono, M. Brockhaus, N.D. LEa, and P. Katila, 2017: REDD+ and Green Growth: synergies or discord in Vietnam and Indonesia. *International Forestry Review*, **19(S1)**, 1.

Phan, T.–H.D., R. Brouwer, and M.D. Davidson, 2017: A Global Survey and Review of the Determinants of Transaction Costs of Forestry Carbon Projects. *Ecological Economics*, **133**, 1-10, doi:10.1016/J.ECOLECON.2016.11.011.

Phelps, J., E.L. Webb, and W.M. Adams, 2012: Biodiversity co-benefits of policies to reduce forest-carbon emissions. *Nature Climate Change*, **2(7)**, 497-503.

Philibert, C., 2017: *Renewable Energy for Industry. From green energy to green materials and fuels*. IEA, Paris, France, 72 pp.

Piccoli, I. et al., 2016: Disentangling the effects of conservation agriculture practices on the vertical distribution of soil organic carbon. Evidence of poor carbon sequestration in North- Eastern Italy. *Agriculture, Ecosystems & Environment*, **230**, 68-78, doi:10.1016/J.AGEE.2016.05.035.

Pickering, N.K. et al., 2015: Animal board invited review: genetic possibilities to reduce enteric methane emissions from ruminants. *animal*, **9(09)**, 1431-1440, doi:10.1017/S1751731115000968.

Pielke, R.A., 2009: An idealized assessment of the economics of air capture of carbon dioxide in mitigation policy. *environmental science & policy*, **12(3)**, 216-225.

Pistorious, T. and L. Kiff, 2017: *From a biodiversity perspective: risks, trade- offs, and international guidance for Forest Landscape Restoration*. 66 pp.

Pittelkow, C.M. et al., 2014: Productivity limits and potentials of the principles of conservation agriculture. *Nature*, **517(7534)**, 365-368, doi:10.1038/nature13809.

Place, F. et al., 2012: Improved Policies for Facilitating the Adoption of Agroforestry. In: *Agroforestry for Biodiversity and Ecosystem Services - Science and Practice* [].

Plantinga, A.J. and T. Mauldin, 2001: A Method for Estimating the Cost of CO_2 Mitigation through Afforestation. *Climatic Change*, **49(1/2)**, 21-40, doi:10.1023/A:1010749214244.

Plantinga, A.J., T. Mauldin, and D.J. Miller, 1999: An Econometric Analysis of the Costs of Sequestering Carbon in Forests. *American Journal of Agricultural Economics*, **81(4)**, 812, doi:10.2307/1244326.

Plevin, R.J., M. O'Hare, A.D. Jones, M.S. Torn, and H.K. Gibbs, 2010: Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated. *Environmental Science & Technology*, **44(21)**, 8015-8021, doi:10.1021/es101946t.

Poff, N.L.R. et al., 2016: Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nature Climate Change*, **6(1)**, 25-34, doi:10.1038/nclimate2765.

Polglase, P.J. et al., 2013: Potential for forest carbon plantings to offset greenhouse emissions in Australia: economics and constraints to implementation. *Climatic Change*, **121(2)**, 161-175, doi:10.1007/s10584-013-0882-5.

Popp, A. et al., 2014: Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3-4)**, 495-509, doi:10.1007/s10584-013-0926-x.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002.

Porpino, G., J. Parente, and B. Wansink, 2015: Food waste paradox: antecedents of food disposal in low income households. *International Journal of Consumer Studies*, **39(6)**, 619-629, doi:10.1111/ijcs.12207.

Porter, J.J., S. Dessai, and E.L. Tompkins, 2014: What do we know about UK household adaptation to climate change? A systematic review. *Climatic Change*, **127(2)**, 371-379, doi:10.1007/s10584-014-1252-7.

Porter, J.R. and L. Xie, 2014: Chapter 7. Food Security and Food Production Systems. .

Porter, W.C., T.N. Rosenstiel, A. Guenther, J.–F. Lamarque, and K. Barsanti, 2015: Reducing the negative human-health impacts of bioenergy crop emissions through region-specific crop selection. *Environmental Research Letters*, **10(5)**, 054004, doi:10.1088/1748-9326/10/5/054004.

Poudyal, M. et al., 2016: Can REDD+ social safeguards reach the 'right' people? Lessons from Madagascar. *Global Environmental Change*, **37**, 31-42, doi:10.1016/J.GLOENVCHA.2016.01.004.

Powell, T.W.R. and T.M. Lenton, 2012: Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. *Energy & Environmental Science*, **5(8)**, 8116, doi:10.1039/c2ee21592f.

Powlson, D.S. et al., 2014: Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, **4(8)**, 678.

Pradhan, A., C. Chan, P.K. Roul, J. Halbrendt, and B. Sipes, 2018: Potential of conservation agriculture (CA) for climate change adaptation and food security under rainfed uplands of India: A transdisciplinary approach. *Agricultural Systems*, **163**, 27-35, doi:10.1016/j.agsy.2017.01.002.

Pratt, K. and D. Moran, 2010: Evaluating the cost-effectiveness of global biochar mitigation potential. *Biomass and Bioenergy*, **34(8)**, 1149-1158, doi:10.1016/J.BIOMBIOE.2010.03.004.

Pretty, J. and Z.P. Bharucha, 2014: Sustainable intensification in agricultural systems. *Annals of Botany*, **114(8)**, 1571-1596, doi:10.1093/aob/mcu205.

Pretty, J., C. Toulmin, and S. Williams, 2011: Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, **9(1)**, 5-24, doi:10.3763/ijas.2010.0583.

Price, J., R. Warren, J. VanDerWal, and E. Graham, 2018: Identifying climate refugia for biodiversity at 1.5° and 2°C of warming in relation to protected areas and land-use patterns. (in press).

Pritchard, C., A. Yang, P. Holmes, and M. Wilkinson, 2015: Thermodynamics, economics and systems thinking: What role for air capture of CO_2? *Process Safety and Environmental Protection*, **94**, 188-195, doi:10.1016/j.psep.2014.06.011.

Prosdocimi, M. et al., 2016: The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. *Science of The Total Environment*, **547**, 323-330, doi:10.1016/j.scitotenv.2015.12.076.

Prudencio, L. and S.E. Null, 2018: Stormwater management and ecosystem services: a review. *Environmental Research Letters*, **13(3)**, 033002, doi:10.1088/1748-9326/aaa81a.

Pullin, A.S. et al., 2013: Human well-being impacts of terrestrial protected areas. *Environmental Evidence*, **2(1)**, doi:10.1186/2047-2382-2-19.

Pütz, S. et al., 2014: Long-term carbon loss in fragmented Neotropical forests. *Nature Communications*, **5**, 5037.

Pyörälä, P. et al., 2014: Effects of Management on Economic Profitability of Forest Biomass Production and Carbon Neutrality of Bioenergy Use in Norway Spruce Stands Under the Changing Climate. *Bioenergy Research*, **7(1)**, 279-294, doi:10.1007/s12155-013-9372-x.

Qazi, S. and W. Young Jr., 2014: Disaster relief management and resilience using photovoltaic energy.

Qin, Z., J.B. Dunn, H. Kwon, S. Mueller, and M.M. Wander, 2016: Soil carbon sequestration and land use change associated with biofuel production: empirical evidence. *GCB Bioenergy*, **8(1)**, 66-80, doi:10.1111/gcbb.12237.

Qiu, H.–H. and J. Yang, 2018: An Assessment of Technological Innovation Capabilities of Carbon Capture and Storage Technology Based on Patent Analysis: A Comparative Study between China and the United States. *Sustainability*, **10(3)**, 877.

Quader, M.A., S. Ahmed, S.Z. Dawal, and Y. Nukman, 2016: Present needs, recent progress and future trends of energy-efficient Ultra-Low Carbon Dioxide (CO_2) Steelmaking (ULCOS) program. *Renewable and Sustainable Energy Reviews*, **55**, 537-549, doi:https://doi.org/10.1016/j.rser.2015.10.101.

Quandt, A., H. Neufeldt, and J.T. McCabe, 2017: The role of agroforestry in building livelihood resilience to floods and drought in semiarid Kenya. *Ecology and Society*, **22(3)**, doi:10.5751/ES-09461-220310.

Quann, C., 2017: Renewables Firming Using Grid-Scale Battery Storage in a Real-time Pricing Market., Colorado State University, Fort Collins, CO, 62 pp.

Rabbani, G., A. Rahman, and N. Islam, 2010a: Coastal Zones and Climate Change. *Coastal Zones and Climate Change*, **15(3)**, 17-29.

Rabbani, G., A.A. Rahman, and N. Islam, 2010b: Climate Change and Sea Level Rise: Issues and Challenges for Coastal Communities in the Indian Ocean Region. *Coastal Zones and Climate Change*, 17-29.

Rahn, E. et al., 2014: Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? *Mitigation and Adaptation Strategies for Global Change*, **19(8)**, 1119-1137, doi:10.1007/s11027-013-9467-x.

Rajé, F. and A. Saffrey, 2016: *The Value of Cycling*. Phil Jones Associates and the University of Birmingham on behalf of the United Kingdom Department for Transport, London, United Kingdom.

Rakatama, A., R. Pandit, C. Ma, and S. Iftekhar, 2017: The costs and benefits of REDD+: A review of the literature. *Forest Policy and Economics*, **75(Supplement C)**, 103-111, doi:https://doi.org/10.1016/j.forpol.2016.08.006.

Rakotovao, N.H. et al., 2017: Carbon footprint of smallholder farms in Central Madagascar: The integration of agroecological practices. *Journal of Cleaner Production*, **140**, 1165-1175, doi:10.1016/j.jclepro.2016.10.045.

Ramankutty, N. et al., 2018: Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Annual Review of Plant Biology*, **69(1)**, annurev-arplant-042817-040256, doi:10.1146/annurev-arplant-042817-040256.

Ramos, A., C. De Jonghe, V. Gómez, and R. Belmans, 2016: Realizing the smart grid's potential: Defining local markets for flexibility. *Utilities Policy*, doi:10.1016/j.jup.2016.03.006.

Ranjan, M. and H.J. Herzog, 2011: Feasibility of air capture. *Energy Procedia*, **4**, 2869-2876.

Rao, N.D., 2013: Distributional impacts of climate change mitigation in Indian electricity: The influence of governance. *Energy Policy*, **61**, 1344-1356, doi:10.1016/j.enpol.2013.05.103.

Rao, N.D. and S. Pachauri, 2017: Energy access and living standards: some observations on recent trends. *Environmental Research Letters*, **12(2)**, 025011, doi:10.1088/1748-9326/aa5b0d.

Rao, N.D. and K. Ummel, 2017: White goods for white people? Drivers of electric appliance growth in emerging economies. *Energy Research & Social Science*, **27**, 106-116, doi:10.1016/j.erss.2017.03.005.

Rao, N.D., Agarwal A, and W. D, 2016: *Impacts of small-scale electricity systems: A study of rural communities in India and Nepal*.

Rapinski, M. et al., 2018: Listening to Inuit and Naskapi peoples in the eastern Canadian Subarctic: a quantitative comparison of local observations with gridded climate data. *Regional Environmental Change*, **18(1)**, 189-203, doi:10.1007/s10113-017-1188-3.

Räsänen, A. et al., 2017: The need for non-climate services - Empirical evidence from Finnish municipalities. *Climate Risk Management*, **16**, 29-42, doi:10.1016/j.crm.2017.03.004.

Rasmussen, J., 2017: The additional benefits of energy efficiency investments-a systematic literature review and a framework for categorisation. *Energy Efficiency*, **10(6)**, 1401-1418, doi:10.1007/s12053-017-9528-1.

Rasul, G. and B. Sharma, 2016: The nexus approach to water-energy-food security: an option for adaptation to climate change. *Climate Policy*, **16(6)**, 682-702, doi:10.1080/14693062.2015.1029865.

Rathmann, R., A. Szklo, and R. Schaeffer, 2012: Targets and results of the Brazilian Biodiesel Incentive Program - Has it reached the Promised Land? *Applied Energy*, **97**, 91-100, doi:10.1016/J.APENERGY.2011.11.021.

Rau, G.H., 2008: Electrochemical splitting of calcium carbonate to increase solution alkalinity: implications for mitigation of carbon dioxide and ocean acidity. *Environmental science & technology*, **42(23)**, 8935-40.

Rau, G.H. and K. Caldeira, 1999: Enhanced carbonate dissolution:: a means of sequestering waste CO_2 as ocean bicarbonate. *Energy Conversion and Management*, **40(17)**, 1803-1813, doi:10.1016/S0196-8904(99)00071-0.

Rau, G.H., K.G. Knauss, W.H. Langer, and K. Caldeira, 2007: Reducing energy-related CO_2 emissions using accelerated weathering of limestone. *Energy*, **32(8)**, 1471-1477, doi:10.1016/J.ENERGY.2006.10.011.

Rau, G.H. et al., 2013: Direct electrolytic dissolution of silicate minerals for air CO_2 mitigation and carbon-negative H2 production. *Proceedings of the National Academy of Sciences of the United States of America*, **110(25)**, 10095-100, doi:10.1073/pnas.1222358110.

Ravi, S. and M. Engler, 2015: Workfare as an Effective Way to Fight Poverty: The Case of India's NREGS. *World Development*, **67**, 57-71, doi:10.1016/j.worlddev.2014.09.029.

Ravi, S. et al., 2016: Particulate matter emissions from biochar-amended soils as a potential tradeoff to the negative emission potential. *Scientific Reports*, **6(1)**, 35984, doi:10.1038/srep35984.

Ravindranath, N.H., P. Sudha, and S. Rao, 2001: Forestry for sustainable biomass production and carbon sequesteration in India. *Mitigation and Adaptation Strategies for Global Change*, **6(3/4)**, 233-256, doi:10.1023/A:1013331220083.

Razzaghmanesh, M., S. Beecham, and T. Salemi, 2016: The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. *Urban Forestry & Urban Greening*, **15**, 89-102, doi:10.1016/j.ufug.2015.11.013.

Reckien, D. et al., 2017: Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environment & Urbanization*, **29(1)**, 159-182, doi:10.1177/0956247816677778.

Refsgaard, K. and K. Magnussen, 2009: Household behaviour and attitudes with respect to recycling food waste - experiences from focus groups. *Journal of Environmental Management*, doi:10.1016/j.jenvman.2008.01.018.

Reid, H., 2016: Ecosystem- and community-based adaptation: learning from community-based natural resource management. *Climate and Development*, **8(1)**, 4-9, doi:10.1080/17565529.2015.1034233.

Reid, H. and S. Huq, 2014: Mainstreaming community-based adaptation into national and local planning. *Climate and Development*, **6(4)**, 291-292, doi:10.1080/17565529.2014.973720.

Reis, R.S. et al., 2016: Scaling up physical activity interventions worldwide: stepping up to larger and smarter approaches to get people moving. *The Lancet*, **388(10051)**, 1337-1348, doi:10.1016/S0140-6736(16)30728-0.

Renforth, P., 2012: The potential of enhanced weathering in the UK. *International Journal of Greenhouse Gas Control*, **10**, 229-243, doi:10.1016/j.ijggc.2012.06.011.

Renforth, P. and T. Kruger, 2013: Coupling Mineral Carbonation and Ocean Liming. *Energy & Fuels*, **27(8)**, 4199-4207, doi:10.1021/ef302030w.

Renforth, P. and G. Henderson, 2017: Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*, doi:10.1002/2016RG000533.

Renforth, P., B.G. Jenkins, and T. Kruger, 2013: Engineering challenges of ocean liming. *Energy*, **60**, 442-452, doi:10.1016/J.ENERGY.2013.08.006.

Renforth, P., C.L. Washbourne, J. Taylder, and D.A. Manning, 2011: Silicate production and availability for mineral carbonation. *Environ Sci Technol*, **45(6)**, 2035-2041, doi:10.1021/es103241w.

Repo, A., J.–P. Tuovinen, and J. Liski, 2015: Can we produce carbon and climate neutral forest bioenergy? *GCB Bioenergy*, **7(2)**, 253-262, doi:10.1111/gcbb.12134.

Reside, A.E., N. Butt, and V.M. Adams, 2017a: Adapting systematic conservation planning for climate change. *Biodiversity and Conservation*, doi:10.1007/s10531-017-1442-5.

Reside, A.E., J. VanDerWal, and C. Moran, 2017b: Trade-offs in carbon storage and biodiversity conservation under climate change reveal risk to endemic species. *Biological Conservation*, **207**, 9-16, doi:10.1016/j.biocon.2017.01.004.

Rey Benayas, J.M. et al., 2009: Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. *Science*, **325(5944)**, 1121-4, doi:10.1126/science.1172460.

Reyes-García, V. et al., 2016: Local indicators of climate change: The potential contribution of local knowledge to climate research. *Wiley Interdisciplinary Reviews: Climate Change*, **7(1)**, 109-124, doi:10.1002/wcc.374.

Reyna, J.L. and M. Chester, 2017: Energy efficiency to reduce residential electricity and natural gas use under climate change. *Nature Communications*, **8**, 14916, doi:10.1038/ncomms14916.

Ribeiro, B.E., 2013: Beyond commonplace biofuels: Social aspects of ethanol. *Energy Policy*, **57**, 355-362, doi:10.1016/J.ENPOL.2013.02.004.

Ribot, J. and A.M. Larson, 2012: Reducing REDD risks: affirmative policy on an uneven playing field. *International Journal of the Commons*, **6(2)**, 233, doi:10.18352/ijc.322.

Richards, K.R. and C. Stokes, 2004: A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research. *Climatic Change*, **63(1)**, 1-48, doi:10.1023/B:CLIM.0000018503.10080.89.

Richards, K.R. and R.N. Stavins, 2005: *The Cost of U.S. Forest-Based Carbon Sequestration*. Pew Center on Global Climate Change, Arlington, VA, USA, 40 pp.

Ringel, M., 2017: Energy efficiency policy governance in a multi-level administration structure - evidence from Germany. *Energy Efficiency*, **10(3)**, 753-776, doi:10.1007/s12053-016-9484-1.

Rinkevich, B., 2014: Rebuilding coral reefs: does active reef restoration lead to sustainable reefs? *Current Opinion in Environmental Sustainability*, **7**, 28-36, doi:10.1016/j.cosust.2013.11.018.

Rinkevich, B., 2015: Climate Change and Active Reef Restoration-Ways of Constructing the "Reefs of Tomorrow". *Journal of Marine Science and Engineering*, **3(1)**, 111-127, doi:10.3390/jmse3010111.

Ritchie, H., D.S. Reay, and P. Higgins, 2018: The impact of global dietary guidelines on climate change. *Global Environmental Change*, **49(January)**, 46-55, doi:10.1016/j.gloenvcha.2018.02.005.

Rivera, C. and C. Wamsler, 2014: Integrating climate change adaptation, disaster risk reduction and urban planning: A review of Nicaraguan policies and regulations. *International Journal of Disaster Risk Reduction*, **7**, 78-90, doi:https://doi.org/10.1016/j.ijdrr.2013.12.008.

Rivera-Ferre, M.G. et al., 2016: Re-framing the climate change debate in the livestock sector: mitigation and adaptation options. *Wiley Interdisciplinary Reviews: Climate Change*, **7(6)**, 869-892, doi:10.1002/wcc.421.

Roberts, K.G., B.A. Gloy, S. Joseph, N.R. Scott, and J. Lehmann, 2010: Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. *Environmental Science & Technology*, **44(2)**, 827-833, doi:10.1021/es902266r.

Robledo-Abad, C. et al., 2017: Bioenergy production and sustainable development: science base for policymaking remains limited. *GCB Bioenergy*, **9(3)**, 541-556, doi:10.1111/gcbb.12338.

Rochedo, P.R.R. et al., 2016: Carbon capture potential and costs in Brazil. *Journal of Cleaner Production*, **131**, 280-295, doi:10.1016/j.jclepro.2016.05.033.

Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science*, **355(6331)**, 1269-1271, doi:10.1126/science.aah3443.

Roco, L., A. Engler, B. Bravo-Ureta, and R. Jara-Rojas, 2014: Farm level adaptation decisions to face climatic change and variability: Evidence from Central Chile. *Environmental Science & Policy*, **44**, 86-96, doi:10.1016/j.envsci.2014.07.008.

Röder, M. and P. Thornley, 2016: Bioenergy as climate change mitigation option within a 2 °C target-uncertainties and temporal challenges of bioenergy systems. *Energy, Sustainability and Society*, **6(1)**, 6, doi:10.1186/s13705-016-0070-3.

Röder, M., C. Whittaker, and P. Thornley, 2015: How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass and Bioenergy*, **79**, 50-63, doi:10.1016/J.BIOMBIOE.2015.03.030.

Rodrigues, J. et al., 2016: *The economic value of seasonal forecasts stochastic economywide analysis for East Africa*.

Rodrigues, R.R., R.A.F. Lima, S. Gandolfi, and A.G. Nave, 2009: On the restoration of high diversity forests: 30 years of experience in the Brazilian Atlantic Forest. *Biological Conservation*, **142(6)**, 1242-1251, doi:10.1016/j.biocon.2008.12.008.

Rogers, D. and V. Tsirkunov, 2010: *Costs and Benefits of Early Warning Systems*.

Rogner, H.–H. et al., 2012: Energy Resources and Potentials. In: *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 423-512.

Rohani, M. and G. Lawrence, 2017: *The relationship between pedestrian connectivity and economic productivity in Auckland's city centre: Technical Report 2017/007*. Auckland Council, Auckland, New Zealand.

Rojas-Rueda, D., A. de Nazelle, O. Teixidó, and M.J. Nieuwenhuijsen, 2012: Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: A health impact assessment study. *Environment International*, **49**, 100-109, doi:10.1016/j.envint.2012.08.009.

Roland, L.R. and Wood, 2009: *Making the Business of Energy Efficiency Both Scalable and Sustainable*.

Romañach, S.S. et al., 2018: Conservation and restoration of mangroves: Global status, perspectives, and prognosis. *Ocean & Coastal Management*, **154**, 72-82, doi:10.1016/j.ocecoaman.2018.01.009.

Röös, E. et al., 2017: Protein futures for Western Europe: potential land use and climate impacts in 2050. *Regional Environmental Change*, **17(2)**, 367-377, doi:10.1007/s10113-016-1013-4.

Rootzén, J.M. et al., 2010: Carbon sequestration versus bioenergy: A case study from South India exploring the relative land-use efficiency of two options for climate change mitigation. *Biomass and Bioenergy*, **34(1)**, 116-123, doi:10.1016/J.BIOMBIOE.2009.10.008.

Rose, A., 2016: Capturing the co-benefits of disaster risk management on the private sector side. Policy Research Working Paper;No. 7634, 33 pp.

Rose, T. and T. Sweeting, 2016: How safe is nuclear power? A statistical study suggests less than expected. *Bulletin of the Atomic Scientists*, **72(2)**, 112-115, doi:10.1080/00963402.2016.1145910.

Rosendo, S., L. Celliers, and M. Mechisso, 2018: Doing more with the same: A reality-check on the ability of local government to implement Integrated Coastal Management for climate change adaptation. *Marine Policy*, **87**, 29-39, doi:10.1016/j.marpol.2017.10.001.

Rothausen, S.G.S.A. and D. Conway, 2011: Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, **1(4)**, 210-219, doi:10.1038/nclimate1147.

Roudier, P., A. Alhassane, C. Baron, S. Louvet, and B. Sultan, 2016: Assessing the benefits of weather and seasonal forecasts to millet growers in Niger. *Agricultural and Forest Meteorology*, **223**, 168-180, doi:10.1016/j.agrformet.2016.04.010.

Rubin, E.S., J.E. Davison, and H.J. Herzog, 2015: The cost of CO_2 capture and storage. *International Journal of Greenhouse Gas Control*, **40**, 378-400, doi:10.1016/j.ijggc.2015.05.018.

Ruiz-Mallén, I., Fernández-Llamazares, and V. Reyes-García, 2017: Unravelling local adaptive capacity to climate change in the Bolivian Amazon: the interlinkages between assets, conservation and markets. *Climatic Change*, **140(2)**, 227-242, doi:10.1007/s10584-016-1831-x.

Ruiz-Rivera, N. and S. Lucatello, 2017: The interplay between climate change and disaster risk reduction policy: evidence from Mexico. *Environmental Hazards*, **16**, 193-209, doi:10.1080/17477891.2016.1211506.

Rumore, D., T. Schenk, and L. Susskind, 2016: Role-play simulations for climate change adaptation education and engagement. *Nature Climate Change*, **6(8)**, 745-750, doi:10.1038/nclimate3084.

Rumsey, M. et al., 2014: A qualitative examination of the health workforce needs during climate change disaster response in Pacific Island Countries. *Human Resources for Health*, **12(1)**, 9, doi:10.1186/1478-4491-12-9.

Ruparathna, R., K. Hewage, and R. Sadiq, 2016: Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews*, **53**, 1032-1045.

Rurinda, J. et al., 2014: Sources of vulnerability to a variable and changing climate among smallholder households in Zimbabwe: A participatory analysis. *Climate Risk Management*, **3**, 65-78, doi:10.1016/j.crm.2014.05.004.

Russell-Smith, J. et al., 2017: Can savanna burning projects deliver measurable greenhouse emissions reductions and sustainable livelihood opportunities in fire-prone settings? *Climatic Change*, **140(1)**, 47-61, doi:10.1007/s10584-013-0910-5.

Ryan, L. and N. Campbell, 2012: *Spreading the Net: The Multiple Benefits of Energy Efficiency Improvements*. OECD Publishing, Paris, France, 40 pp.

Ryan, M.G. et al., 2010: A synthesis of the science on forests and carbon for US forests. *Issues in ecology*, **13(1)**, 16.

Sakaguchi, A. et al., 2012: Isotopic determination of U, Pu and Cs in environmental waters following the Fukushima Daiichi Nuclear Power Plant accident. *Geochemical Journal*, **46(4)**, 355-360, doi:10.2343/geochemj.2.0216.

Sakwa-Novak, M.A., C.–J. Yoo, S. Tan, F. Rashidi, and C.W. Jones, 2016: Poly (ethylenimine)-Functionalized Monolithic Alumina Honeycomb Adsorbents for CO_2 Capture from Air. *ChemSusChem*, **9(14)**, 1859-1868.

Salati, S., M. Spagnol, and F. Adani, 2010: The impact of crop plant residues on carbon sequestration in soil: a useful strategy to balance the atmospheric CO_2.

Salleh, S.F., M.E. Roslan, A. Mohd Isa, M.F. Basri Nair, and S.S. Salleh, 2018: The Impact of Minimum Energy Performance Standards (MEPS) Regulation on Electricity Saving in Malaysia. *IOP Conference Series: Materials Science and Engineering*, **341**, 012022, doi:10.1088/1757-899X/341/1/012022.

Salvalai, G., M.M. Sesana, and G. Iannaccone, 2017: Deep renovation of multi-storey multi-owner existing residential buildings: A pilot case study in Italy. *Energy and Buildings*, **148**, 23-36, doi:10.1016/j.enbuild.2017.05.011.

Salvo, A., J. Brito, P. Artaxo, and F.M. Geiger, 2017: Reduced ultrafine particle levels in São Paulo's atmosphere during shifts from gasoline to ethanol use. *Nature Communications*, **8(1)**, 77, doi:10.1038/s41467-017-00041-5.

Samaddar, S. et al., 2015: Evaluating Effective Public Participation in Disaster Management and Climate Change Adaptation: Insights From Northern Ghana Through a User-Based Approach. *Risk, Hazards & Crisis in Public Policy*, **6(1)**, 117-143, doi:10.1002/rhc3.12075.

Sanchez, D.L. and D.S. Callaway, 2016: Optimal scale of carbon-negative energy facilities. *Applied Energy*, **170**, 437-444, doi:10.1016/j.apenergy.2016.02.134.

Sánchez, P., F. James, and G. Lindsay, 2002: Coastal Aquaculture Sustainable Livelihoods in Mecoacan, Tabasco, Mexico. *Universidad y Ciencia*, **35(18)**, 42-52.

Sanderman, J. and J.A. Baldock, 2010: Accounting for soil carbon sequestration in national inventories: a soil scientist's perspective. *Environmental Research Letters*, **5(3)**, 034003, doi:10.1088/1748-9326/5/3/034003.

Sanesi, G., G. Colangelo, R. Lafortezza, E. Calvo, and C. Davies, 2017: Urban green infrastructure and urban forests: a case study of the Metropolitan Area of Milan. *Landscape Research*, **42(2)**, 164-175, doi:10.1080/01426397.2016.1173658.

Sanna, A., M. Dri, M.R. Hall, and M. Maroto-Valer, 2012: Waste materials for carbon capture and storage by mineralisation (CCSM) - A UK perspective. *Applied Energy*, **99**, 545-554, doi:10.1016/J.APENERGY.2012.06.049.

Santangeli, A. et al., 2016: Global change synergies and trade-offs between renewable energy and biodiversity. *GCB Bioenergy*, **8(5)**, 941-951, doi:10.1111/gcbb.12299.

Sanz-Cobena, A. et al., 2017: Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. *Agriculture, Ecosystems & Environment*, **238**, 5-24, doi:10.1016/j.agee.2016.09.038.

Sanz-Pérez, E.S., C.R. Murdock, S.A. Didas, and C.W. Jones, 2016: Direct Capture of CO_2 from Ambient Air. *Chemical Reviews*, **116(19)**, 11840-11876, doi:10.1021/acs.chemrev.6b00173.

Savo, V. et al., 2016: Observations of climate change among subsistence-oriented communities around the world. *Nature Climate Change*, **6(5)**, 462-473, doi:10.1038/nclimate2958.

Schachter, J.A. and P. Mancarella, 2016: A critical review of Real Options thinking for valuing investment flexibility in Smart Grids and low carbon energy systems. *Renewable and Sustainable Energy Reviews*, **56(C)**, 261-271, doi:10.1016/j.rser.2015.11.071.

Schaeffer, R. et al., 2012: Energy sector vulnerability to climate change: A review. *Energy*, **38(1)**, 1-12, doi:10.1016/j.energy.2011.11.056.

Schirmer, J. and L. Bull, 2014: Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects. *Global Environmental Change*, **24**, 306-320, doi:10.1016/J.GLOENVCHA.2013.11.009.

Schlag, A.K., 2010: Aquaculture: An emerging issue for public concern. *Journal of Risk Research*, **13(7)**, 829-844, doi:10.1080/13669871003660742.

Schlör, H., W. Fischer, and J.–F. Hake, 2015: The system boundaries of sustainability. *Journal of Cleaner Production*, **88**, 52-60, doi:10.1016/j.jclepro.2014.04.023.

Schmidt, O., A. Hawkes, A. Gambhir, and I. Staffell, 2017: The future cost of electrical energy storage based on experience rates. *Nature Energy*, **2(8)**, 17110, doi:10.1038/nenergy.2017.110.

Schmitz, O.J. et al., 2015: Conserving Biodiversity: Practical Guidance about Climate Change Adaptation Approaches in Support of Land-use Planning. *Natural Areas Journal*, **35(1)**, 190-203, doi:10.3375/043.035.0120.

Scholte, S.S.K., M. Todorova, A.J.A. van Teeffelen, and P.H. Verburg, 2016: Public Support for Wetland Restoration: What is the Link With Ecosystem Service Values? *Wetlands*, **36(3)**, 467-481, doi:10.1007/s13157-016-0755-6.

Schoneveld, G.C., L.A. German, and E. Nutakor, 2011: Land-based Investments for Rural Development? A Grounded Analysis of the Local Impacts of Biofuel Feedstock Plantations in Ghana. *Ecology and Society*, **16(4)**, art10, doi:10.5751/ES-04424-160410.

Schrobback, P., D. Adamson, and J. Quiggin, 2011: Turning Water into Carbon: Carbon Sequestration and Water Flow in the Murray-Darling Basin. *Environmental and Resource Economics*, **49(1)**, 23-45, doi:10.1007/s10640-010-9422-1.

Schuiling, R.D. and P. Krijgsman, 2006: Enhanced Weathering: An Effective and Cheap Tool to Sequester CO_2. *Climatic Change*, **74(1)**, 349-354, doi:10.1007/s10584-005-3485-y.

Schulze, E.–D., C. Körner, B.E. Law, H. Haberl, and S. Luyssaert, 2012: Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy*, **4(6)**, 611-616, doi:10.1111/j.1757-1707.2012.01169.x.

Schwan, S. and X. Yu, 2017: Social protection as a strategy to address climate-induced migration. *International Journal of Climate Change Strategies and Management*, IJCCSM-01-2017-0019, doi:10.1108/IJCCSM-01-2017-0019.

Schwanghart, W., R. Worni, C. Huggel, M. Stoffel, and O. Korup, 2016: Uncertainty in the Himalayan energy-water nexus: estimating regional exposure to glacial lake outburst floods. *Environmental Research Letters*, **11(7)**, 074005, doi:10.1088/1748-9326/11/7/074005.

Scolobig, A., T. Prior, D. Schröter, J. Jörin, and A. Patt, 2015: Towards people-centred approaches for effective disaster risk management: Balancing rhetoric with reality. *International Journal of Disaster Risk Reduction*, **12**, 202-212, doi:10.1016/j.ijdrr.2015.01.006.

Scott, M.J., J.M. Roop, R.W. Schultz, D.M. Anderson, and K.A. Cort, 2008: The impact of DOE building technology energy efficiency programs on U.S. employment, income, and investment. *Energy Economics*, **30(5)**, 2283-2301, doi:10.1016/j.eneco.2007.09.001.

Scott, V., R.S. Haszeldine, S.F.B. Tett, and A. Oschlies, 2015: Fossil fuels in a trillion tonne world. *Nature Climate Change*, **5(5)**, 419-423.

Scyphers, S.B., S.P. Powers, K.L. Heck, and D. Byron, 2011: Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLoS ONE*, **6(8)**, doi:10.1371/journal.pone.0022396.

SEAB, 2016: *Task Force Report on* CO_2 *Utilization and Negative Emissions Technologies*. Secretary of Energy Advisory Board - CO_2 Utilization Task Force.

Searchinger, T.D., T. Beringer, and A. Strong, 2017: Does the world have low-carbon bioenergy potential from the dedicated use of land? *Energy Policy*, **110**, 434-446, doi:10.1016/J.ENPOL.2017.08.016.

Searle, S. and C. Malins, 2015: A reassessment of global bioenergy potential in 2050. *GCB Bioenergy*, **7(2)**, 328-336, doi:10.1111/gcbb.12141.

Seigo, S.L.O., S. Dohle, and M. Siegrist, 2014: Public perception of carbon capture and storage (CCS): A review. *Renewable and Sustainable Energy Reviews*, **38**, 848-863, doi:10.1016/j.rser.2014.07.017.

Selosse, S. and O. Ricci, 2017: Carbon capture and storage: Lessons from a storage potential and localization analysis. *Applied Energy*, **188(February)**, 32-44, doi:10.1016/j.apenergy.2016.11.117.

Sen, B., M. Dhimal, A.T. Latheef, and U. Ghosh, 2017: Climate change: health effects and response in South Asia. *BMJ*, **359**, j5117, doi:10.1136/bmj.j5117.

Sendzimir, J., C.P. Reija, and P. Magnuszewski, 2011: Rebuilding Resilience in the Sahel. *Ecology and society*, **16(3)**, 1-29, doi:10.5751/ES-04198-160301.

Serrao-Neumann, S., M. Renouf, S.J. Kenway, and D. Low Choy, 2017: Connecting land-use and water planning: Prospects for an urban water metabolism approach. *Cities*, **60(Part A)**, 13-27, doi:https://doi.org/10.1016/j.cities.2016.07.003.

Serrao-Neumann, S., F. Crick, B. Harman, G. Schuch, and D.L. Choy, 2015: Maximising synergies between disaster risk reduction and climate change adaptation: Potential enablers for improved planning outcomes. *Environmental Science and Policy*, **50**, 46-61, doi:10.1016/j.envsci.2015.01.017.

Shackley, S., J. Hammond, J. Gaunt, and R. Ibarrola, 2011: The feasibility and costs of biochar deployment in the UK. *Carbon Management*, **2(3)**, 335-356, doi:10.4155/cmt.11.22.

Shackley, S. et al., 2009: The acceptability of CO_2 capture and storage (CCS) in Europe: An assessment of the key determining factors. Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation. *International Journal of Greenhouse Gas Control*, **3(3)**, 344-356, doi:10.1016/j.ijggc.2008.09.004.

Shafiee, M., F. Brennan, and I.A. Espinosa, 2016: A parametric whole life cost model for offshore wind farms. *The International Journal of Life Cycle Assessment*, **21(7)**, 961-975, doi:10.1007/s11367-016-1075-z.

Shah, N., N. Sathaye, A. Phadke, and V. Letschert, 2015: Efficiency improvement opportunities for ceiling fans. *Energy Efficiency*, **8(1)**, 37-50, doi:10.1007/s12053-014-9274-6.

Shapiro, S., 2016: The realpolitik of building codes: overcoming practical limitations to climate resilience. *Building Research & Information*, **44(5-6)**, 490-506, doi:10.1080/09613218.2016.1156957.

Sharma, R., 2018: Financing Indian Urban Rail through Land Development: Case Studies and Implications for the Accelerated Reduction in Oil Associated with 1.5 °C. *Urban Planning*, **3(2)**, 21-34, doi:10.17645/up.v3i2.1158.

Sharma, U., A. Patwardhan, and A.G. Patt, 2013: Education as a Determinant of Response to Cyclone Warnings: Evidence from Coastal Zones in India. *Ecology and Society*, **18(2)**, doi:10.5751/ES-05439-180218.

Sheehan, M.C., M.A. Fox, C. Kaye, and B. Resnick, 2017: Integrating Health into Local Climate Response: Lessons from the U.S. CDC Climate-Ready States and Cities Initiative. *Environmental Health Perspectives*, **125(9)**, doi:10.1289/EHP1838.

Sheng, Y., Y. Zhan, and L. Zhu, 2016: Reduced carbon sequestration potential of biochar in acidic soil. *Science of The Total Environment*, **572**, 129-137, doi:10.1016/j.scitotenv.2016.07.140.

Shepon, A., G. Eshel, E. Noor, and R. Milo, 2016: Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. *Environmental Research Letters*, **11(10)**, 105002, doi:10.1088/1748-9326/11/10/105002.

Sherman, M., J. Ford, A. Llanos-Cuentas, and M.J. Valdivia, 2016: Food system vulnerability amidst the extreme 2010--2011 flooding in the Peruvian Amazon: a case study from the Ucayali region. *Food Security*, **8(3)**, 551-570, doi:10.1007/s12571-016-0583-9.

Shi, L. et al., 2016: Roadmap towards justice in urban climate adaptation research. *Nature Climate Change*, **6(2)**, 131-137, doi:10.1038/nclimate2841.

Shi, Y., 2016: Reducing greenhouse gas emissions from international shipping: Is it time to consider market-based measures? *Marine Policy*, **64**, 123-134, doi:10.1016/j.marpol.2015.11.013.

Shiferaw, B. et al., 2014: Managing vulnerability to drought and enhancing livelihood resilience in sub-Saharan Africa: Technological, institutional and policy options. *Weather and Climate Extremes*, **3**, 67-79, doi:10.1016/j.wace.2014.04.004.

Shimamoto, M.M. and S. McCormick, 2017: The Role of Health in Urban Climate Adaptation: An Analysis of Six U.S. Cities. *Weather, Climate, and Society*, doi:10.1175/WCAS-D-16-0142.1.

Shively, D., 2017: Flood risk management in the USA: implications of national flood insurance program changes for social justice. *Regional Environmental Change*, **17(8)**, 2323, doi:10.1007/s10113-017-1228-z.

Shomali, A. and J. Pinkse, 2016: The consequences of smart grids for the business model of electricity firms. *Journal of Cleaner Production*, **112(P5)**, 3830-3841, doi:10.1016/j.jclepro.2015.07.078.

Shrimali, G. and S. Rohra, 2012: India's solar mission: A review. *Renewable and Sustainable Energy Reviews*, **16(8)**, 6317-6332, doi:10.1016/j.rser.2012.06.018.

Shukla, A.K., K. Sudhakar, P. Baredar, and R. Mamat, 2018: Solar PV and BIPV system: Barrier, challenges and policy recommendation in India. *Renewable and Sustainable Energy Reviews*, **82**, 3314-3322, doi:10.1016/j.rser.2017.10.013.

Shvidenko, A., S. Nilsson, and V. Roshkov, 1997: Possibilities for Increased Carbon Sequestration through the Implementation of Rational Forest Management in Russia. *Water, Air, and Soil Pollution*, **94(1)**, 137-162, doi:10.1023/A:1026494514131.

Sida, T.S., F. Baudron, H. Kim, and K.E. Giller, 2018: Climate-smart agroforestry: Faidherbia albida trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. *Agricultural and Forest Meteorology*, **248**, 339-347, doi:10.1016/j.agrformet.2017.10.013.

Siders, A.R., 2017: A role for strategies in urban climate change adaptation planning: Lessons from London. *Regional Environmental Change*, **17(6)**, 1801-1810, doi:10.1007/s10113-017-1153-1.

Siikamäki, J., J.N. Sanchirico, and S.L. Jardine, 2012: Global economic potential for reducing carbon dioxide emissions from mangrove loss. *Proceedings of the National Academy of Sciences of the United States of America*, **109(36)**, 14369-74, doi:10.1073/pnas.1200519109.

Sikorska, P.E., 2015: The need for legal regulation of global emissions from the aviation industry in the context of emerging aerospace vehicles. *International Comparative Jurisprudence*, **1(2)**, 133-142, doi:10.1016/j.icj.2015.12.004.

Silalertruksa, T., S.H. Gheewala, K. Hünecke, and U.R. Fritsche, 2012: Biofuels and employment effects: Implications for socio-economic development in Thailand. *Biomass and Bioenergy*, **46**, 409-418, doi:10.1016/J.BIOMBIOE.2012.07.019.

Silva Herran, D., H. Dai, S. Fujimori, and T. Masui, 2016: Global assessment of onshore wind power resources considering the distance to urban areas. *Energy Policy*, **91**, 75-86, doi:10.1016/j.enpol.2015.12.024.

Simon, A.J., N.B. Kaahaaina, S. Julio Friedmann, and R.D. Aines, 2011: Systems analysis and cost estimates for large scale capture of carbon dioxide from air. *Energy Procedia***, 4**, 2893-2900, doi:10.1016/J.EGYPRO.2011.02.196.

Singh, C., 2018: Is participatory watershed development building local adaptive capacity? Findings from a case study in Rajasthan, India. *Environmental Development***, 25**, 43-58, doi:10.1016/j.envdev.2017.11.004.

Singh, C., P. Urquhart, and E. Kituyi, 2016: From pilots to systems: Barriers and enablers to scaling up the use of climate information services in smallholder farming communities. CARIAA Working Paper no. 3, 56 pp.

Singh, C. et al., 2017: The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. *Climate and Development*, 1-17, doi:10.1080/17565529.2017.1318744.

Sinha, A., L.A. Darunte, C.W. Jones, M.J. Realff, and Y. Kawajiri, 2017: Systems Design and Economic Analysis of Direct Air Capture of CO 2 through Temperature Vacuum Swing Adsorption Using MIL-101(Cr)-PEI-800 and mmen-Mg 2 (dobpdc) MOF Adsorbents. *Industrial & Engineering Chemistry Research***, 56(3)**, 750-764, doi:10.1021/acs.iecr.6b03887.

Sioshansi, R. and P. Denholm, 2009: Emissions Impacts and Benefits of Plug-In Hybrid Electric Vehicles and Vehicle-to-Grid Services. *Environmental Science & Technology***, 43(4)**, 1199-1204, doi:10.1021/es802324j.

Sirakaya, A., A. Cliquet, and J. Harris, 2018: Ecosystem services in cities: Towards the international legal protection of ecosystem services in urban environments. *Ecosystem Services***, 29**, 205-212, doi:10.1016/j.ecoser.2017.01.001.

Sivak, M. and B. Schoettle, 2018: *Relative Costs of Driving Electric and Gasoline Vehicles in the Individual U.S. States*. University of Michigan, Sustainable Worldwide Transportation, Ann Arbor, MI, USA.

Sivakumar, M.V.K., C. Collins, A. Jay, and J. Hansen, 2014: Regional prioritie s for strengthening climate services for farmers in Africa and South Asia. CCAFS Working Paper, 36 pp.

Skougaard Kaspersen, P., N. Høegh Ravn, K. Arnbjerg-Nielsen, H. Madsen, and M. Drews, 2015: Influence of urban land cover changes and climate change for the exposure of European cities to flooding during high-intensity precipitation. *Proceedings of the International Association of Hydrological Sciences***, 370**, 21-27, doi:10.5194/piahs-370-21-2015.

Slade, R., A. Bauen, and R. Gross, 2014: Global bioenergy resources. *Nature Climate Change***, 4(2)**, 99-105.

Sleenhoff, S. and P. Osseweijer, 2016: How people feel their engagement can have efficacy for a bio-based society. *Public Understanding of Science***, 25(6)**, 719-736, doi:10.1177/0963662514566749.

Smajgl, A. et al., 2015: Responding to rising sea levels in the Mekong Delta. *Nature Climate Change***, 5(2)**, 167.

Smale, R., M. Krahé, and T. Johnson, 2012: *Aviation Report: Market Based Mechanisms to Curb Greenhouse Gas Emissions from International Aviation*. Vivid Economics, Aviation Environment Trust and WWF Global and Energy initiative on behalf of World Wildlife Fund (WWF) International., Gland, Switzerland, 86 pp.

Smeets, E.M.W. and A.P.C. Faaij, 2007: Bioenergy potentials from forestry in 2050: An assessment of the drivers that determine the potentials. *Climatic Change***, 81(3-4)**, 353-390, doi:10.1007/s10584-006-9163-x.

Smeets, E.M.W., A.P.C. Faaij, I.M. Lewandowski, and W.C. Turkenburg, 2007: A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science***, 33(1)**, 56-106, doi:10.1016/j.pecs.2006.08.001.

Smith, A. et al., 2017: Measuring sustainable intensification in smallholder agroecosystems: A review. *Global Food Security***, 12**, 127-138, doi:https://doi.org/10.1016/j.gfs.2016.11.002.

Smith, H., E. Kruger, J. Knot, and J. Blignaut, 2017: Conservation Agriculture in South Africa: Lessons from Case Studies. In: *Building Resilient Farming Systems in a Changing Climate* [Kassam, A.H. (ed.)].

Smith, K.R. et al., 2014: Human health: Impacts, adaptation, and co-benefits. In: *Climate Change 2014 Impacts, Adaptation, and Vulnerability* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, and T.E. Bilir (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709-754.

Smith, L.J. and M.S. Torn, 2013: Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change*, **118(1)**, 89-103, doi:10.1007/s10584-012-0682-3.

Smith, M.D. et al., 2015: Geoengineering Coastlines? From Accidental to Intentional. *Coastal Zones*, 99-122, doi:10.1016/B978-0-12-802748-6.00007-3.

Smith, P., 2012: Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learnt in the last 20 years? *Global Change Biology*, **18(1)**, 35-43, doi:10.1111/j.1365-2486.2011.02517.x.

Smith, P., 2016: Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, **22(3)**, 1315-1324, doi:10.1111/gcb.13178.

Smith, P. and P.J. Gregory, 2013: Climate change and sustainable food production. *Proceedings of the Nutrition Society*, **72(1)**, 21-28, doi:10.1017/S0029665112002832.

Smith, P. et al., 2008: Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, **363(1492)**, 789-813.

Smith, P. et al., 2012: Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: current capability and future vision. *Global Change Biology*, **18(7)**, 2089-2101, doi:10.1111/j.1365-2486.2012.02689.x.

Smith, P. et al., 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, Cambridge, United Kingdom and New York, NY, USA, pp. 811-922.

Smith, P. et al., 2016: Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, **6(1)**, 42-50, doi:10.1038/nclimate2870.

Smith, T., D. Thomsen, S. Gould, K. Schmitt, and B. Schlegel, 2013: Cumulative Pressures on Sustainable Livelihoods: Coastal Adaptation in the Mekong Delta. *Sustainability*, **5(1)**, 228-241, doi:10.3390/su5010228.

Smith, W.K., M. Zhao, and S.W. Running, 2012: Global Bioenergy Capacity as Constrained by Observed Biospheric Productivity Rates. *BioScience*, **62(10)**, pp. 911-922, doi:10.1525/bio.2012.62.10.11.

Snow, J.T. et al., 2016: *A New Vision for Weather and Climate Services in Africa*. UNDP, New York, NY, USA.

Soccol, C.R. et al., 2009: Bioethanol from lignocelluloses: Status and perspectives in Brazil. *Bioresource technology*, doi:10.1016/j.biortech.2009.11.067.

Socolow, R. et al., 2011: *Direct air capture of* CO_2 *with chemicals: A technology assessment for the APS Panel on Public Affairs*. 100 pp.

Soderlund, J. and P. Newman, 2015: Biophilic architecture: a review of the rationale and outcomes. *AIMS Environmental Science*, **2(4)**, 950-969, doi:10.3934/environsci.2015.4.950.

Sohngen, B. and R. Alig, 2000: Mitigation, adaptation, and climate change: results from recent research on US timber markets. *Environmental Science & Policy*, **3(5)**, 235-248, doi:10.1016/S1462-9011(00)00094-0.

Sohngen, B. and R. Mendelsohn, 2003: An optimal control model of forest carbon sequestration. *Am J Agric Econ*, **85(2)**, 448-457.

Soito, J.L.S. and M.A.V. Freitas, 2011: Amazon and the expansion of hydropower in Brazil: Vulnerability, impacts and possibilities for adaptation to global climate change. *Renewable and Sustainable Energy Reviews*, **15(6)**, 3165-3177, doi:10.1016/J.RSER.2011.04.006.

Sommer, R. and D. Bossio, 2014: Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management*, **144**, 83-87, doi:10.1016/j.jenvman.2014.05.017.

Somorin, O.A., I.J. Visseren-Hamakers, B. Arts, A.–M. Tiani, and D.J. Sonwa, 2016: Integration through interaction? Synergy between adaptation and mitigation (REDD+) in Cameroon. *Environment and Planning C: Government and Policy*, **34(3)**, 415-432, doi:10.1177/0263774X16645341.

Song, G., M. Li, P. Fullana-i-Palmer, D. Williamson, and Y. Wang, 2017: Dietary changes to mitigate climate change and benefit public health in China. *Science of The Total Environment*, **577**, 289-298, doi:10.1016/j.scitotenv.2016.10.184.

Sonntag, S., J. Pongratz, C.H. Reick, and H. Schmidt, 2016: Reforestation in a high-CO_2 world - Higher mitigation potential than expected, lower adaptation potential than hoped for. *Geophysical Research Letters*, **43(12)**, 6546-6553, doi:10.1002/2016GL068824.

Soussana, J.–F. and G. Lemaire, 2014: Coupling carbon and nitrogen cycles for environmentally sustainable intensification of grasslands and crop-livestock systems. *Agriculture, Ecosystems & Environment*, **190**, 9-17.

Sovacool, B.K., B.–O. Linnér, and M.E. Goodsite, 2015: The political economy of climate adaptation. *Nature Clim. Change*, **5(7)**, 616-618, doi:10.1038/nclimate2665.

Soz, S.A., Z. Stanton-Geddes, and J. Kryspin-Watson, 2016: *The role of green infrastructure solutions in urban flood risk management*. World Bank Group, Washington D.C. 1-18 pp.

Spalding, M.D. et al., 2014: The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean and Coastal Management*, **90**, 50-57, doi:10.1016/j.ocecoaman.2013.09.007.

Sparovek, G. et al., 2018: Asymmetries of cattle and crop productivity and efficiency during Brazil's agricultural expansion from 1975 to 2006. *Elem Sci Anth*, **6(1)**, 25, doi:10.1525/elementa.187.

Späth, P. and H. Rohracher, 2015: Conflicting strategies towards sustainable heating at an urban junction of heat infrastructure and building standards. *Energy Policy*, **78**, 273-280, doi:10.1016/j.enpol.2014.12.019.

Spencer, B. et al., 2017: Case studies in co-benefits approaches to climate change mitigation and adaptation. *Journal of Environmental Planning and Management*, **60(4)**, 647-667, doi:10.1080/09640568.2016.1168287.

Star, J. et al., 2016: Supporting adaptation decisions through scenario planning: Enabling the effective use of multiple methods. *Climate Risk Management*, **13(Supplement C)**, 88-94, doi:https://doi.org/10.1016/j.crm.2016.08.001.

Stattman, S.L., O. Hospes, and A.P.J. Mol, 2013: Governing biofuels in Brazil: A comparison of ethanol and biodiesel policies. *Energy Policy*, **61**, 22-30, doi:10.1016/J.ENPOL.2013.06.005.

Stavi, I. and R. Lal, 2013: Agriculture and greenhouse gases, a common tragedy. A review. *Agronomy for Sustainable Development*, **33(2)**, 275-289, doi:10.1007/s13593-012-0110-0.

Steenhof, P. and E. Sparling, 2011: The role of codes, standards, and related instruments in facilitating adaptation to climate change. In: *Climate Change Adaptation in Developed Nations: From Theory to Practice* [Ford, J.D. and L. Berrang-Ford (eds.)]. Advances in Global Change Research, Springer, Dordrecht, Netherlands, pp. 243-254.

Steg, L., 2003: Can Public Transport Compete With the Private Car? *IATSS Research*, **27(2)**, 27-35, doi:10.1016/S0386-1112(14)60141-2.

Stephan, A. and R.H. Crawford, 2016: Total water requirements of passenger transport modes. *Transportation Research Part D*, **49**, 94-109, doi:10.1016/j.trd.2016.09.007.

Sterman, J.D., L. Siegel, and J.N. Rooney-Varga, 2018: Does replacing coal with wood lower CO 2 emissions? Dynamic lifecycle analysis of wood bioenergy. *Environmental Research Letters*, **13(1)**, 015007, doi:10.1088/1748-9326/aaa512.

Stevanović, M. et al., 2017: Mitigation Strategies for Greenhouse Gas Emissions from Agriculture and Land-Use Change: Consequences for Food Prices. *Environmental Science & Technology*, **51(1)**, 365-374, doi:10.1021/acs.est.6b04291.

Stevens, C.J. and J.N. Quinton, 2009: Diffuse Pollution Swapping in Arable Agricultural Systems. *Critical Reviews in Environmental Science and Technology*, **39(6)**, 478-520, doi:10.1080/10643380801910017.

Stevenson, J.R., R. Serraj, and K.G. Cassman, 2014: Evaluating conservation agriculture for small-scale farmers in Sub-Saharan Africa and South Asia. *Agriculture, Ecosystems & Environment*, **187**, 1-10, doi:10.1016/j.agee.2014.01.018.

Stevenson, M. et al., 2016: Land use, transport, and population health: estimating the health benefits of compact cities. *The Lancet*, **388(10062)**, 2925-2935, doi:10.1016/S0140-6736(16)30067-8.

Stewart, M.G., 2015: Risk and economic viability of housing climate adaptation strategies for wind hazards in southeast Australia. *Mitigation and Adaptation Strategies for Global Change*, **20(4)**, 601-622, doi:10.1007/s11027-013-9510-y.

Stocker, E. and D. Koch, 2017: Cost-Effective Refurbishment of Residential Buildings in Austria. *Cost-Effective Energy Efficient Building Retrofitting*, 489-513, doi:10.1016/B978-0-08-101128-7.00017-4.

Stolaroff, J.K., D.W. Keith, and G. Lowry, 2008: Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spray. *Environmental Science & Technology*, **42(8)**, 2728-2735, doi:10.1021/es702607w.

Stoll-Kleemann, S. and U.J. Schmidt, 2017: Reducing meat consumption in developed and transition countries to counter climate change and biodiversity loss: a review of influence factors. *Regional Environmental Change*, **17(5)**, 1261-1277, doi:10.1007/s10113-016-1057-5.

Storlazzi, C.D. et al., 2018: Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, **4(4)**.

Stoy, P.C. et al., 2018: Opportunities and Trade-offs among BECCS and the Food, Water, Energy, Biodiversity, and Social Systems Nexus at Regional Scales. *BioScience*, **68(2)**, 100-111.

Strassburg, B.B.N. et al., 2014: Biophysical suitability, economic pressure and land-cover change: a global probabilistic approach and insights for REDD+. *Sustainability Science*, **9(2)**, 129-141, doi:10.1007/s11625-013-0209-5.

Strefler, J., T. Amann, N. Bauer, E. Kriegler, and J. Hartmann, 2018a: Potential and costs of carbon dioxide removal by Enhanced Weathering of rocks. *Environmental Research Letters*, **13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.

Strefler, J., N. Bauer, T. Amann, E. Kriegler, and J. Hartmann, 2018b: Supply curves for carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, **13(3)**.

Strefler, J. et al., 2018c: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environmental Research Letters*, **13(4)**.

Strengers, B.J., J.G. Van Minnen, and B. Eickhout, 2008: The role of carbon plantations in mitigating climate change: potentials and costs. *Climatic Change*, **88(3)**, 343-366, doi:10.1007/s10584-007-9334-4.

Striessnig, E., W. Lutz, and A.G. Patt, 2013: Effects of Educational Attainment on Climate Risk Vulnerability. *Ecology and Society*, **18(1)**, doi:10.5751/ES-05252-180116.

Stringer, L.C. et al., 2012: Challenges and opportunities in linking carbon sequestration, livelihoods and ecosystem service provision in drylands. *Environmental Science & Policy*, **19-20**, 121-135, doi:10.1016/J.ENVSCI.2012.02.004.

Struik, P.C. and T.W. Kuyper, 2017: Sustainable intensification in agriculture: the richer shade of green. A review. *Agronomy for Sustainable Development*, **37(5)**, 39, doi:10.1007/s13593-017-0445-7.

Strzalka, R., D. Schneider, and U. Eicker, 2017: Current status of bioenergy technologies in Germany. *Renewable and Sustainable Energy Reviews*, **72**, 801-820, doi:10.1016/J.RSER.2017.01.091.

Stults, M. and S.C. Woodruff, 2017: Looking under the hood of local adaptation plans: shedding light on the actions prioritized to build local resilience to climate change. *Mitigation and Adaptation Strategies for Global Change*, **22(8)**, 1249-1279, doi:10.1007/s11027-016-9725-9.

Su, S., Q. Zhang, J. Pi, C. Wan, and M. Weng, 2016: Public health in linkage to land use: Theoretical framework, empirical evidence, and critical implications for reconnecting health promotion to land use policy. *Land Use Policy*, **57**, 605-618, doi:10.1016/j.landusepol.2016.06.030.

Suarez, P., J. de Suarez, B. Koelle, and M. Boykoff, 2014: Serious fun: Scaling up community based adaptation through experiential learning. *Community based adaptation to climate change: Scaling it*, 136-151.

Suckall, N., L.C. Stringer, and E.L. Tompkins, 2015: Presenting Triple-Wins? Assessing Projects That Deliver Adaptation, Mitigation and Development Co-benefits in Rural Sub-Saharan Africa. *AMBIO*, **44(1)**, 34-41, doi:10.1007/s13280-014-0520-0.

Sunderlin, W.D. et al., 2014: How are REDD+ Proponents Addressing Tenure Problems? Evidence from Brazil, Cameroon, Tanzania, Indonesia, and Vietnam. *World Development*, **55**, 37-52, doi:10.1016/j.worlddev.2013.01.013.

Surendra, K.C., D. Takara, A.G. Hashimoto, and S.K. Khanal, 2014: Biogas as a sustainable energy source for developing countries: Opportunities and challenges. *Renewable and Sustainable Energy Reviews*, **31**, 846-859, doi:10.1016/J.RSER.2013.12.015.

Surminski, S. and J. Eldridge, 2017: Flood insurance in England - an assessment of the current and newly proposed insurance scheme in the context of rising flood risk. *Journal of Flood Risk Management*, **10(4)**, 415-435, doi:10.1111/jfr3.12127.

Surminski, S. and A.H. Thieken, 2017: Promoting flood risk reduction: The role of insurance in Germany and England. *Earth's Future*, **5(10)**, 979-1001, doi:10.1002/2017EF000587.

Surminski, S., L.M. Bouwer, and J. Linnerooth-Bayer, 2016: How insurance can support climate resilience. *Nature Climate Change*, **6(4)**, 333-334, doi:10.1038/nclimate2979.

Sütterlin, B. and M. Siegrist, 2017: Public acceptance of renewable energy technologies from an abstract versus concrete perspective and the positive imagery of solar power. *Energy Policy*, **106**, 356-366, doi:10.1016/j.enpol.2017.03.061.

Sutton-Grier, A.E., K. Wowk, and H. Bamford, 2015: Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy*, **51**, 137-148, doi:10.1016/j.envsci.2015.04.006.

Suzuki, S.S. et al., 2016: Comprehensive Survey Results of Childhood Thyroid Ultrasound Examinations in Fukushima in the First Four Years After the Fukushima Daiichi Nuclear Power Plant Accident. *Thyroid*, **26(6)**, 843-851, doi:10.1089/thy.2015.0564.

Sweet, M., 2014: Traffic Congestion's Economic Impacts: Evidence from US Metropolitan Regions. *Urban Studies*, **51(10)**, 2088-2110, doi:10.1177/0042098013505883.

Swilling, M., J. Musango, and J. Wakeford, 2016: Developmental States and Sustainability Transitions: Prospects of a Just Transition in South Africa. *Journal of Environmental Policy & Planning*, **18(5)**, 650-672, doi:10.1080/1523908X.2015.1107716.

Swim, J.K., N. Geiger, and S.J. Zawadzki, 2014: Psychology and Energy-Use Reduction Policies. *Policy Insights from the Behavioral and Brain Sciences*, **1(1)**, 180-188, doi:10.1177/2372732214548591.

Swisher, J.N., 1994: Forestry and biomass energy projects: Bottom-up comparisons of CO_2 storage and costs. *Biomass and Bioenergy*, **6(5)**, 359-368, doi:10.1016/0961-9534(94)00061-W.

Tacoli, C., B. Bukhari, and S. Fisher, 2013: *Urban poverty, food security and climate change*. IIED, Human Settlements Group.

Tadgell, A., L. Mortsch, and B. Doberstein, 2017: Assessing the feasibility of resettlement as a climate change adaptation strategy for informal settlements in Metro Manila, Philippines. *International Journal of Disaster Risk Reduction*, **22**, 447-457, doi:10.1016/j.ijdrr.2017.01.005.

Taebi, B. and M. Mayer, 2017: By accident or by design? Pushing global governance of nuclear safety. *Progress in Nuclear Energy*, **99**, 19-25, doi:https://doi.org/10.1016/j.pnucene.2017.04.014.

Taibi, E., D. Gielen, and M. Bazilian, 2012: The potential for renewable energy in industrial applications. *Renewable and Sustainable Energy Reviews*, **16(1)**, 735-744, doi:https://doi.org/10.1016/j.rser.2011.08.039.

Tait, L. and M. Euston-Brown, 2017: What role can African cities play in low-carbon development? A multilevel governance perspective of Ghana, Uganda and South Africa. *Journal of Energy in Southern Africa*, **28(3)**, 43, doi:10.17159/2413-3051/2017/v28i3a1959.

Takahashi, N. et al., 2015: Community Trial on Heat Related-Illness Prevention Behaviors and Knowledge for the Elderly. *International Journal of Environmental Research and Public Health*, **12(3)**, doi:10.3390/ijerph120303188.

Tallis, M., G. Taylor, D. Sinnett, and P. Freer-Smith, 2011: Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. *Landscape and Urban Planning*, **103(2)**, 129-138, doi:10.1016/j.landurbplan.2011.07.003.

Tarr, N.M. et al., 2017: Projected gains and losses of wildlife habitat from bioenergy-induced landscape change. *GCB Bioenergy*, **9(5)**, 909-923, doi:10.1111/gcbb.12383.

Taylor, L.L. et al., 2016: Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nature Clim. Change*, **6(4)**, 402-406.

Teferi, Z. and P. Newman, 2017: Slum Regeneration and Sustainability: Applying the Extended Metabolism Model and the SDGs. *Sustainability*, **9(12)**, 2273, doi:10.3390/su9122273.

Teferi, Z.A. and P. Newman, 2018: Slum Upgrading: Can the 1.5 °C Carbon Reduction Work with SDGs in these Settlements? *Urban Planning*, **3(2)**, 52, doi:10.17645/up.v3i2.1239.

Teh, T.–L., 2015: Sovereign disaster risk financing and insurance impact appraisal. *British Actuarial Journal*, **20(2)**, 241-256, doi:DOI: 10.1017/S1357321715000033.

Terraube, J., Fernández-Llamazares, and M. Cabeza, 2017: The role of protected areas in supporting human health: a call to broaden the assessment of conservation outcomes. *Current Opinion in Environmental Sustainability*, **25**, 50-58, doi:10.1016/j.cosust.2017.08.005.

Terrier, S., M. Bieri, F. Jordan, and A.J. Schleiss, 2015: Impact du retrait glaciaire et adaptation du potentiel hydroélectrique dans les Alpes suisses. *La Houille Blanche*, 93-101, doi:10.1051/lhb/2015012.

Terrier, S. et al., 2011: Optimized and adapted hydropower management considering glacier shrinkage scenarios in the Swiss Alps. In: *International Symposium on Dams and Reservoirs under Changing Challenges: 79th Annual Meeting of ICOLD*. pp. 12.

Thi Hong Phuong, L., G.R. Biesbroek, and A.E.J. Wals, 2017: The interplay between social learning and adaptive capacity in climate change adaptation: A systematic review. *NJAS - Wageningen Journal of Life Sciences*, **82**, 1-9, doi:10.1016/j.njas.2017.05.001.

Thierfelder, C. et al., 2015: Conservation agriculture in Southern Africa: Advances in knowledge. *Renewable Agriculture and Food Systems*, **30(04)**, 328-348, doi:10.1017/S1742170513000550.

Thierfelder, C. et al., 2017: How climate-smart is conservation agriculture (CA)? - its potential to deliver on adaptation, mitigation and productivity on smallholder farms in southern Africa. *Food Security*, **9(3)**, 537-560, doi:10.1007/s12571-017-0665-3.

Thomas, A. and L. Benjamin, 2018: Policies and mechanisms to address climate-induced migration and displacement in Pacific and Caribbean small island developing states. *International Journal of Climate Change Strategies and Management*, **10(1)**, 86-104, doi:10.1108/IJCCSM-03-2017-0055.

Thomas, C.D. and P.K. Gillingham, 2015: The performance of protected areas for biodiversity under climate change. *Biological Journal of the Linnean Society*, **115(3)**, 718-730, doi:10.1111/bij.12510.

Thompson, J.L. et al., 2016: Ecosystem - What? Public Understanding and Trust in Conservation Science and Ecosystem Services. *Frontiers in Communication*, **1**, 3, doi:10.3389/fcomm.2016.00003.

Thomson, A.M., R. César Izaurralde, S.J. Smith, and L. Clarke, 2008: Integrated estimates of global terrestrial carbon sequestration. *Global Environmental Change*, **18(1)**, 192-203, doi:16/j.gloenvcha.2007.10.002.

Thomson, G. and P. Newman, 2018: Urban fabrics and urban metabolism - from sustainable to regenerative cities. *Resources Conservation and Recycling*, **132**, 218-229, doi:10.1016/j.resconrec.2017.01.010.

Thornley, P., P. Upham, and J. Tomei, 2009: Sustainability constraints on UK bioenergy development. *Energy Policy*, **37(12)**, 5623-5635, doi:10.1016/J.ENPOL.2009.08.028.

Thornton, P.K. and M. Herrero, 2014: Climate change adaptation in mixed crop-livestock systems in developing countries. *Global Food Security*, **3(2)**, 99-107, doi:10.1016/j.gfs.2014.02.002.

Thornton, P.K. and M. Herrero, 2015: Adapting to climate change in the mixed crop and livestock farming systems in sub-Saharan Africa. *Nature Climate Change*, **5(9)**, 830-836.

Thornton, P.K. et al., 2017: Climate-Smart Agriculture Options in Mixed Crop-Livestock Systems in Africa South of the Sahara. In: *Climate Smart Agriculture: Building Resilience to Climate Change* [Zilberman, D., N. McCarthy, S. Asfaw, and L. Lipper (eds.)]. Springer Science & Business Media, New York, NY, USA.

Thornton, P.K. et al., 2018: A Qualitative Evaluation of CSA Options in Mixed Crop-Livestock Systems in Developing Countries. In: *Climate Smart Agriculture : Building Resilience to Climate Change* [Lipper, L., N. McCarthy, D. Zilberman, S. Asfaw, and G. Branca (eds.)]. Springer International Publishing, Cham, pp. 385-423.

Thornton, T.F. and N. Manasfi, 2010: Adaptation-Genuine and Spurious: Demystifying Adaptation Processes in Relation to Climate Change. *Environment and Society*, **1(1)**, doi:10.3167/ares.2010.010107.

Thornton, T.F. and C. Comberti, 2017: Synergies and trade-offs between adaptation, mitigation and development. *Climatic Change*, **140(1)**, 5-18, doi:10.1007/s10584-013-0884-3.

Thrän, D., T. Seidenberger, J. Zeddies, and R. Offermann, 2010: Global biomass potentials - Resources, drivers and scenario results. *Energy for Sustainable Development*, **14(3)**, 200-205, doi:10.1016/j.esd.2010.07.004.

Thyberg, K.L. and D.J. Tonjes, 2016: Drivers of food waste and their implications for sustainable policy development. *Resources, Conservation and Recycling*, **106**, 110-123, doi:10.1016/j.resconrec.2015.11.016.

Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515(7528)**, 518-522, doi:10.1038/nature13959.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort, 2011a: Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, **108(50)**, 20260-20264, doi:10.1073/pnas.1116437108.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort, 2011b: Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, **108(50)**, 20260-20264, doi:10.1073/pnas.1116437108.

Timilsina, G.R., J.C. Beghin, D. van der Mensbrugghe, and S. Mevel, 2012: The impacts of biofuels targets on land-use change and food supply: A global CGE assessment. *Agricultural Economics*, **43(3)**, 315-332, doi:10.1111/j.1574-0862.2012.00585.x.

Tokimatsu, K., R. Yasuoka, and M. Nishio, 2017: Global zero emissions scenarios: The role of biomass energy with carbon capture and storage by forested land use. *Applied Energy*, **185**, 1899-1906, doi:10.1016/j.apenergy.2015.11.077.

Toloo, G., G. FitzGerald, P. Aitken, K. Verrall, and S. Tong, 2013: Are heat warning systems effective? *Environmental Health*, **12(1)**, 27, doi:10.1186/1476-069X-12-27.

Toovey, N. and N. Malin, 2016: *Solar Rates business case Phase 2 - Final Business Case report*. Urban Elements & Practices Pty Ltd on behalf of the Eastern Alliance for Greenhouse Action (EAGA), Clifton Hill, VIC, 56 pp.

Torres, A.B., R. Marchant, J.C. Lovett, J.C.R. Smart, and R. Tipper, 2010: Analysis of the carbon sequestration costs of afforestation and reforestation agroforestry practices and the use of cost curves to evaluate their potential for implementation of climate change mitigation. *Ecological Economics*, **69(3)**, 469-477, doi:10.1016/j.ecolecon.2009.09.007.

Torssonen, P. et al., 2016: Effects of climate change and management on net climate impacts of production and utilization of energy biomass in Norway spruce with stable age-class distribution. *GCB Bioenergy*, **8(2)**, 419-427, doi:10.1111/gcbb.12258.

Tosa, H., 2015: The failed risk governance - reflections on the boundary between misfortune and injustice in the case of the Fukushima Daiichi Nuclear Disaster. *ProtoSociology - An International Journal of Interdisciplinary Research*, **32**, 125-149.

Townsend, P.V. et al., 2012: Multiple environmental services as an opportunity for watershed restoration. *Forest Policy and Economics*, **17**, 45-58, doi:10.1016/J.FORPOL.2011.06.008.

Trenberth, K.E., M. Marquis, and S. Zebiak, 2016: The vital need for a climate information system. *Nature Climate Change*, **6(12)**, 1057-1059, doi:10.1038/nclimate3170.

Trevisan, A.C.D., A.L. Schmitt-Filho, J. Farley, A.C. Fantini, and C. Longo, 2016: Farmer perceptions, policy and reforestation in Santa Catarina, Brazil. *Ecological Economics*, **130**, 53-63, doi:10.1016/J.ECOLECON.2016.06.024.

Triberti, L., A. Nastri, and G. Baldoni, 2016: Long-term effects of crop rotation, manure and mineral fertilisation on carbon sequestration and soil fertility. *European Journal of Agronomy*, **74**, 47-55, doi:10.1016/J.EJA.2015.11.024.

Triviño, M., H. Kujala, M.B. Araújo, and M. Cabeza, 2018: Planning for the future: identifying conservation priority areas for Iberian birds under climate change. *Landscape Ecology*, **33(4)**, 659-673, doi:10.1007/s10980-018-0626-z.

Trubka, R., P. Newman, and D. Bilsborough, 2010: Costs of Urban Sprawl - Infrastructure and Transport. *Environment Design Guide*, **83**, 1-6.

Tschakert, P. et al., 2014: Learning and Envisioning under Climatic Uncertainty: An African Experience. *Environment and Planning A*, **46(5)**, 1049-1068, doi:10.1068/a46257.

Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8(5)**, doi:10.1002/wcc.476.

Tschirley, D.L. et al., 2015: Africa ' s unfolding diet transformation: implications for agrifood system employment. *Journal of Agribusiness in Developing and Emerging Economies*, **5(2)**, 102-136, doi:10.1108/JADEE-01-2015-0003.

Tsujikawa, N., S. Tsuchida, and T. Shiotani, 2016: Changes in the Factors Influencing Public Acceptance of Nuclear Power Generation in Japan Since the 2011 Fukushima Daiichi Nuclear Disaster. *Risk Analysis*, **36(1)**, 98-113, doi:10.1111/risa.12447.

Tsumune, D., T. Tsubono, M. Aoyama, and K. Hirose, 2012: Distribution of oceanic 137Cs from the Fukushima Dai-ichi Nuclear Power Plant simulated numerically by a regional ocean model. *Journal of Environmental Radioactivity*, **111**, 100-108, doi:10.1016/j.jenvrad.2011.10.007.

Turner, W.R., M. Oppenheimer, and D.S. Wilcove, 2009: A force to fight global warming. *Nature*, **462(7271)**, 278-279, doi:10.1038/462278a.

Turnhout, E. et al., 2017: Envisioning REDD+ in a post-Paris era: between evolving expectations and current practice. *Wiley Interdisciplinary Reviews: Climate Change*, **8(1)**, e425, doi:10.1002/wcc.425.

Ueda, S. et al., 2013: Fluvial discharges of radiocaesium from watersheds contaminated by the Fukushima Dai-ichi Nuclear Power Plant accident, Japan. *Journal of Environmental Radioactivity*, **118**, 96-104, doi:10.1016/j.jenvrad.2012.11.009.

UNEP, 2013: Fisheries & Aquaculture. *Green Economy and Trade*, 89-117.

UNEP, 2017a: *Renewables 2017 Global Status Report*. UNEP, Paris, France, 302 pp.

UNEP, 2017b: *The Emissions Gap Report 2017*. United Nations Environment Programme (UNEP), Nairobi, Kenya, 116 pp.

UNEP-WCMC, 2006: *In the front line: Shoreline protection and other ecosystem services from mangroves and coral reefs*. UNEP World Conservation Monitoring Centre (UNEP-WCMC), 33 pp.

Unruh, J.D., 2011: Tree-Based Carbon Storage in Developing Countries: Neglect of the Social Sciences. *Society & Natural Resources*, **24(2)**, 185-192, doi:10.1080/08941920903410136.

Urban, M.C. et al., 2016: Improving the forecast for biodiversity under climate change. *Science*, **353(6304)**, doi:10.1126/science.aad8466.

Urge-Vorsatz, D., E. Wójcik-Gront, and S. Tirado Herrero, 2012: *Employment Impacts of a Large-Scale Deep Building Energy Retrofit Programme in Poland*.

Ürge-Vorsatz, D. et al., 2018: Locking in positive climate responses in cities. *Nature Climate Change*, **8(3)**, 174-177, doi:10.1038/s41558-018-0100-6.

Valdivia, C., C. Barbieri, and M.A. Gold, 2012: Between Forestry and Farming: Policy and Environmental Implications of the Barriers to Agroforestry Adoption. *Canadian Journal of Agricultural Economics*, **60(2)**, 155-175, doi:10.1111/j.1744-7976.2012.01248.x.

van der Giesen, C. et al., 2017: A Life Cycle Assessment Case Study of Coal-Fired Electricity Generation with Humidity Swing Direct Air Capture of CO_2 versus MEA-Based Postcombustion Capture. *Environmental Science & Technology*, **51(2)**, 1024-1034, doi:10.1021/acs.est.6b05028.

van der Keur, P. et al., 2016: Identification and analysis of uncertainty in disaster risk reduction and climate change adaptation in South and Southeast Asia. *International Journal of Disaster Risk Reduction*, **16**, 208-214, doi:10.1016/j.ijdrr.2016.03.002.

van der Land, V. and D. Hummel, 2013: Vulnerability and the Role of Education in Environmentally Induced Migration in Mali and Senegal. *Ecology and Society*, **18(4)**, doi:10.5751/ES-05830-180414.

van Kooten, G.C., L.M. Arthur, and W.R. Wilson, 1992: Potential to Sequester Carbon in Canadian Forests: Some Economic Considerations. *Canadian Public Policy / Analyse de Politiques*, **18(2)**, 127-138, doi:10.2307/3551419.

van Kooten, G.C., E. Krcmar-Nozic, B. Stennes, and R. van Gorkom, 1999: Economics of fossil fuel substitution and wood product sinks when trees are planted to sequester carbon on agricultural lands in western Canada. *Canadian Journal of Forest Research*, **29(11)**, 1669-1678, doi:10.1139/x99-145.

van Loenhout, A.J., M.J. Rodriguez-Llanes, and D. Guha-Sapir, 2016: Stakeholders' Perception on National Heatwave Plans and Their Local Implementation in Belgium and The Netherlands. *International Journal of Environmental Research and Public Health*, **13(11)**, doi:10.3390/ijerph13111120.

van Minnen, J.G., B.J. Strengers, B. Eickhout, R.J. Swart, and R. Leemans, 2008: Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. *Carbon Balance and Management*, **3**, 3, doi:10.1186/1750-0680-3-3.

van Noordwijk, M., Y.–S. Kim, B. Leimona, K. Hairiah, and L.A. Fisher, 2016: Metrics of water security, adaptive capacity, and agroforestry in Indonesia. *Current Opinion in Environmental Sustainability*, **21**, 1-8, doi:10.1016/J.COSUST.2016.10.004.

Van Straaten, P., 2006: Farming with rocks and minerals: challenges and opportunities. *Anais da Academia Brasileira de Ciências*, **78(4)**, 731-747, doi:10.1590/S0001-37652006000400009.

van Vliet, M.T.H., D. Wiberg, S. Leduc, and K. Riahi, 2016: Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, **6(4)**, 375-380, doi:10.1038/nclimate2903.

van Vliet, O.P.R., A.P.C. Faaij, and C. Dieperink, 2003: Forestry Projects under the Clean Development Mechanism? *Climatic Change*, **61(1/2)**, 123-156, doi:10.1023/A:1026370624352.

van Vuuren, D.P., J. van Vliet, and E. Stehfest, 2009: Future bio-energy potential under various natural constraints. *Energy Policy*, **37(11)**, 4220-4230, doi:10.1016/J.ENPOL.2009.05.029.

Varela-Ortega, C. et al., 2016: How can irrigated agriculture adapt to climate change? Insights from the Guadiana Basin in Spain. *Regional Environmental Change*, **16(1)**, 59.

Vaughan, C. and S. Dessai, 2014: Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *WIREs Climate Change*, **5(5)**, 587-603, doi:10.1002/wcc.290.

Vaughan, C., L. Buja, A. Kruczkiewicz, and L. Goddard, 2016: Identifying research priorities to advance climate services. *Climate Services*, **4**, 65-74, doi:10.1016/j.cliser.2016.11.004.

Vaughan, C. et al., 2018: Surveying climate services: What can we learn from a bird's eye view? *Weather, Climate, and Society*, WCAS-D-17-0030.1, doi:10.1175/WCAS-D-17-0030.1.

Vaughan, N.E. and C. Gough, 2016: Expert assessment concludes negative emissions scenarios may not deliver. *Environmental Research Letters*, **11(9)**, 095003, doi:10.1088/1748-9326/11/9/095003.

Vaughan, N.E. et al., 2018: Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios. *Environmental Research Letters*, **13(4)**, 044014, doi:10.1088/1748-9326/aaaa02.

Veldman, J.W. et al., 2015: Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. *BioScience*, **65(10)**, 1011-1018, doi:10.1093/biosci/biv118.

Venot, J.–P. et al., 2014: Beyond the promises of technology: a review of the discourses and actors who make drip irrigation. *Irrigation and Drainage*, **63(2)**, 186-194, doi:10.1002/ird.1839.

Venter, M., O. Venter, S. Laurance, and M. Bird, 2012: Recarbonization of the Humid Tropics. In: *Recarbonization of the Biosphere: Ecosystems and the Global Carbon Cycle* [Lal, R., K. Lorenz, R.F. Hüttl, B.U. Schneider, and J. von Braun (eds.)]. Springer Netherlands, Dordrecht, pp. 229-252.

Verchot, L.V. et al., 2007: Climate change: Linking adaptation and mitigation through agroforestry. *Mitigation and Adaptation Strategies for Global Change*, **12(5)**, 901-918, doi:10.1007/s11027-007-9105-6.

Verguet, S. et al., 2015: Health gains and financial risk protection afforded by public financing of selected interventions in Ethiopia: an extended cost-effectiveness analysis. *The Lancet Global Health*, **3(5)**, 288-296, doi:10.1016/S2214-109X(14)70346-8.

Vesnic-Alujevic, L., M. Breitegger, and G. Pereira, 2016: What smart grids tell about innovation narratives in the European Union: Hopes, imaginaries and policy. *Energy Research & Social Science*, **12**, 16-26, doi:10.1016/j.erss.2015.11.011.

Vierros, M., 2017: Communities and blue carbon: the role of traditional management systems in providing benefits for carbon storage, biodiversity conservation and livelihoods. *Climatic Change*, **140(1)**, 89-100, doi:10.1007/s10584-013-0920-3.

Viger, M., R.D. Hancock, F. Miglietta, and G. Taylor, 2015: More plant growth but less plant defence? First global gene expression data for plants grown in soil amended with biochar. *GCB Bioenergy*, **7(4)**, 658-672, doi:10.1111/gcbb.12182.

Villarroel Walker, R., M.B. Beck, J.W. Hall, R.J. Dawson, and O. Heidrich, 2014: The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. *Journal of Environmental Management*, **141**, 104-115, doi:10.1016/j.jenvman.2014.01.054.

Vimmerstedt, L.J., B.W. Bush, D.D. Hsu, D. Inman, and S.O. Peterson, 2015: Maturation of biomass-to-biofuels conversion technology pathways for rapid expansion of biofuels production: A system dynamics perspective. *Biofuels, Bioproducts and Biorefining*, **9(2)**, 158-176, doi:10.1002/bbb.1515.

Vincent, K., A.J. Dougill, J.L. Dixon, L.C. Stringer, and T. Cull, 2015: Identifying climate services needs for national planning: insights from Malawi. *Climate Policy*, **3062(August)**, 1-14, doi:10.1080/14693062.2015.1075374.

Vincent, S., M. Radhakrishnan, L. Hayde, and A. Pathirana, 2017: Enhancing the Economic Value of Large Investments in Sustainable Drainage Systems (SuDS) through Inclusion of Ecosystems Services Benefits. *Water*, **9(11)**, 841, doi:10.3390/w9110841.

Vinke-de Kruijf, J. and C. Pahl-Wostl, 2016: A multi-level perspective on learning about climate change adaptation through international cooperation. *Environmental Science & Policy*, **66**, 242-249, doi:10.1016/j.envsci.2016.07.004.

Virkkala, R., J. Pöyry, R.K. Heikkinen, A. Lehikoinen, and J. Valkama, 2014: Protected areas alleviate climate change effects on northern bird species of conservation concern. *Ecology and Evolution*, **4(15)**, 2991-3003, doi:10.1002/ece3.1162.

Vivoda, V. and G. Graetz, 2015: Nuclear Policy and Regulation in Japan after Fukushima: Navigating the Crisis. *Journal of Contemporary Asia*, **45(3)**, 490-509, doi:10.1080/00472336.2014.981283.

Vochozka, M., A. Maroušková, J. Váchal, and J. Straková, 2016: The economic impact of biochar use in Central Europe. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, **38(16)**, 2390-2396, doi:10.1080/15567036.2015.1072600.

Voormolen, J.A., H.M. Junginger, and W.G.J.H.M. van Sark, 2016: Unravelling historical cost developments of offshore wind energy in Europe. *Energy Policy*, **88(88)**, 435-444, doi:10.1016/j.enpol.2015.10.047.

Voskamp, I.M. and F.H.M. Van de Ven, 2015: Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events. *Building and Environment*, **83**, 159-167, doi:10.1016/j.buildenv.2014.07.018.

Vousdoukas, M.I., E. Voukouvalas, A. Annunziato, A. Giardino, and L. Feyen, 2016: Projections of extreme storm surge levels along Europe. *Climate Dynamics*, **47(9)**, 3171-3190, doi:10.1007/s00382-016-3019-5.

Wakabayashi, M., 2013: Voluntary business activities to mitigate climate change: Case studies in Japan. *Energy Policy*, **63**, 1086-1090, doi:https://doi.org/10.1016/j.enpol.2013.08.027.

Waldron, A. et al., 2017: Agroforestry Can Enhance Food Security While Meeting Other Sustainable Development Goals. *Tropical Conservation Science*, **10**, 194008291772066, doi:10.1177/1940082917720667.

Walker, M.E., Z. Lv, and E. Masanet, 2013: Industrial steam systems and the energy-water nexus. *Environmental Science and Technology*, **47(22)**, 13060-13067, doi:10.1021/es403715z.

Wallace, B., 2017: A framework for adapting to climate change risk in coastal cities. *Environmental Hazards*, **16(2)**, 149-164, doi:10.1080/17477891.2017.1298511.

Wallbott, L., 2014: Indigenous Peoples in UN REDD+ Negotiations: "Importing Power" and Lobbying for Rights through Discursive Interplay Management. *Ecology and Society*, **19(1)**, art21, doi:10.5751/ES-06111-190121.

Wallquist, L., S.L.O. Seigo, V.H.M. Visschers, and M. Siegrist, 2012: Public acceptance of CCS system elements: A conjoint measurement. *International Journal of Greenhouse Gas Control***, 6**, 77-83, doi:10.1016/j.ijggc.2011.11.008.

Wamsler, C., E. Brink, and O. Rantala, 2012: Climate Change, Adaptation, and Formal Education: the Role of Schooling for Increasing Societies' Adaptive Capacities in El Salvador and Brazil. *Ecology and Society***, 17(2)**, 2, doi:10.5751/ES-04645-170202.

Wang, C., X. Zheng, W. Cai, X. Gao, and P. Berrill, 2017: Unexpected water impacts of energy-saving measures in the iron and steel sector: Tradeoffs or synergies? *Applied Energy***, 205**, 1119-1127, doi:10.1016/j.apenergy.2017.08.125.

Wang, F.M. et al., 2018: Assessing Stakeholder Needs for Adaptation Tracking. In: *Adaptation Metricsn* [Christiansen, L. (ed.)]. UNEP-DTU Partnership, Copenhagen.

Wang, J., J. O'Donnell, and A.R. Brandt, 2017: Potential solar energy use in the global petroleum sector. *Energy***, 118**, 884-892, doi:https://doi.org/10.1016/j.energy.2016.10.107.

Wang, X. et al., 2016: Taking account of governance: Implications for land-use dynamics, food prices, and trade patterns. *Ecological Economics***, 122(Supplement C)**, 12-24, doi:https://doi.org/10.1016/j.ecolecon.2015.11.018.

Wang, X.J. et al., 2011: A strategy to deal with water crisis under climate change for mainstream in the middle reaches of Yellow River. *Mitigation and Adaptation Strategies for Global Change***, 16(5)**, 555-566, doi:10.1007/s11027-010-9279-1.

Wang, Y., X. Yan, and Z. Wang, 2014: The biogeophysical effects of extreme afforestation in modeling future climate. *Theoretical and Applied Climatology***, 118(3)**, 511-521, doi:10.1007/s00704-013-1085-8.

Watanabe, T., A.C. Byers, M.A. Somos-Valenzuela, and D.C. McKinney, 2016: The Need for Community Involvement in Glacial Lake Field Research: The Case of Imja Glacial Lake, Khumbu, Nepal Himalaya. In: *Climate Change, Glacier Response, and Vegetation Dynamics in the Himalaya: Contributions Toward Future Earth Initiatives* [Singh, R.B., U. Schickhoff, and S. Mal (eds.)]. Springer International Publishing, Cham, pp. 235-250.

Watkins, K., 2015: *Power, people, planet: seizing Africa's energy and climate opportunities*.

Watts, N. et al., 2015: Health and climate change: Policy responses to protect public health. *The Lancet***, 386(10006)**, 1861-1914, doi:10.1016/S0140-6736(15)60854-6.

WBCSD, 2017: *LCTPi Progress Report 2017*. World Business Council for Sustainable Development (WBCSD), Geneva, Switzerland, 47 pp.

Webber, S., 2017: Circulating climate services: Commercializing science for climate change adaptation in Pacific Islands. *Geoforum***, 85(July)**, 82-91.

Webber, S. and S.D. Donner, 2017: Climate service warnings: cautions about commercializing climate science for adaptation in the developing world. *Wiley Interdisciplinary Reviews: Climate Change***, 8(1)**, e424, doi:10.1002/wcc.424.

Webster, A.J. and R.H. Clarke, 2017: Insurance companies should collect a carbon levy. *Nature***, 549(7671)**, 152-154, doi:10.1038/549152a.

WEC, 2016: *Wind 2016, London, United Kingdom: WEC*. World Energy Council (WEC), London, United Kingdom, 71 pp.

Wee, B., 2015: Peak car: The first signs of a shift towards ICT-based activities replacing travel? A discussion paper. *Transport Policy***, 42**, 1-3, doi:10.1016/j.tranpol.2015.04.002.

Wehkamp, J., N. Koch, S. Lübbers, and S. Fuss, 2018a: Governance and deforestation - a meta-analysis in economics. *Ecological Economics***, 144**, 214-227, doi:10.1016/j.ecolecon.2017.07.030.

Wehkamp, J. et al., 2018b: Accounting for institutional capacity in global forest modeling. *Environmental Modelling & Software* (in press), doi:10.1016/j.envsoft.2018.01.020.

Wei, M., S. Patadia, and D.M. Kammen, 2010: Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy***, 38(2)**, 919-931, doi:https://doi.org/10.1016/j.enpol.2009.10.044.

Wei, Y., D. Tang, Y. Ding, and G. Agoramoorthy, 2016: Incorporating water consumption into crop water footprint: A case study of China's South-North Water Diversion Project. *Science of The Total Environment***, 545-546**, 601-608, doi:10.1016/J.SCITOTENV.2015.12.062.

Weindl, I. et al., 2015: Livestock in a changing climate: production system transitions as an adaptation strategy for agriculture. *Environmental Research Letters***, 10(9)**, 94021.

Weinhofer, G. and T. Busch, 2013: Corporate Strategies for Managing Climate Risks. *Business Strategy and the Environment***, 22(2)**, 121-144, doi:10.1002/bse.1744.

Weisse, R. et al., 2015: Climate services for marine applications in Europe. *Earth Perspectives***, 2(1)**, 3, doi:10.1186/s40322-015-0029-0.

Weldegebriel, Z.B. and M. Prowse, 2013: Climate-Change Adaptation in Ethiopia: To What Extent Does Social Protection Influence Livelihood Diversification? *Development Policy Review*, **31**, o35-o56, doi:10.1111/dpr.12038.

Weldu, Y.W., G. Assefa, and O. Jolliet, 2017: Life cycle human health and ecotoxicological impacts assessment of electricity production from wood biomass compared to coal fuel. *Applied Energy*, **187**, 564-574, doi:10.1016/J.APENERGY.2016.11.101.

Well, M. and A. Carrapatoso, 2017: REDD+ finance: policy making in the context of fragmented institutions. *Climate Policy*, **17(6)**, 687-707, doi:10.1080/14693062.2016.1202096.

Wellesley, L., C. Happer, and A. Froggatt, 2015: *Changing Climate, Changing Diets Pathways to Lower Meat Consumption*. Chatham House: The Royal Institute of International Affairs, 64 pp.

Wells, L., B. Rismanchi, and L. Aye, 2018: A review of Net Zero Energy Buildings with reflections on the Australian context. *Energy and Buildings*, **158**, 616-628, doi:10.1016/j.enbuild.2017.10.055.

Wernberg, T. et al., 2016: Climate-driven regime shift of a temperate marine ecosystem. *Science*, **353(6295)**, 169-172, doi:10.1126/science.aad8745.

Wescott, A., 2010: Facing up to Rising sea-LeveLs: RetReat? DeFenD? attacK? .

Wesseling, J.H. et al., 2017: The transition of energy intensive processing industries towards deep decarbonization: Characteristics and implications for future research. *Renewable and Sustainable Energy Reviews*, **79(Supplement C)**, 1303-1313, doi:10.1016/j.rser.2017.05.156.

West, P.C. et al., 2014: Food Security and the Environment. *Science*, **345(6194)**, 325-328.

Westengen, O.T., P. Nyanga, D. Chibamba, M. Guillen-Royo, and D. Banik, 2018: A climate for commerce: the political agronomy of conservation agriculture in Zambia. *Agriculture and Human Values*, **35(1)**, 255-268, doi:10.1007/s10460-017-9820-x.

Westhoek, H. et al., 2014: Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change*, **26(1)**, 196-205, doi:10.1016/j.gloenvcha.2014.02.004.

Wheatley, S., B.K. Sovacool, and D. Sornette, 2016: Reassessing the safety of nuclear power. *Energy Research & Social Science*, **15**, 96-100, doi:10.1016/j.erss.2015.12.026.

White, C.J. et al., 2017: Potential applications of subseasonal-to-seasonal (S2S) predictions. *Meteorological Applications*, doi:10.1002/met.1654.

White, R., J. Turpie, and G.L. Letley, 2017: *Greening Africa's Cities: Enhancing the Relationship between Urbanization, Environmental Assets, and Ecosystem Services*. 56 pp.

Whitelegg, J., 2016: World transport Policy and Practice Special Edition: Outputs from EU Evidence Project. *World transport Policy and Practice*, **22.1(2)**, 1-226.

Whitman, T. and J. Lehmann, 2009: Biochar-One way forward for soil carbon in offset mechanisms in Africa? *Environmental Science & Policy*, **12(7)**, 1024-1027, doi:10.1016/J.ENVSCI.2009.07.013.

WHO, 2011: *Preliminary dose estimation from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami*. 52 pp.

WHO, 2015: *Lessons learned on health adaptation to climate variability and change: experiences across low- and middle-income countries*.

Wicke, B., E. Smeets, A. Tabeau, J. Hilbert, and A. Faaij, 2009: Macroeconomic impacts of bioenergy production on surplus agricultural land-A case study of Argentina. *Renewable and Sustainable Energy Reviews*, **13(9)**, 2463-2473, doi:10.1016/J.RSER.2009.05.010.

Wijaya, S., M. Imran, and J. McNeill, 2017: Multi-level policy tensions in Bus Rapid Transit (BRT) development in low-income Asian cities. *Transportation Research Procedia*, **25**, 5104-5120, doi:10.1016/j.trpro.2018.02.040.

Wiktorowicz, J. et al., 2018: WGV: An Australian Urban Precinct Case Study to Demonstrate the 1.5 °C Agenda Including Multiple SDGs. *Urban Planning*, **3(2)**, 64, doi:10.17645/up.v3i2.1245.

Wilhite, D.A., M.V.K. Sivakumar, and R. Pulwarty, 2014: Managing drought risk in a changing climate: The role of national drought policy. *Weather and Climate Extremes*, **3**, 4-13, doi:10.1016/j.wace.2014.01.002.

Wilkinson, E., L. Schipper, C. Simonet, and Z. Kubik, 2016: Climate change, migration and the 2030 Agenda for Sustainable Development. *London: Overseas Development Institute (ODI)*.

Williams, A.T., N. Rangel-Buitrago, E. Pranzini, and G. Anfuso, 2018: The management of coastal erosion. *Ocean & Coastal Management*, **156**, 4-20, doi:10.1016/j.ocecoaman.2017.03.022.

Williams, P. et al., 2017: Community-based observing networks and systems in the Arctic: Human perceptions of environmental change and instrument-derived data. *Regional Environmental Change*, doi:10.1007/s10113-017-1220-7.

Williamson, P., 2016: Emissions reduction: Scrutinize CO_2 removal methods. *Nature*, **530(153)**, 5-7, doi:10.1038/530153a.

Wilmsen, B. and M. Webber, 2015: What can we learn from the practice of development-forced displacement and resettlement for organised resettlements in response to climate change? *Geoforum*, **58**, 76-85, doi:10.1016/j.geoforum.2014.10.016.

Wilson, S.A. et al., 2009: Carbon Dioxide Fixation within Mine Wastes of Ultramafic-Hosted Ore Deposits: Examples from the Clinton Creek and Cassiar Chrysotile Deposits, Canada. *Economic Geology*, **104(1)**, 95-112.

Win, K.T. et al., 2015: Effects of water saving irrigation and rice variety on greenhouse gas emissions and water use efficiency in a paddy field fertilized with anaerobically digested pig slurry. *Paddy and Water Environment*, **13(1)**, 51-60, doi:10.1007/s10333-013-0406-y.

Winjum, J.K., R.K. Dixon, and P.E. Schroeder, 1992: Estimating the global potential of forest and agroforest management practices to sequester carbon. *Water, Air, & Soil Pollution*, **64(1-2)**, 213-227, doi:10.1007/BF00477103.

Winjum, J.K., R.K. Dixon, and P.E. Schroeder, 1993: Forest management and carbon storage: An analysis of 12 key forest nations. *Water, Air, and Soil Pollution*, **70(1)**, 239-257, doi:10.1007/BF01105000.

Winsten, J., S. Walker, S. Brown, and S. Grimland, 2011: Estimating carbon supply curves from afforestation of agricultural land in the Northeastern U.S.. *Mitigation and Adaptation Strategies for Global Change*, **16(8)**, 925-942, doi:10.1007/s11027-011-9303-0.

Winward, J., P. Schiellerup, and B. Boardman, 1998: *Cool Labels: the first three years of the European Energy Label*.

Wirasingha, S.G., N. Schofield, and A. Emadi, 2008: Plug-in hybrid electric vehicle developments in the US: Trends, barriers, and economic feasibility. *IEEE Vehicle Power and Propulsion Conference*, 1-8, doi:10.1109/VPPC.2008.4677702.

Wise, R.M. et al., 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, **28**, 325-336, doi:10.1016/J.GLOENVCHA.2013.12.002.

WMO, 2015: *Valuing Weather and Climate: Economic Assessment of Meteorological and Hydrological Services*. WMO-No. 1153, World Meteorological Organization (WMO), 308 pp.

Wolfrom, L. and M. Yokoi-Arai, 2015: Financial instruments for managing disaster risks related to climate change. *OECD Journal: Financial Market Trends*, **2015(1)**, 25-47.

Wolshon, B., V. Dixit, and J. Renne, 2013: Special issue on interdisciplinary and multimodal nature of evacuations: Nexus of research and practice. .

Wood, S.A., A.S. Jina, M. Jain, P. Kristjanson, and R.S. DeFries, 2014: Smallholder farmer cropping decisions related to climate variability across multiple regions. *Global Environmental Change*, **25**, 163-172, doi:10.1016/j.gloenvcha.2013.12.011.

Woodcock, J. et al., 2009: Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. *The Lancet*, **374(9705)**, 1930-1943, doi:10.1016/S0140-6736(09)61714-1.

Woodruff, S.C. and M. Stults, 2016: Numerous strategies but limited implementation guidance in US local adaptation plans. *Nature Climate Change*, **6(8)**, 796-802, doi:10.1038/nclimate3012.

Woolf, D., D. Solomon, and J. Lehmann, 2018: Land restoration in food security programmes: synergies with climate change mitigation. *Climate Policy*, 1-11, doi:10.1080/14693062.2018.1427537.

Woolf, D., J.E. Amonette, A. Street-Perrott, J. Lehmann, and S. Joseph, 2010: Sustainable bio-char to mitigate global climate change. *Nature Communications*, **1(56)**, doi:doi:10.1038/ncomms1053.

World Bank, 2017: *Pacific Possible: Long-term Economic Opportunities and Challenges for Pacific Island Countries*. World Bank, Washington, DC.

World Bank, 2018: *Groundswell: Preparing for Internal Climate Migration*. World Bank.

Worrell, E., L. Bernstein, J. Roy, L. Price, and J. Harnisch, 2008: Industrial energy efficiency and climate change mitigation. *Energy Efficiency*, **2(2)**, 109, doi:10.1007/s12053-008-9032-8.

Wright, H. et al., 2014: Farmers, food and climate change: ensuring community-based adaptation is mainstreamed into agricultural programmes. *Climate and Development*, **6(4)**, 318-328, doi:10.1080/17565529.2014.965654.

Wright, M.J., D.A.H. Teagle, and P.M. Feetham, 2014: A quantitative evaluation of the public response to climate engineering. *Nature Climate Change*, **4(2)**, 106-110, doi:10.1038/nclimate2087.

Wu, Y., 2017: Public acceptance of constructing coastal/inland nuclear power plants in post-Fukushima China. *Energy Policy*, **101**, 484-491, doi:10.1016/j.enpol.2016.11.008.

Wylie, L., A.E. Sutton-Grier, and A. Moore, 2016: Keys to successful blue carbon projects: Lessons learned from global case studies. *Marine Policy*, **65**, 76-84, doi:10.1016/J.MARPOL.2015.12.020.

Xiao, J., W. Fan, Y. Deng, S. Li, and P. Yan, 2016: Nurses' knowledge and attitudes regarding potential impacts of climate change on public health in central of China. *International Journal of Nursing Sciences*, **3(2)**, 158-161, doi:https://doi.org/10.1016/j.ijnss.2016.04.002.

Xie, J. et al., 2017: An integrated assessment of urban flooding mitigation strategies for robust decision making. *Environmental Modelling & Software*, **95(Supplement C)**, 143-155, doi:10.1016/j.envsoft.2017.06.027.

Xiong, Y., U. Krogmann, G. Mainelis, L.A. Rodenburg, and C.J. Andrews, 2015: Indoor air quality in green buildings: A case-study in a residential high-rise building in the northeastern United States. *Journal of Environmental Science and Health, Part A*, **50(3)**, 225-242, doi:10.1080/10934529.2015.981101.

Xue, X. et al., 2015: Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches. *Water Research*, **77**, 155-169, doi:10.1016/j.watres.2015.03.017.

Yamamoto, H., J. Fujino, and K. Yamaji, 2001: Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model. *Biomass and Bioenergy*, **21(3)**, 185-203, doi:10.1016/S0961-9534(01)00025-3.

Yamamoto, L., D.A. Serraglio, and F.S. Cavedon-Capdeville, 2017: Human mobility in the context of climate change and disasters: a South American approach. *International Journal of Climate Change Strategies and Management*, IJCCSM-03-2017-0069, doi:10.1108/IJCCSM-03-2017-0069.

Yang, Y.C.E., S. Wi, P.A. Ray, C.M. Brown, and A.F. Khalil, 2016: The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories. *Global Environmental Change*, **37**, 16-30, doi:10.1016/j.gloenvcha.2016.01.002.

Yangka, D. and P. Newman, 2018: Bhutan: Can the 1.5 °C Agenda Be Integrated with Growth in Wealth and Happiness? *Urban Planning*, **3(2)**, 94, doi:10.17645/up.v3i2.1250.

Ye, Y. et al., 2018: Low-Carbon Transportation Oriented Urban Spatial Structure: Theory, Model and Case Study. *Sustainability*, **10(1)**, 19-34, doi:10.3390/su10010019.

Yemshanov, D., D.W. McKenney, T. Hatton, and G. Fox, 2005: Investment Attractiveness of Afforestation in Canada Inclusive of Carbon Sequestration Benefits. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, **53(4)**, 307-323, doi:10.1111/j.1744-7976.2005.00021.x.

Yu, S. et al., 2017: Improving building energy efficiency in India: State-level analysis of building energy efficiency policies. *Energy Policy*, **110**, 331-341, doi:10.1016/j.enpol.2017.07.013.

Yu, X. and P.W. Gillis, 2014: Do Hazard Mitigation and Preparedness Reduce Physical Damage to Businesses in Disasters? Critical Role of Business Disaster Planning. *Natural Hazards Review*, **15(3)**, 4014007, doi:10.1061/(ASCE)NH.1527-6996.0000137.

Zanchi, G., N. Pena, and N. Bird, 2012: Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, **4(6)**, 761-772, doi:10.1111/j.1757-1707.2011.01149.x.

Zeman, F., 2014: Reducing the Cost of Ca-Based Direct Air Capture of CO 2. *Environmental Science & Technology*, **48(19)**, 11730-11735, doi:10.1021/es502887y.

Zeman, F.S., 2003: An investigation into the feasibility of capturing carbon dioxide directly from the atmosphere. In: *Proceedings of the 2nd Annual Conference on Carbon Sequestration*. Exchange Monitor.

Zha, D. and N. Ding, 2015: Threshold characteristic of energy efficiency on substitution between energy and non-energy factors. *Economic Modelling*, **46**, 180-187, doi:https://doi.org/10.1016/j.econmod.2014.12.021.

Zhang, C. and J. Yan, 2015: CDM's influence on technology transfers: A study of the implemented clean development mechanism projects in China. *Applied Energy*, **158**, 355-365, doi:10.1016/j.apenergy.2015.06.072.

Zhang, H., 2016: Towards global green shipping: the development of international regulations on reduction of GHG emissions from ships. *International Environmental Agreements: Politics, Law and Economics*, **16(4)**, 561-577, doi:10.1007/s10784-014-9270-5.

Zhang, K. et al., 2012: The role of mangroves in attenuating storm surges. *Estuarine, Coastal and Shelf Science*, **102-103**, 11-23, doi:10.1016/j.ecss.2012.02.021.

Zhang, R., K. Matsushima, and K. Kobayashi, 2018: Can land use planning help mitigate transport-related carbon emissions? A case of Changzhou. *Land Use Policy*, **74**, 32-40, doi:10.1016/j.landusepol.2017.04.025.

Zhang, S., E. Worrell, and W. Crijns-Graus, 2015: Evaluating co-benefits of energy efficiency and air pollution abatement in China's cement industry. *Applied Energy*, **147**, 192-213, doi:https://doi.org/10.1016/j.apenergy.2015.02.081.

Zhang, S., E. Worrell, W. Crijns-Graus, F. Wagner, and J. Cofala, 2014: Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry. *Energy*, **78**, 333-345, doi:https://doi.org/10.1016/j.energy.2014.10.018.

Zhang, S., H. Ren, W. Zhou, Y. Yu, and C. Chen, 2018: Assessing air pollution abatement co-benefits of energy efficiency improvement in cement industry: A city level analysis. *Journal of Cleaner Production*, **185**, 761-771, doi:https://doi.org/10.1016/j.jclepro.2018.02.293.

Zhang, W., H. Liu, C. Sun, T.C. Drage, and C.E. Snape, 2014: Capturing CO_2 from ambient air using a polyethyleneimine-silica adsorbent in fluidized beds. *Chemical Engineering Science*, **116**, 306-316, doi:10.1016/J.CES.2014.05.018.

Zhang, Y., Y. Yu, and B. Zou, 2011: Analyzing public awareness and acceptance of alternative fuel vehicles in China: The case of EV. *Energy Policy*, **39(11)**, 7015-7024, doi:10.1016/j.enpol.2011.07.055.

Zheng, B. and J. Xu, 2014: Carbon Capture and Storage Development Trends from a Techno-Paradigm Perspective. *Energies*, **7(8)**, 5221-5250, doi:10.3390/en7085221.

Zheng, Y., Z. Hu, J. Wang, and Q. Wen, 2014: IRSP (integrated resource strategic planning) with interconnected smart grids in integrating renewable energy and implementing DSM (demand side management) in China. *Energy*, **76**, 863-874, doi:10.1016/j.energy.2014.08.087.

Zhou, Y., M. Ma, F. Kong, K. Wang, and J. Bi, 2018: Capturing the co-benefits of energy efficiency in China - A perspective from the water-energy nexus. *Resources, Conservation and Recycling*, **132**, 93-101, doi:10.1016/j.resconrec.2018.01.019.

Ziervogel, G. and L. Joubert, 2014: New ways to deal with Cape town's flooded communities. *Water Wheel*, **13(5)**, 24-25.

Ziervogel, G., A. Cowen, and J. Ziniades, 2016a: Moving from Adaptive to Transformative Capacity: Building Foundations for Inclusive, Thriving, and Regenerative Urban Settlements. *Sustainability*, **8(9)**, 955, doi:10.3390/su8090955.

Ziervogel, G., J. Waddell, W. Smit, and A. Taylor, 2016b: Flooding in Cape Town's informal settlements: barriers to collaborative urban risk governance. *South African Geographical Journal*, **98(1)**, 1-20, doi:10.1080/03736245.2014.924867.

Ziervogel, G. et al., 2017: Inserting rights and justice into urban resilience: a focus on everyday risk. *Environment and Urbanization*, **29(1)**, 123-138, doi:10.1177/0956247816686905.

Zimmermann, M. et al., 2012: Rapid degradation of pyrogenic carbon. *Global Change Biology*, **18(11)**, 3306-3316, doi:10.1111/j.1365-2486.2012.02796.x.

Zinda, J.A., C.J. Trac, D. Zhai, and S. Harrell, 2017: Dual-function forests in the returning farmland to forest program and the flexibility of environmental policy in China. *Geoforum*, **78**, 119-132, doi:10.1016/J.GEOFORUM.2016.03.012.

Zinia, N.J. and P. McShane, 2018: Ecosystem services management: An evaluation of green adaptations for urban development in Dhaka, Bangladesh. *Landscape and Urban Planning*, **173**, 23-32, doi:10.1016/j.landurbplan.2018.01.008.

Zogg, R. et al., 2009: *Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances*. Report for DOE Office of Energy Efficiency and Renewable Energy Building Technologies Program.

Zomer, R.J., D.A. Bossio, R. Sommer, and L. Verchot, 2017: Global Sequestration Potential of Increased Organic Carbon in Cropland Soils. *Scientific Reports*, **7(1)**, 1-8, doi:10.1038/s41598-017-15794-8.

Zou, X., Y.– Li, Q. Gao, and Y. Wan, 2012: How water saving irrigation contributes to climate change resilience-a case study of practices in China. *Mitigation and Adaptation Strategies for Global Change*, **17(2)**, 111-132, doi:10.1007/s11027-011-9316-8.

Zubelzu, S., R. Alvarez, and A. Hernández, 2015: Methodology to calculate the carbon footprint of household land use in the urban planning stage. *Land Use Policy*, **48**, 223-235, doi:10.1016/j.landusepol.2015.06.005.

Żukiewicz-Sobczak, W. et al., 2014: Obesity and poverty paradox in developed countries. *Annals of Agricultural and Environmental Medicine*, **21(3)**, 590-594, doi:10.5604/12321966.1120608.

Chapter 5: Sustainable Development, Poverty Eradication and Reducing Inequalities

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Where reference is made to Table 5.3, this is available as a supplementary pdf (file Chapter 5 – Table 5.3)

Executive Summary

This chapter takes sustainable development as the starting point and focus for analysis. It considers the broad and multifaceted bi-directional interplay between sustainable development, including its focus on eradicating poverty and reducing inequality in their multidimensional aspects, and climate actions in a 1.5°C warmer world. These fundamental connections are embedded in the Sustainable Development Goals (SDGs). The chapter also examines synergies and trade-offs of adaptation and mitigation options with sustainable development and the SDGs and offers insights into possible pathways, especially climate-resilient development pathways toward a 1.5°C warmer world.

Sustainable Development, Poverty, and Inequality in a 1.5°C Warmer World

Limiting global warming to 1.5°C rather than 2°C would make it markedly easier to achieve many aspects of sustainable development, with greater potential to eradicate poverty and reduce inequalities (*medium evidence, high agreement*). Impacts avoided with the lower temperature limit could reduce the number of people exposed to climate risks and vulnerable to poverty by 62 to 457 million, and lessen the risks of poor people to experience food and water insecurity, adverse health impacts, and economic losses, particularly in regions that already face development challenges (*medium evidence, medium agreement*) {5.2.2, 5.2.3}. Avoided impacts between 1.5°C and 2°C warming would also make it easier to achieve certain SDGs, such as those that relate to poverty, hunger, health, water and sanitation, cities, and ecosystems (SDGs 1, 2, 3, 6, 12, 14, and 15) (*medium evidence, high agreement*) {5.2.3, Table 5.3 available as a supplementary pdf }.

Compared to current conditions, 1.5°C of global warming would nonetheless pose heightened risks to eradicating poverty, reducing inequalities and ensuring human and ecosystem well-being (*medium evidence, high agreement*). Warming of 1.5°C is not considered ‘safe’ for most nations, communities, ecosystems and sectors and poses significant risks to natural and human systems as compared to current warming of 1°C (*high confidence*) {Cross-Chapter Box 12 in Chapter 5}. The impacts of 1.5°C would disproportionately affect disadvantaged and vulnerable populations through food insecurity, higher food prices, income losses, lost livelihood opportunities, adverse health impacts, and population displacements (*medium evidence, high agreement*) {5.2.1}. Some of the worst impacts on sustainable development are expected to be felt among agricultural and coastal dependent livelihoods, indigenous people, children and the elderly, poor labourers, poor urban dwellers in African cities, and people and ecosystems in the Arctic and Small Island Developing States (SIDS) (*medium evidence, high agreement*) {5.2.1 Box 5.3, Chapter 3 Box 3.5, Cross-Chapter Box 9 in Chapter 4}.

Climate Adaptation and Sustainable Development

Prioritisation of sustainable development and meeting the SDGs is consistent with efforts to adapt to climate change (*high confidence*). Many strategies for sustainable development enable transformational adaptation for a 1.5°C warmer world, provided attention is paid to reducing poverty in all its forms and to promoting equity and participation in decision-making (*medium evidence, high agreement*). As such, sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations (*high confidence*) {5.3.1}.

Synergies between adaptation strategies and the SDGs are expected to hold true in a 1.5°C warmer world, across sectors and contexts (*medium evidence, medium agreement*). Synergies between adaptation and sustainable development are significant for agriculture and health, advancing SDGs 1 (extreme poverty), 2 (hunger), 3 (healthy lives and well-being), and 6 (clean water) (*robust evidence, medium agreement*) {5.3.2}. Ecosystem- and community-based adaptation, along with the incorporation of indigenous and local knowledge, advances synergies with SDGs 5 (gender equality), 10 (reducing inequalities), and 16 (inclusive societies), as exemplified in drylands and the Arctic (*high evidence, medium agreement*) {5.3.2, Box 5.1, Cross-Chapter Box 10 in Chapter 4}.

Adaptation strategies can result in trade-offs with and among the SDGs (*medium evidence, high agreement*). Strategies that advance one SDG may create negative consequences for other SDGs, for instance SDGs 3 versus 7 (health and energy consumption) and agricultural adaptation and SDG 2 (food security) versus SDGs 3, 5, 6, 10, 14, and 15 (*medium evidence, medium agreement*) {5.3.2}.

Pursuing place-specific adaptation pathways toward a 1.5°C warmer world has the potential for significant positive outcomes for well-being, in countries at all levels of development (*medium evidence, high agreement*). Positive outcomes emerge when adaptation pathways (i) ensure a diversity of adaptation options based on people's values and trade-offs they consider acceptable, (ii) maximise synergies with sustainable development through inclusive, participatory, and deliberative processes, and (iii) facilitate equitable transformation. Yet, such pathways would be difficult to achieve without redistributive measures to overcome path dependencies, uneven power structures, and entrenched social inequalities (*medium evidence, high agreement*) {5.3.3}.

Mitigation and Sustainable Development

The deployment of mitigation options consistent with 1.5°C pathways leads to multiple synergies across a range of sustainable development dimensions. At the same time, the rapid pace and magnitude of change that would be required to limit warming to 1.5°C, if not carefully managed, would lead to trade-offs with some sustainable development dimensions (*high confidence*). The number of synergies between mitigation response options and sustainable development exceeds the number of trade-offs in energy demand and supply sectors, Agriculture, Forestry and Other Land Use (AFOLU) and for oceans (*very high confidence*) {Figure 5.3, Table 5.3 available as a supplementary pdf }. 1.5°C pathways indicate robust synergies particularly for the SDGs 3 (health), 7 (energy), 12 (responsible consumption and production), and 14 (oceans) (*very high confidence*) {5.4.2, Figure 5.4}. For SDGs 1 (poverty), 2 (hunger), 6 (water), and 7 (energy), there is a risk of trade-offs or negative side-effects from stringent mitigation actions compatible with 1.5°C (*medium evidence, high agreement*) {5.4.2}.

Appropriately designed mitigation actions to reduce energy demand can advance multiple SDGs simultaneously. Pathways compatible with 1.5°C that feature low energy demand show the most pronounced synergies and the lowest number of trade-offs with respect to sustainable development and the SDGs (*very high confidence*). Accelerating energy efficiency in all sectors has synergies with SDG 7, 9,11, 12, 16, 17 {5.4.1, Figure 5.3, Table 5.2} (*robust evidence, high agreement*). Low demand pathways, which would reduce or completely avoid the reliance on Bioenergy with Carbon Capture and Storage (BECCS) in 1.5°C pathways, would result in significantly reduced pressure on food security, lower food prices, and fewer people at risk of hunger (*medium evidence, high agreement*) {5.4.2, Figure 5.4}.

The impacts of Carbon Dioxide Removal (CDR) options on SDGs depend on the type of options and the scale of deployment (*high confidence*). If poorly implemented, CDR options such as bioenergy, BECCS and AFOLU would lead to trade-offs. Appropriate design and implementation requires considering local people´s needs, biodiversity, and other sustainable development dimensions (*very high confidence*) {5.4.1.3, Cross-Chapter Box 7 in Chapter 3}.

The design of the mitigation portfolios and policy instruments to limit warming to 1.5°C will largely determine the overall synergies and trade-offs between mitigation and sustainable development (*very high confidence*). Redistributive policies that shield the poor and vulnerable can resolve trade-offs for a range of SDGs (*medium evidence, high agreement*). Individual mitigation options are associated with both positive and negative interactions with the SDGs (*very high confidence*) {5.4.1}. However, appropriate choices across the mitigation portfolio can help to maximize positive side-effects while minimizing negative side-effects (*high confidence*) {5.4.2, 5.5.2}. Investment needs for complementary policies resolving trade-offs with a range of SDGs are only a small fraction of the overall mitigation investments in 1.5°C pathways (*medium evidence, high agreement*) {5.4.2, Figure 5.5}. Integration of mitigation with adaptation and sustainable development compatible with 1.5°C requires a systems perspective (*high confidence*) {5.4.2, 5.5.2}.

Mitigation measures consistent with 1.5°C create high risks for sustainable development in countries with high dependency on fossil fuels for revenue and employment generation (*high confidence*). These risks are caused by the reduction of global demand affecting mining activity and export revenues and challenges to rapidly decrease high carbon intensity of the domestic economy (*robust evidence, high agreement*) {5.4.1.2, Box 5.2}. Targeted policies that promote diversification of the economy and the energy sector could ease this transition (*medium evidence, high agreement*) {5.4.1.2, Box 5.2}.

Sustainable Development Pathways to 1.5°C

Sustainable development broadly supports and often enables the fundamental societal and systems transformations that would be required for limiting warming to 1.5°C (*high confidence*). Simulated pathways that feature the most sustainable worlds (e.g., Shared Socioeconomic Pathways (SSP)1) are associated with relatively lower mitigation and adaptation challenges and limit warming to 1.5°C at comparatively lower mitigation costs. In contrast, development pathways with high fragmentation, inequality and poverty (e.g., SSP3) are associated with comparatively higher mitigation and adaptation challenges. In such pathways, it is not possible to limit warming to 1.5°C for the vast majority of the integrated assessment models (*medium evidence, high agreement*) {5.5.2}. In all SSPs, mitigation costs substantially increase in 1.5°C pathways compared to 2°C pathways. No pathway in the literature integrates or achieves all 17 SDGs (*high confidence*) {5.5.2}. Real-world experiences at the project level show that the actual integration between adaptation, mitigation, and sustainable development is challenging as it requires reconciling trade-offs across sectors and spatial scales (*very high confidence*) {5.5.1}.

Without societal transformation and rapid implementation of ambitious greenhouse gas reduction measures, pathways to limiting warming to 1.5°C and achieving sustainable development will be exceedingly difficult, if not impossible, to achieve (*high confidence*). The potential for pursuing such pathways differs between and within nations and regions, due to different development trajectories, opportunities, and challenges (*very high confidence*) {5.5.3.2, Figure 5.1}. Limiting warming to 1.5°C would require all countries and non-state actors to strengthen their contributions without delay. This could be achieved through sharing of efforts based on bolder and more committed cooperation, with support for those with the least capacity to adapt, mitigate, and transform (*medium evidence, high agreement*) {5.5.3.1, 5.5.3.2}. Current efforts toward reconciling low-carbon trajectories and reducing inequalities, including those that avoid difficult trade-offs associated with transformation, are partially successful yet demonstrate notable obstacles (*medium evidence, medium agreement*) {5.5.3.3 Box 5.3, Cross-Chapter Box 13 in this Chapter}.

Social justice and equity are core aspects of climate-resilient development pathways for transformational social change. Addressing challenges and widening opportunities between and within countries and communities would be necessary to achieve sustainable development and limit warming to 1.5°C, without making the poor and disadvantaged worse off (*high confidence*). Identifying and navigating inclusive and socially acceptable pathways toward low-carbon, climate-resilient futures is a challenging yet important endeavour, fraught with moral, practical, and political difficulties and inevitable trade-offs (*very high confidence*) {5.5.2, 5.5.3.3 Box 5.3}. It entails deliberation and problem-solving processes to negotiate societal values, well-being, risks, and resilience and determine what is desirable and fair, and to whom (*medium evidence, high agreement*). Pathways that encompass joint, iterative planning and transformative visions, for instance in Pacific SIDS like Vanuatu and in urban contexts, show potential for liveable and sustainable futures (*high confidence*) {5.5.3.1, 5.5.3.3, Figure 5.6, Box 5.3, Cross-Chapter Box 13 in this Chapter}.

The fundamental societal and systemic changes to achieve sustainable development, eradicate poverty and reduce inequalities while limiting warming to 1.5°C would require a set of institutional, social, cultural, economic and technological conditions to be met (*high confidence*). The coordination and monitoring of policy actions across sectors and spatial scales is essential to support sustainable development in 1.5°C warmer conditions (*very high confidence*) {5.6.2, Box 5.3}. External funding and technology transfer better support these efforts when they consider recipients' context-specific needs (*medium evidence, high agreement*) {5.6.1}. Inclusive processes can facilitate transformations by ensuring participation, transparency, capacity building, and iterative social learning (*high confidence*) {5.5.3.3, Cross-Chapter Box 13, 5.6.3}. Attention to power asymmetries and unequal opportunities for development, among and within countries is key to adopting 1.5°C-compatible development pathways that benefit all populations (*high confidence*) {5.5.3, 5.6.4, Box 5.3}. Re-examining individual and collective values could help spur urgent, ambitious, and cooperative change (*medium evidence, high agreement*) {5.5.3, 5.6.5}.

5.1 Scope and Delineations

This chapter takes sustainable development as the starting point and focus for analysis, considering the broader bi-directional interplay and multifaceted interactions between development patterns and climate actions in a 1.5°C warmer world and in the context of eradicating poverty and reducing inequality. It assesses the impacts of keeping temperatures at or below 1.5°C global warming above pre-industrial levels on sustainable development and compares the avoided impacts to 2°C (Section 5.2). It then examines the interactions, synergies and trade-offs of adaptation (Section 5.3) and mitigation (Section 5.4) measures with sustainable development and the Sustainable Development Goals (SDGs). The chapter offers insights into possible pathways toward a 1.5°C warmer world, especially through climate-resilient development pathways providing a comprehensive vision across different contexts (Section 5.5). We also identify the conditions that would be needed to simultaneously achieve sustainable development, poverty eradication, the reduction of inequalities, and the 1.5°C climate objective (Section 5.6).

5.1.1 Sustainable Development, SDGs, Poverty Eradication and Reducing Inequalities

Chapter 1 (see Cross-Chapter Box 4 in Chapter 1) defines sustainable development as ‘development that meets the needs of the present and future generations’ through balancing economic, social and environmental considerations, and then introduces the United Nations (UN) 2030 Agenda for Sustainable Development which sets out 17 ambitious goals for sustainable development for all countries by 2030. These Sustainable Development Goals (SDGs) are: no poverty (SDG 1), zero hunger (SDG 2), good health and well-being (SDG 3), quality education (SDG 4), gender equality (SDG 5), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry, innovation and infrastructure (SDG 9), reduced inequalities (SDG 10), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), climate action (SDG 13), life below water (SDG 14), life on land (SDG 15), peace, justice and strong institutions (SDG 16), and partnerships for the goals (SDG 17).

The IPCC Fifth Assessment Report (AR5) included extensive discussion of links between climate and sustainable development, especially in Chapter 13 (Olsson et al., 2014) and Chapter 20 (Denton et al., 2014) in WGII and Chapter 4 (Fleurbaey et al., 2014) in WGIII. However, the AR5 preceded the 2015 adoption of the SDGs and the literature that argues for their fundamental links to climate (Wright et al., 2015; Salleh, 2016; von Stechow et al., 2016; Hammill and Price-Kelly, 2017; ICSU, 2017; Maupin, 2017; Gomez-Echeverri, 2018).

The SDGs build on efforts under the UN Millennium Development Goals to reduce poverty, hunger and other deprivations. According to the UN, the Millennium Development Goals were successful in reducing poverty and hunger and improving water security (UN, 2015a). However, critics argued that they failed to address within-country disparities, human rights, and key environmental concerns, focused only on developing countries, and had numerous measurement and attribution problems (Langford et al., 2013; Fukuda-Parr et al., 2014). While improvements in water security, slums, and health may have reduced some aspects of climate vulnerability, increases in incomes were linked to rising greenhouse gas (GHG) emissions and thus to a trade-off between development and climate change (Janetos et al., 2012; UN, 2015a; Hubacek et al., 2017).

While the SDGs capture many important aspects of sustainable development, including the explicit goals of poverty eradication and reducing inequality, there are direct connections from climate to other measures of sustainable development including multidimensional poverty, equity, ethics, human security, well-being, and climate-resilient development (Bebbington and Larrinaga, 2014; Robertson, 2014; Redclift and Springett, 2015; Barrington-Leigh, 2016; Helliwell et al., 2018; Kirby and O’Mahony, 2018) (see Glossary). The UN proposes sustainable development as ‘eradicating poverty in all its forms and dimensions, combating inequality within and among countries, preserving the planet, creating sustained, inclusive and sustainable economic growth and fostering social inclusion’ (UN, 2015b). There is *robust evidence* of the links between climate change and poverty (see Chapter 1, Cross-Chapter Box 4). The AR5 concluded with *high confidence* that disruptive levels of climate change would preclude reducing poverty (Denton et al., 2014; Fleurbaey et al., 2014). International organisations have since stated that climate changes ‘undermine the ability of all countries to achieve sustainable development’ (UN, 2015b) and can reverse or erase improvements in living conditions and decades of development (Hallegatte et al., 2016).

Climate warming has unequal impacts on different people and places as a result of differences in regional climate changes, vulnerabilities and impacts, and these differences then result in unequal impacts on sustainable development and poverty (Section 5.2). Responses to climate change also interact in complex ways with goals of poverty reduction. The benefits of adaptation and mitigation projects and funding may accrue to some and not others, responses may be costly and unaffordable to some people and countries, and projects may disadvantage some individuals, groups and development initiatives (Sections 5.3 and 5.4; Cross-Chapter Box 11 in Chapter 4).

5.1.2 Pathways to 1.5°C

Pathways to 1.5°C (see Chapter 1, Cross-Chapter Box 1 in Chapter 1, Glossary) include ambitious reductions in emissions and strategies for adaptation that are transformational, as well as complex interactions with sustainable development, poverty eradication, and reducing inequalities. The AR5 WGII introduced the concept of climate-resilient development pathways (CRDPs) (see Glossary) which combine adaptation and mitigation to reduce climate change and its impacts, and emphasise the importance of addressing structural, intersecting inequalities, marginalisation, and multidimensional poverty to ‘transform […] the development pathways themselves toward greater social and environmental sustainability, equity, resilience, and justice’ (Olsson et al., 2014). This chapter assesses literature on CRDPs relevant to 1.5°C global warming (Section 5.5.3), to understand better the possible societal and systems transformations (see Glossary) that reduce inequality and increase well-being (Figure 5.1). It also summarises the knowledge on conditions to achieve such transformations, including changes in technologies, culture, values, financing, and institutions that support low-carbon and resilient pathways and sustainable development (Section 5.6).

[INSERT FIGURE 5.1 HERE]

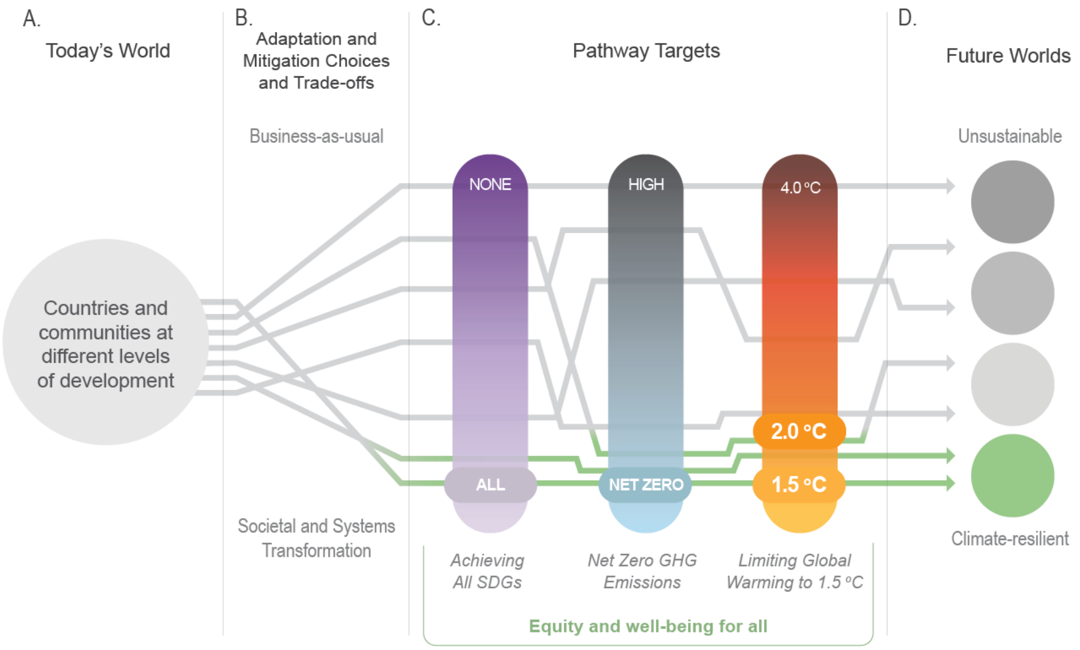

Figure 5.1: Climate-resilient development pathways (CRDPs) (green arrows) between a current world in which countries and commuities exist at different levels of development (A) and future worlds that range from

climate-resilient (bottom) to unsustainable (top) (D). CRDPs involve societal transformation rather than business-as-usual approaches, and all pathways involve adaptation and mitigation choices and trade-offs (B). Pathways that achieve the Sustainable Development Goals by 2030 and beyond, strive for net zero emissions around mid-21st century, and stay within the global 1.5°C warming target by the end of the 21st century, while ensuring equity and well-being for all, are best positioned to achieve climate-resilient futures (C). Overshooting on the path to 1.5°C will make achieving CRDPs and other sustainable trajectories more difficult; yet, the limited literature does not allow meaningful estimates.

5.1.3 Types of evidence

We use a variety of sources of evidence to assess the interactions of sustainable development and the SDGs with the causes, impacts, and responses to climate change of 1.5°C warming. We build on Chapter 3 to assess the sustainable development implications of impacts at 1.5°C and 2°C, and Chapter 4 to examine the implications of response measures. We assess scientific and grey literature, with a post-AR5 focus, and data that evaluate, measure, and model sustainable development-climate links from various perspectives, quantitatively and qualitatively, across scales, and through well documented case studies.

Literature that explicitly links 1.5°C global warming to sustainable development across scales remains scarce; yet, we find relevant insights in many recent publications on climate and development that assess impacts across warming levels, the effects of adaptation and mitigation response measures, and interactions with the SDGs. Relevant evidence also stems from emerging literature on possible pathways, overshoot, and enabling conditions (see Glossary) for integrating sustainable development, poverty eradication, and reducing inequalities in the context of 1.5°C.

5.2 Poverty, Equality, and Equity Implications of a 1.5°C Warmer World

Climate change could lead to significant impacts on extreme poverty by 2030 (Hallegatte et al., 2016; Hallegatte and Rozenberg, 2017). The AR5 concluded, with *very high confidence*, that climate change and climate variability worsen existing poverty and exacerbate inequalities, especially for those disadvantaged by gender, age, race, class, caste, indigeneity and (dis)ability (Olsson et al., 2014). New literature on these links is substantial, showing that the poor will continue to experience climate change severely, and climate change will exacerbate poverty (Fankhauser and Stern, 2016; Hallegatte et al., 2016; O'Neill et al., 2017a; Winsemius et al., 2018) (*very high confidence*). The understanding of regional impacts and risks of 1.5°C global warming and interactions with patterns of societal vulnerability and poverty remains limited. Yet, identifying and addressing poverty and inequality is at the core of staying within a safe and just space for humanity (Raworth, 2017; Bathiany et al., 2018). Building on relevant findings from Chapter 3 (see Section 3.4), this section examines anticipated impacts and risks of 1.5°C and higher warming on sustainable development, poverty, inequality, and equity (see Glossary).

5.2.1 Impacts and Risks of a 1.5°C Warmer World: Implications for Poverty and Livelihoods

Global warming of 1.5°C will have consequences for sustainable development, poverty and inequalities. This includes residual risks, limits to adaptation, and losses and damages (Cross-Chapter Box 12 in this Chapter; see Glossary). Some regions have already experienced a 1.5°C warming with impacts on food and water security, health, and other components of sustainable development (*medium evidence, medium agreement*) (see Chapter 3, Section 3.4). Climate change is also already affecting poorer subsistence communities through decreases in crop production and quality, increases in crop pests and diseases, and disruption to culture (Savo et al., 2016). It disproportionally affects children and the elderly and can increase gender inequality (Kaijser and Kronsell, 2014; Vinyeta et al., 2015; Carter et al., 2016; Hanna and Oliva, 2016; Li et al., 2016).

At 1.5°C warming, compared to current conditions, further negative consequences are expected for poor people, and inequality and vulnerability (*medium evidence, high agreement*). Hallegatte and Rozenberg (2017) report that, by 2030 (roughly approximating a 1.5°C warming), 122 million additional people could experience extreme poverty, based on a 'poverty scenario' of limited socio-economic progress, comparable to the Shared Socioeconomic Pathway (SSP)4 (inequality), mainly due to higher food prices and declining health, with substantial income losses for the poorest 20% across 92 countries. Pretis et al. (2018) estimate negative impacts on economic growth in lower-income countries at 1.5°C warming, despite uncertainties. Impacts are likely to occur simultaneously across livelihood, food, human, water, and ecosystem security (Byers et al., 2018) (*limited evidence, high agreement*), but the literature on interacting and cascading effects remains scarce (Hallegatte et al., 2014; O'Neill et al., 2017b; Reyer et al., 2017a, b).

Chapter 3 outlines future impacts and risks for ecosystems and human systems, many of which could also undermine sustainable development and efforts to eradicate poverty and hunger, and protect health and ecosystems. Chapter 3 findings (see Section 3.5.2.1) suggest increasing Reasons for Concern from moderate to high at a warming of 1.1 to 1.6°C, including for indigenous people, their livelihoods, and ecosystems in the Arctic (O'Neill et al., 2017b). In 2050, based on the Hadley Centre Climate Prediction Model 3 (HadCM3) and the Special Report on Emission Scenarios (SRES) A1b scenario (roughly comparable to 1.5°C warming), 450 million more flood-prone people would be exposed to doubling in flood frequency, and global flood risk would increase substantially (Arnell and Gosling, 2016). For droughts, poor people are expected to be more exposed (85% in population terms) in a warming scenario greater >1.5°C for several countries in Asia and Southern and Western Africa (Winsemius et al., 2018). In urban Africa, a 1.5°C warming could expose many households to water poverty and increased flooding (Pelling et al., 2018). At 1.5ºC warming, fisheries-dependent and coastal livelihoods, of often disadvantaged populations, would suffer from the loss of coral reefs (see Chapter 3, Box 3.4).

Global heat stress is projected to increase in a 1.5°C warmer world and by 2030, compared to 1961-1990, climate change could be responsible for additional annual deaths of 38,000 people from heat stress, particularly among the elderly, and 48,000 from diarrhoea, 60,000 from malaria, and 95,000 from childhood undernutrition (WHO, 2014). Each 1°C increase could reduce work productivity by 1 to 3% for people working outdoors or without air conditioning, typically the poorer segments of the workforce (Park et al., 2015).

The regional variation in the 'warming experience at 1.5°C' (see Chapter 1, Section 1.3.1) is large (see Chapter 3, Section 3.3.2). Declines in crop yields are widely reported for Africa (60% of observations), with serious consequences for subsistence and rain-fed agriculture and food security (Savo et al., 2016). In Bangladesh, by 2050, damages and losses are expected for poor households dependent on freshwater fish stocks due to lack of mobility, limited access to land, and strong reliance on local ecosystems (Dasgupta et al., 2017). Small Island Developing States (SIDS) are expected to experience challenging conditions at 1.5°C warming due to increased risk of internal migration and displacement and limits to adaptation (see Chapter 3, Box 3.5, Cross-Chapter Box 12 in this Chapter). An anticipated decline of marine fisheries of 3 million metric tonnes per degree warming would have serious regional impacts for the Indo-Pacific region and the Arctic (Cheung et al., 2016).

5.2.2 Avoided Impacts of 1.5°C versus 2°C Warming for Poverty and Inequality

Avoided impacts between 1.5°C and 2°C warming are expected to have significant positive implications for sustainable development, and reducing poverty and inequality. Using the SSPs (see Chapter 1, Cross-Chapter Box 1 in Chapter 1; Section 5.5.2), Byers et al. (2018) model the number of people exposed to multi-sector climate risks and vulnerable to poverty (income < $10/day), comparing 2°C and 1.5°C; the respective declines are from 86 million to 24 million for SSP1 (sustainability), from 498 million to 286 million for SSP2 (middle of the road), and from 1220 million to 763 million for SSP3 (regional rivalry), which suggests overall 62-457 million less people exposed and vulnerable at 1.5°C warming. Across the SSPs, the largest populations exposed and vulnerable are in South Asia (Byers et al., 2018). The avoided impacts on poverty at 1.5°C relative to 2°C are projected to depend at least as much or more on development scenarios than on warming (Wiebe et al., 2015; Hallegatte and Rozenberg, 2017).

Limiting warming to 1.5°C is expected to reduce the people exposed to hunger, water stress, and disease in Africa (Clements, 2009). It is also expected to limit the number of poor people exposed to floods and droughts at higher degrees of warming, especially in African and Asian countries (Winsemius et al., 2018). Challenges for poor populations relating to food and water security, clean energy access, and environmental well-being are projected to be less at 1.5°C, particularly for vulnerable people in Africa and Asia (Byers et al., 2018). The overall projected socio-economic losses compared to present day are less at 1.5°C (8% loss of gross domestic product per capita) compared to 2°C (13%), with lower-income countries projected to experience greater losses, which may increase economic inequality between countries (Pretis et al., 2018).

5.2.3 Risks from 1.5°C versus 2°C Global Warming and the Sustainable Development Goals

The risks that can be avoided by limiting global warming to 1.5ºC rather than 2°C have many complex implications for sustainable development (ICSU, 2017; Gomez-Echeverri, 2018). There is *high confidence* that constraining warming to 1.5°C rather than 2°C would reduce risks for unique and threatened ecosystems, safeguarding the services they provide for livelihoods and sustainable development, and making adaptation much easier (O'Neill et al., 2017b), particularly in Central America, the Amazon, South Africa, and Australia (Schleussner et al., 2016; O'Neill et al., 2017b; Reyer et al., 2017b; Bathiany et al., 2018).

In places that already bear disproportionate economic and social challenges to their sustainable development, people will face lower risks at 1.5°C compared to 2°C. These include North Africa and the Levant (less water scarcity), West Africa (less crop loss), South America and South-East Asia (less intense heat), and many other coastal nations and island states (lower sea-level rise, less coral reef loss) (Schleussner et al., 2016; Betts et al., 2018). The risks for food, water, and ecosystems, particularly in subtropical regions such as Central America, and countries such as South Africa and Australia, are expected to be lower at 1.5°C than at 2°C warming (Schleussner et al., 2016). Less people would be exposed to droughts and heat waves and the associated health impacts in countries such as Australia and India (King et al., 2017; Mishra et al., 2017).

Limiting warming to 1.5°C will make it markedly easier to achieve the SDGs for poverty eradication, water access, safe cities, food security, healthy lives, and inclusive economic growth, and will help to protect terrestrial ecosystems and biodiversity (*medium evidence, high agreement)* (Table 5.3 (see available as a supplementary pdf)). For example, limiting species loss and expanding climate refugia will make it easier to achieve SDG 15 (see Chapter 3, Section 3.4.3). One indication of how lower temperatures benefit the SDGs is to compare the impacts of Representative Concentration Pathway (RCP)4.5 (lower emissions) and RCP8.5 (higher emissions) on the SDGs (Ansuategi et al., 2015). A low emissions pathway allows for greater success in achieving SDGs for reducing poverty and hunger, providing access to clean energy, reducing inequality, ensuring education for all, and making cities more sustainable. Even at lower emissions, a medium risk of failure exists to meet goals for water and sanitation, and marine and terrestrial ecosystems.

Action on climate change (SDG 13), including slowing the rate of warming, would help reach the goals for water, energy, food, and land (SDGs 6, 7, 2, and 15) (Obersteiner et al., 2016; ICSU, 2017) and contribute to poverty eradication (SDG 1) (Byers et al., 2018). Although the literature that connects 1.5°C to the SDGs is limited, stabilising warming at 1.5°C by the end of the century is expected to increase the chances of achieving the SDGs by 2030, with greater potentials to eradicate poverty, reduce inequality, and foster equity (*limited evidence*, *medium agreement*). There are no studies on overshoot and dimensions of sustainable development, although literature on 4°C suggests the impacts would be severe (Reyer et al., 2017b).

Table 5.1: Sustainable development implications of avoided impacts between 1.5°C and 2°C global warming

Impacts	Chapter 3 section	1.5°C	2°C	Sustainable development goals (SDGs) more easily achieved when limiting warming to 1.5°C
Water scarcity	3.4.2.1	4% more people exposed to water stress	8% more people exposed to water stress with 184-270 million people more exposed	SDG 6 water availability for all
	Table 3.4	496 (range 103-1159) million people exposed and vulnerable to water stress	586 (range 115-1347) million people exposed and vulnerable to water stress	
Ecosystems	3.4.3 Table 3.4	Around 7% of land area experiences biome shifts	Around 13% (range 8-20%) of land area experiences biome shifts	SDG 15 to protect terrestrial ecosystems and halt biodiversity loss
	Box 3.5	70-90% of coral reefs at risk from bleaching	99% of coral reefs at risk from bleaching	
Coastal cities	3.4.5.2	Less cities and coasts exposed to sea level rise and extreme events	More people and cities exposed to flooding	SDG 11 to make cities and human settlements safe and resilient
	3.4.5.1	31-69 million people exposed to coastal flooding	32-79 million exposed to coastal flooding	
Food systems	3.4.6 and Box 3.1	Significant declines in crop yields avoided, some yields may increase	Average crop yields decline	SDG 2 to end hunger and achieve food security
	Table 3.4	32-36 million people exposed to lower yields	330-396 million people exposed to lower yields	
Health	3.4.7	Lower risk of temperature related morbidity and smaller mosquito range	Higher risks of temperature related morbidity and mortality and larger range of mosquitoes	SDG 3 to ensure healthy lives for all
	Table 3.4	3546-4508 million people exposed to heatwaves	5417-6710 million people exposed to heatwaves	

[INSERT CROSS-CHAPTER BOX 12 HERE]

Cross-Chapter Box 12: Residual risks, limits to adaptation and loss and damage

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Introduction

Residual climate-related risks, limits to adaptation, and loss and damage (see Glossary) are increasingly assessed in the scientific literature (van der Geest and Warner, 2015; Boyd et al., 2017; Mechler et al., 2018). The AR5 (IPCC, 2013; Oppenheimer et al., 2014) documented impacts that have been detected and attributed to climate change, projected increasing climate-related risks with continued global warming, and recognised barriers and limits to adaptation. It recognised that adaptation is constrained by biophysical, institutional, financial, social, and cultural factors, and that the interaction of these factors with climate change can lead to soft adaptation limits (adaptive actions currently not available) and hard adaptation limits (adaptive actions appear infeasible leading to unavoidable impacts) (Klein et al., 2014).

Loss and damage - concepts and perspectives

"Loss and Damage" (L&D) has been discussed in international climate negotiations for three decades (INC, 1991; Calliari, 2016; Vanhala and Hestbaek, 2016). A work programme on L&D was established as part of the Cancun Adaptation Framework in 2010 supporting developing countries particularly vulnerable to climate change impacts (UNFCCC, 2010). Conference of the Parties (COP) 19 in 2013 established the Warsaw International Mechanism for Loss and Damage (WIM) as a formal part of the United Nations Framework Convention on Climate Change (UNFCCC) architecture (UNFCCC, 2013). It acknowledges that L&D "includes, and in some cases involves more than, that which can be reduced by adaptation" (UNFCCC, 2013). The Paris Agreement recognised "the importance of averting, minimising and addressing loss and damage associated with the adverse effects of climate change" through Article 8 (UNFCCC, 2015).

There is no one definition of L&D in climate policy, and analysis of policy documents and stakeholder views has demonstrated ambiguity (Vanhala and Hestbaek, 2016; Boyd et al., 2017). UNFCCC documents suggest that L&D is associated with adverse impacts of climate change on human and natural systems, including impacts from extreme events and slow-onset processes (UNFCCC, 2011, 2013, 2015). Some documents focus on impacts in developing or particularly vulnerable countries (UNFCCC, 2011, 2013). They refer to economic (loss of assets and crops) and non-economic (biodiversity, culture, health) impacts, the latter also being an action area under the WIM workplan, and irreversible and permanent loss and damage. Lack of clarity of what the term addresses (avoidance through adaptation and mitigation, unavoidable losses, climate risk management, existential risk) was expressed among stakeholders, with further disagreement ensuing about what constitutes anthropogenic climate change *versus* natural climate variability (Boyd et al., 2017).

Limits to adaptation and residual risks

The AR5 described adaptation limits as points beyond which actors' objectives are compromised by intolerable risks threatening key objectives such as good health or broad levels of well-being, thus requiring transformative adaptation for overcoming soft limits (Dow et al., 2013; Klein et al., 2014) (see Chapter 4, Sections 4.2.2.3 and 4.5.3; Cross-Chapter Box 9 in Chapter 4; Section 5.3.1). The AR5 WGII risk tables, based on expert judgment, depicted the potential for, and the limits of, additional adaptation to reduce risk. Near-term (2030-2040) risks can be used as a proxy for 1.5°C warming by the end of the century, and compared to longer-term (2080-2100) risks associated with an approximate 2°C warming. Building on the AR5 risk approach, Figure 5.2 provides a stylised application example to poverty and inequality.

[INSERT CROSS-CHAPTER BOX 12, FIGURE 5.2 HERE]

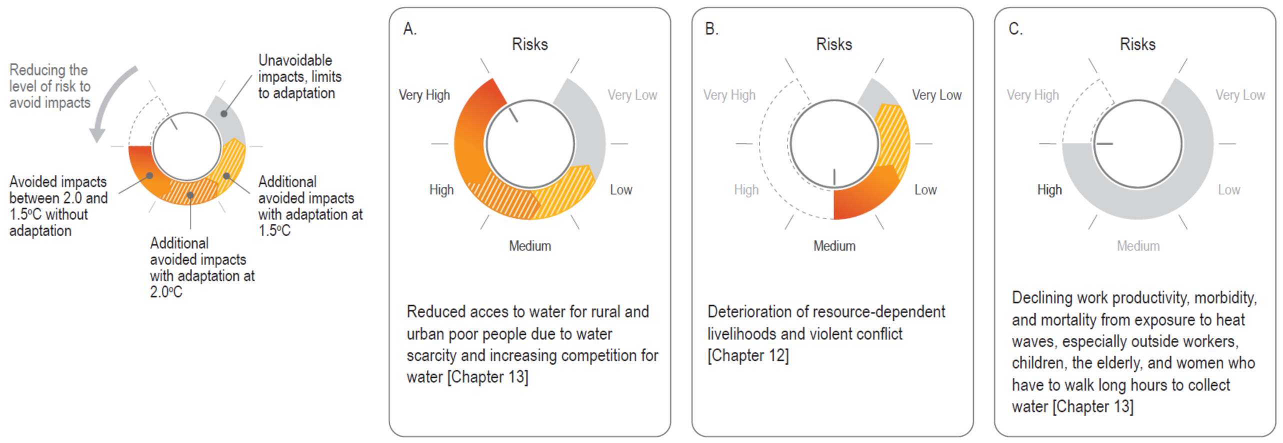

Figure 5.2: Stylised reduced risk levels due to avoided impacts between 2°C and 1.5°C warming (in solid red-orange), additional avoided impacts with adaptation under 2°C (striped orange) and under 1.5°C (striped yellow), and unavoidable impacts (losses) with no or very limited potential for adaptation (grey), extracted from the AR5 WGII risk tables (Field et al., 2014), and underlying chapters by Adger et al. (2014) and Olsson et al. (2014). For some systems and sectors (A), achieving 1.5°C could reduce risks to low (with adaptation) from very high (without adaptation) and high (with adaptation) under 2°C. For other areas (C), no or very limited adaptation potential is anticipated, suggesting limits, with the same risks for 1.5°C and 2°C. Other risks are projected to be medium under 2°C with further potential for reduction, especially with adaptation, to very low levels (B).

Limits to adaptation, residual risks, and losses in a 1.5°C warmer world
The literature on risks at 1.5°C (versus 2°C and more) and potentials for adaptation remains limited, particularly for specific regions, sectors, and vulnerable and disadvantaged populations. Adaptation potential at 1.5°C and 2°C is rarely assessed explicitly, making an assessment of residual risk challenging. Substantial progress has been made since the AR5 to assess which climate change impacts on natural and human systems can be attributed to anthropogenic emissions (Hansen and Stone, 2016) and to examine the influence of anthropogenic emissions on extreme weather events (NASEM, 2016), and on consequent impacts on human life (Mitchell et al., 2016), but less so on monetary losses and risks (Schaller et al., 2016). There has also been some limited research to examine local-level limits to adaptation (Warner and Geest, 2013; Filho and Nalau, 2018). What constitutes losses and damages is context-dependent and often requires place-based research into what people value and consider worth protecting (Barnett et al., 2016; Tschakert et al., 2017). Yet, assessments of non-material and intangible losses are particularly challenging, such as loss of sense of place, belonging, identity, and damages to emotional and mental wellbeing (Serdeczny et al., 2017; Wewerinke-Singh, 2018a). Warming of 1.5°C is not considered 'safe' for most nations, communities, ecosystems, and sectors and poses significant risks to natural and human systems as compared to current warming of 1°C (*high confidence*) (see Chapter 3, Section 3.4, Box 3.4, Box 3.5, Cross-Chapter Box 6 in Chapter 3). Table 5.2, drawing on findings from Chapters 3, 4 and 5, presents examples of soft and hard limits in natural and human systems in the context of 1.5°C and 2°C of warming.

Table 5.2: Soft and hard adaptation limits in the context of 1.5°C and 2°C of global warming

System/Region	**Example**	**Soft Limit**	**Hard Limit**
Coral reefs	Loss of 70-90% of tropical coral reefs by mid-century under 1.5°C scenario (total loss under 2°C scenario) (se Chapter 3, Sections 3.4.4 and 3.5.2.1, Box 3.4)		✓
Biodiversity	6% of insects, 8% of plants and 4% of vertebrates lose over 50% of the climatically determined geographic range at 1.5°C (18% of insects, 16% of plants, 8% of vertebrates at 2°C) (see Chapter 3, Section 3.4.3.3)		✓
Poverty	24-357 million people exposed to multi-sector climate risks and vulnerable to poverty at 1.5°C (86-1,220 million at 2°C) (see Section 5.2.2)	✓	
Human health	Twice as many megacities exposed to heat stress at 1.5°C compared to present, potentially exposing 350 million additional people to deadly heat wave conditions by 2050 (see Chapter 3, Section 3.4.8)	✓	✓
Coastal livelihoods	Large-scale changes in oceanic systems (temperature, acidification) inflict damage and losses to livelihoods, income, cultural identity and health for coastal-dependent communities at 1.5°C (potential higher losses at 2°C) (see Chapter 3, Sections 3.4.4, 3.4.5, 3.4.6.3, Box 3.4, Box 3.5, Cross-Chapter Box 6; Chapter 4, Section 4.3.5; Section 5.2.3)	✓	✓
Small Island Developing States	Sea level rise and increased wave run up combined with increased aridity and decreased freshwater availability at 1.5°C warming potentially leaving several atoll islands uninhabitable (see Chapter 3, Sections 3.4.3, 3.4.5, Box 3.5; Chapter 4, Cross-Chapter Box 9)		✓

Approaches and policy options to address residual risk and loss and damage
Conceptual and applied work since the AR5 has highlighted the synergies and differences with adaptation and disaster risk reduction policies (van der Geest and Warner, 2015; Thomas and Benjamin, 2017), suggesting more integration of existing mechanisms, yet careful consideration is advised for slow-onset and potentially irreversible impacts and risk (Mechler and Schinko, 2016). Scholarship on justice and equity has

provided insight on compensatory, distributive, and procedural equity considerations for policy and practice to address loss and damage (Roser et al., 2015; Wallimann-Helmer, 2015; Huggel et al., 2016). A growing body of legal literature considers the role of litigation in preventing and addressing loss and damage and finds that litigation risks for governments and business are bound to increase with improved understanding of impacts and risks as climate science evolves (*high confidence*) (Mayer, 2016; Banda and Fulton, 2017; Marjanac and Patton, 2018; Wewerinke-Singh, 2018b). Policy proposals include international support for experienced losses and damages (Crosland et al., 2016; Page and Heyward, 2017), addressing climate displacement, donor-supported implementation of regional public insurance systems (Surminski et al., 2016) and new global governance systems under the UNFCCC (Biermann and Boas, 2017).

[END CROSS-CHAPTER BOX 12]

5.3 Climate Adaptation and Sustainable Development

Adaptation will be extremely important in a 1.5°C warmer world since substantial impacts will be felt in every region (*high confidence*) (Chapter 3, Section 3.3), even if adaptation needs will be lower than in a 2°C warmer world (see Chapter 4, Sections 4.3.1 to 4.3.5, 4.5.3, Cross-Chapter Box 10 in Chapter 4). Climate adaptation options comprise structural, physical, institutional, and social responses, with their effectiveness depending largely on governance (see Glossary), political will, adaptive capacities, and availability of finance (Betzold and Weiler, 2017; Sonwa et al., 2017; Sovacool et al., 2017) (see Chapter 4, Sections 4.4.1 to 4.4.5). Even though the literature is scarce on the expected impacts of future adaptation measures on sustainable development specific to warming experiences of 1.5°C, this section assesses available literature on how (i) prioritising sustainable development enhances or impedes climate adaptation efforts (Section 5.3.1); (ii) climate adaptation measures impact sustainable development and the Sustainable Development Goals (SDGs) in positive (synergies) or negative (trade-offs) ways (Section 5.3.2); and (iii) adaptation pathways towards a 1.5°C warmer world affect sustainable development, poverty, and inequalities (Section 5.3.3). The section builds on Chapter 4 (see Section 4.3.5) regarding available adaptation options to reduce climate vulnerability and build resilience (see Glossary) in the context of 1.5°C-compatible trajectories, here with emphasis on sustainable development implications.

5.3.1 Sustainable Development in Support of Climate Adaptation

Making sustainable development a priority, and meeting the SDGs, is consistent with efforts to adapt to climate change (*very high confidence*). Sustainable development is effective in building adaptive capacity if it addresses poverty and inequalities, social and economic exclusion, and inadequate institutional capacities (Noble et al., 2014; Abel et al., 2016; Colloff et al., 2017). Four ways in which sustainable development leads to effective adaptation are described below.

Firstly, sustainable development enables transformational adaptation (see Chapter 4, Section 4.2.2.2) when an integrated approach is adopted, with inclusive, transparent decision making, rather than addressing current vulnerabilities as stand-alone climate problems (Mathur et al., 2014; Arthurson and Baum, 2015; Shackleton et al., 2015; Lemos et al., 2016; Antwi-Agyei et al., 2017b). Ending poverty in its multiple dimensions (SDG 1) is often a highly effective form of climate adaptation (Fankhauser and McDermott, 2014; Leichenko and Silva, 2014; Hallegatte and Rozenberg, 2017). However, ending poverty is not sufficient, and the positive outcome as an adaptation strategy depends on whether increased household wealth is actually directed towards risk reduction and management strategies (Nelson et al., 2016), as shown in urban municipalities (Colenbrander et al., 2017; Rasch, 2017) and agrarian communities (Hashemi et al., 2017), and whether finance for adaptation is made available (Section 5.6.1).

Secondly, local participation is effective when wider socio-economic barriers are addressed via multi-scale planning (McCubbin et al., 2015; Nyantakyi-Frimpong and Bezner-Kerr, 2015; Toole et al., 2016). This is the case, for instance, when national education efforts (SDG 4) (Muttarak and Lutz, 2014; Striessnig and

Loichinger, 2015) and indigenous knowledge (Nkomwa et al., 2014; Pandey and Kumar, 2018) enhance information sharing, which also builds resilience (Santos et al., 2016; Martinez-Baron et al., 2018) and reduces risks for maladaptation (Antwi-Agyei et al., 2018; Gajjar et al., 2018).

Thirdly, development promotes transformational adaptation when addressing social inequalities (Section 5.5.3, 5.6.4), as in SDGs 4, 5, 16, and 17 (O'Brien et al., 2015; K. O'Brien, 2016). For example, SDG 5 supports measures that reduce women's vulnerabilities and allow women to benefit from adaptation (Antwi-Agyei et al., 2015; Van Aelst and Holvoet, 2016; Cohen, 2017). Mobilisation of climate finance, carbon taxation, and environmentally-motivated subsidies can reduce inequalities (SDG 10), advance climate mitigation and adaptation (Chancel and Picketty, 2015), and be conducive to strengthening and enabling environments for resilience building (Nhamo, 2016; Halonen et al., 2017).

Fourthly, when sustainable development promotes livelihood security, it enhances the adaptive capacities of vulnerable communities and households. Examples include SDG 11 supporting adaptation in cities to reduce harm from disasters (Kelman, 2017; Parnell, 2017); access to water and sanitation (SDG 6) with strong institutions (SDG 16) (Rasul and Sharma, 2016); SDG 2 and its targets that promote adaptation in agricultural and food systems (Lipper et al., 2014); and targets for SDG 3 such as reducing infectious diseases and providing health cover are consistent with health-related adaptation (ICSU, 2017; Gomez-Echeverri, 2018).

Sustainable development has the potential to significantly reduce systemic vulnerability, enhance adaptive capacity, and promote livelihood security for poor and disadvantaged populations (*high confidence*). Transformational adaptation (see Chapter 4, Sections 4.2.2.2 and 4.5.3) would require development that takes into consideration multidimensional poverty and entrenched inequalities, local cultural specificities, and local knowledge in decision-making, thereby making it easier to achieve the SDGs in a 1.5°C warmer world (*medium evidence, high agreement*).

5.3.2 Synergies and Trade-offs between Adaptation Options and Sustainable Development

There are short-, medium-, and long-term positive impacts (synergies) and negative impacts (trade-offs) between the dual goal of keeping temperatures below 1.5°C global warming and achieving sustainable development. The extent of synergies between development and adaptation goals will vary by the development process adopted for a particular SDG and underlying vulnerability contexts (*medium evidence, high agreement*). Overall, the impacts of adaptation on sustainable development, poverty eradication, and reducing inequalities in general, and the SDGs specifically, are expected to be largely positive, given that the inherent purpose of adaptation is to lower risks. Building on Chapter 4 (see Section 4.3.5), this section examines synergies and trade-offs between adaptation and sustainable development for some key sectors and approaches, also.

Agricultural adaptation: The most direct synergy is between SDG 2 (zero hunger) and adaptation in cropping, livestock, and food systems, designed to maintain or increase production (Lipper et al., 2014; Rockström et al., 2017). Farmers with effective adaptation strategies tend to enjoy higher food security and experience lower levels of poverty (FAO, 2015; Douxchamps et al., 2016; Ali and Erenstein, 2017). Vermeulen et al. (2016) report strong positive returns on investment across the world from agricultural adaptation with side benefits for environment and economic well-being. Well-adapted agricultural systems contribute to safe drinking water, health, biodiversity, and equity goals (DeClerck et al., 2016; Myers et al., 2017). Climate-smart agriculture has synergies with food security, though it can be biased towards technological solutions, may not be gender sensitive, and can create specific challenges for institutional and distributional aspects (Lipper et al., 2014; Arakelyan et al., 2017; Taylor, 2017).

At the same time, adaptation options increase risk for human health, oceans, and access to water if fertiliser and pesticides are used without regulation or when irrigation reduces water availability for other purposes (Shackleton et al., 2015; Campbell et al., 2016). When agricultural insurance and climate services overlook the poor, inequality may rise (Dinku et al., 2014; Carr and Owusu-Daaku, 2015; Carr and Onzere, 2017; Georgeson et al., 2017a). Agricultural adaptation measures may increase workloads, especially for women, while changes in crop mix can result in loss of income or culturally inappropriate food (Carr and Thompson, 2014; Thompson-Hall et al., 2016; Bryan et al., 2017), and they may benefit farmers with more land to the detriment of land-poor farmers, as seen in the Mekong River Basin (see Chapter 3, Cross-Chapter Box 6 in Chapter 3).

Adaptation to protect human health: Adaptation options in the health sector are expected to reduce morbidity and mortality (Arbuthnott et al., 2016; Ebi and Del Barrio, 2017). Heat-early-warning systems help lower injuries, illnesses, and deaths (Hess and Ebi, 2016), with positive impacts for SDG 3. Institutions better equipped to share information, indicators for detecting climate-sensitive diseases, improved provision of basic health care services, and coordination with other sectors also improve risk management, thus reducing adverse health outcomes (Dasgupta et al., 2016; Dovie et al., 2017). Effective adaptation creates synergies via basic public health measures (K.R. Smith et al., 2014; Dasgupta, 2016) and health infrastructure protected from extreme weather events (Watts et al., 2015). Yet, trade-offs can occur when adaptation in one sector leads to negative impacts in another sector. Examples include the creation of urban wetlands through flood control measures which can breed mosquitoes, and migration eroding physical and mental well-being, hence adversely affecting SDG 3 (K.R. Smith et al., 2014; Watts et al., 2015). Similarly, increased use of air conditioning enhances resilience to heat stress (Petkova et al., 2017); yet it can result in higher energy consumption, undermining SDG 13.

Coastal adaptation: Adaptation to sea-level rise remains essential in coastal areas even under a climate stabilisation scenario of 1.5°C (Nicholls et al., 2018). Coastal adaptation to restore ecosystems (for instance by planting mangrove forests) support SDGs for enhancing life and livelihoods on land and oceans (see Chapter 4, Sections 4.3.2.3). Synergistic outcomes between development and relocation of coastal communities are enhanced by participatory decision-making and settlement designs that promote equity and sustainability (Voorn et al., 2017). Limits to coastal adaptation may rise, for instance in low-lying islands in the Pacific, Caribbean, and Indian Ocean, with attendant implications for loss and damage (see Chapter 3 Box 3.5, Chapter 4, Cross-Chapter Box 9 in Chapter 4, Cross-Chapter 12 in Chapter 5, Box 5.3).

Migration as adaptation: Migration has been used in various contexts to protect livelihoods from challenges related to climate change (Marsh, 2015; Jha et al., 2017), including through remittances (Betzold and Weiler, 2017). Synergies between migration and the achievement of sustainable development depend on adaptive measures and conditions in both sending and receiving regions (Fatima et al., 2014; McNamara, 2015; Entzinger and Scholten, 2016; Ober and Sakdapolrak, 2017; Schwan and Yu, 2017). Adverse developmental impacts arise when vulnerable women or the elderly are left behind or if migration is culturally disruptive (Wilkinson et al., 2016; Albert et al., 2017; Islam and Shamsuddoha, 2017).

Ecosystem-based adaptation (EBA): EBA can offer synergies with sustainable development (Morita and Matsumoto, 2015; Ojea, 2015; Szabo et al., 2015; Brink et al., 2016; Butt et al., 2016; Conservation International, 2016; Huq et al., 2017), although assessments remain difficult (Doswald et al., 2014) (see Chapter 4, Section 4.3.2.2). Examples include mangrove restoration reducing coastal vulnerability, protecting marine and terrestrial ecosystems, and increasing local food security; as well as watershed management reducing flood risks and improving water quality (Chong, 2014). In drylands, EBA practices, combined with community-based adaptation, have shown how to link adaptation with mitigation to improve livelihood conditions of poor farmers (Box 5.1). Synergistic developmental outcomes arise where EBA is cost effective, inclusive of indigenous and local knowledge, and easily accessible by the poor (Ojea, 2015; Daigneault et al., 2016; Estrella et al., 2016). Payment for ecosystem services can provide incentives to land owners and natural resource managers to preserve environmental services with synergies with SDGs 1 and 13 (Arriagada et al., 2015), when implementation challenges are overcome (Calvet-Mir et al., 2015; Wegner, 2016; Chan et al., 2017). Trade-offs include loss of other economic land use types, tension between biodiversity and adaptation priorities, and conflicts over governance (Wamsler et al., 2014; Ojea, 2015).

Community-based adaptation (CBA): CBA (see Chapter 4, Sections 4.3.3.2) enhances resilience and sustainability of adaptation plans (Ford et al., 2016; Fernandes-Jesus et al., 2017; Grantham and Rudd, 2017; Gustafson et al., 2017). Yet, negative impacts occur if it fails to fairly represent vulnerable populations and to foster long-term social resilience (Ensor, 2016; Taylor Aiken et al., 2017). Mainstreaming CBA into planning and decision-making enables the attainment of SDG 5, 10, and 16 (Archer et al., 2014; Reid and Huq, 2014; Vardakoulias and Nicholles, 2014; Cutter, 2016; Kim et al., 2017). Incorporating multiple forms of indigenous and local knowledge (ILK) is an important element of CBA, as shown for instance in the Arctic region (Apgar et al., 2015; Armitage, 2015; Pearce et al., 2015; Chief et al., 2016; Cobbinah and Anane, 2016; Ford et al., 2016) (see Chapter 4, Cross-Chapter Box 9, Box 4.3, Section 4.3.5.5). ILK can be synergistic with achieving SDGs 2, 6, and 10 (Ayers et al., 2014; Lasage et al., 2015; Regmi and Star, 2015; Berner et al., 2016; Chief et al., 2016; Murtinho, 2016; Reid, 2016).

There are clear synergies between adaptation options and several SDGs, such as poverty eradication, elimination of hunger, clean water, and health (*robust evidence, high agreement*) as well-integrated adaptation supports sustainable development (Eakin et al., 2014; Weisser et al., 2014; Adam, 2015; Smucker et al., 2015). Substantial synergies are observed in the agricultural and health sectors, and in ecosystem-based adaptations. However, particular adaptation strategies can lead to adverse consequences for developmental outcomes (*medium evidence, high agreement*). Adaptation strategies that advance one SDG can result in trade-offs with other SDGs, for instance, agricultural adaptation to enhance food security (SDG 2) causing negative impacts for health, equality, and healthy ecosystems (SDGs 3, 5, 6, 10, 14 and 15), and resilience to heat stress increasing energy consumption (SDGs 3 and 7), and high-cost adaptation in resource-constrained contexts (*medium evidence, medium agreement*).

5.3.3 Adaptation Pathways toward a 1.5°C Warmer World and Implications for Inequalities

In a 1.5°C warmer world, adaptation measures and options would need to be intensified, accelerated, and scaled up. This entails not only the right 'mix' of options (asking 'right for whom and for what?') but also a forward-looking understanding of dynamic trajectories, that is adaptation pathways (see Chapter 1, Cross-Chapter Box 1 in Chapter 1), best understood as decision-making processes over sets of potential action sequenced over time (Câmpeanu and Fazey, 2014; Wise et al., 2014). Given the scarcity of literature on adaptation pathways that navigate place-specific warming experiences at 1.5°C, this section presents insights into current local decision making for adaptation futures. This grounded evidence shows that choices between possible pathways, at different scales and for different groups of people, are shaped by uneven power structures and historical legacies that create their own, often unforeseen change (Fazey et al., 2016; Bosomworth et al., 2017; Lin et al., 2017; Murphy et al., 2017; Pelling et al., 2018).

Pursuing a place-specific adaptation pathway approach toward a 1.5°C warmer world harbours the potential for significant positive outcomes, with synergies for well-being possibilities to 'leap-frog the SDGs' (J.R.A. Butler et al., 2016), in countries at all levels of development (*medium evidence, high agreement*). It allows for identifying local, socially-salient tipping points before they are crossed, based on what people value and trade-offs that are acceptable to them (Barnett et al., 2014, 2016; Gorddard et al., 2016; Tschakert et al., 2017). Yet, evidence also reveals adverse impacts that reinforce rather than reduce existing social inequalities and hence may lead to poverty traps (Nagoda, 2015; Warner et al., 2015; Barnett et al., 2016; J.R.A. Butler et al., 2016; Godfrey-Wood and Naess, 2016; Pelling et al., 2016; Albert et al., 2017; Murphy et al., 2017) (*medium evidence, high agreement*).

Past development trajectories as well as transformational adaptation plans can constrain adaptation futures by reinforcing dominant political-economic structures and processes, and narrowing option spaces; this leads to maladaptive pathways that preclude alternative, locally-relevant, and sustainable development initiatives and increase vulnerabilities (Warner and Kuzdas, 2017; Gajjar et al., 2018). Such dominant pathways tend to validate the practices, visions, and values of existing governance regimes and powerful members of a community while devaluing those of less privileged stakeholders. Examples from Romania, the Solomon Islands, and Australia illustrate such pathway dynamics in which individual economic gains and prosperity matter more than community cohesion and solidarity; this discourages innovation, exacerbates inequalities, and further erodes adaptive capacities of the most vulnerable (Davies et al., 2014; Fazey et al., 2016; Bosomworth et al., 2017). In the city of London, United Kingdom, the dominant adaptation and disaster risk management pathway promotes resilience that emphasises self-reliance; yet, it intensifies the burden on low-income citizens, the elderly, migrants, and others unable to afford flood insurance or protect themselves against heat waves (Pelling et al., 2016). Adaptation pathways in the Bolivian Altiplano have transformed subsistence farmers into world-leading quinoa producers, but loss of social cohesion and traditional values, dispossession, and loss of ecosystem services now constitute undesirable trade-offs (Chelleri et al., 2016).

A narrow view of adaptation decision making, for example focused on technical solutions, tends to crowd out more participatory processes (Lawrence and Haasnoot, 2017; Lin et al., 2017), obscures contested values, and reinforces power asymmetries (Bosomworth et al., 2017; Singh, 2018). A situated and context-specific understanding of adaptation pathways that galvanises diverse knowledge, values, and joint initiatives, helps to overcome dominant path dependencies, avoid trade-offs that intensify inequities, and challenge policies detached from place (Fincher et al., 2014; Wyborn et al., 2015; Murphy et al., 2017; Gajjar et al., 2018). These insights suggest that adaptation pathway approaches to prepare for 1.5°C warmer futures would be difficult to achieve without considerations for inclusiveness, place-specific trade-off deliberations, redistributive measures, and procedural justice mechanisms to facilitate equitable transformation (*medium evidence, high agreement*).

[INSERT BOX 5.1 HERE]

Box 5.1: Ecosystem- and Community-based Practices in Drylands

Drylands face severe challenges in building climate resilience (Fuller and Lain, 2017), yet, small-scale farmers can play a crucial role as agents of change through ecosystem- and community-based practices that combine adaptation, mitigation, and sustainable development.

Farmer Managed Natural Regeneration (FMNR) of trees in cropland is practised in 18 countries across Sub-Saharan Africa, Southeast Asia, Timor-Leste, India, and Haiti and has, for example, permitted the restoration of over five million hectares of land in the Sahel (Niang et al., 2014; Bado et al., 2016). In Ethiopia, the Managing Environmental Resources to Enable Transitions (MERET) programme, which entails community-based watershed rehabilitation in rural landscapes, supported around 648,000 people, resulting in the rehabilitation of 25,400,000 hectares of land in 72 severely food-insecure districts across Ethiopia during 2012–2015 (Gebrehaweria et al., 2016). In India, local farmers have benefitted from watershed programmes across different agro-ecological regions (Singh et al., 2014; Datta, 2015).

These low-cost, flexible community-based practices represent low-regrets adaptation and mitigation strategies. These strategies often contribute to strengthened ecosystem resilience and biodiversity, increased agricultural productivity and food security, reduced household poverty and drudgery for women, and enhanced agency and social capital (Niang et al., 2014; Francis et al., 2015; Kassie et al., 2015; Mbow et al., 2015; Reij and Winterbottom, 2015; Weston et al., 2015; Bado et al., 2016; Dumont et al., 2017). Small check dams in dryland areas and conservation agriculture can significantly increase agricultural output (Kumar et al., 2014; Agoramoorthy and Hsu, 2016; Pradhan et al., 2018). Mitigation benefits have also been quantified (Weston et al., 2015); for example, FMNR over five million hectares in Niger has sequestered 25–30 Mtonnes of carbon over 30 years (Stevens et al., 2014).

However, several constraints hinder scaling-up efforts: inadequate attention to the socio-technical processes of innovation (Grist et al., 2017; Scoones et al., 2017), difficulties in measuring the benefits of an innovation (Coe et al., 2017), farmers' inability to deal with long-term climate risk (Singh et al., 2017), and difficulties for matching practices with agro-ecological conditions and complementary modern inputs (Kassie et al., 2015). Key conditions to overcome these challenges include: developing agroforestry value chains and markets (Reij and Winterbottom, 2015) and adaptive planning and management (Gray et al., 2016). Others include inclusive processes giving greater voice to women and marginalised groups (MRFCJ, 2015a; UN Women and MRFCJ, 2016; Dumont et al., 2017), strengthening of community land and forest rights

(Stevens et al., 2014; Vermeulen et al., 2016) and co-learning among communities of practice at different scales (Coe et al., 2014; Reij and Winterbottom, 2015; Sinclair, 2016; Binam et al., 2017; Dumont et al., 2017; Epule et al., 2017).

[END BOX 5.1]

5.4 Mitigation and Sustainable Development

The AR5 WGIII examined the potential of various mitigation options for specific sectors (energy supply, industry, buildings, transport, and Agriculture, Forestry, and Other Land Use (AFOLU); it provided a narrative of dimensions of sustainable development and equity as a framing for evaluating climate responses and policies, respectively, in Chapters 4, 7, 8, 9, 10, and 11 (IPCC, 2014a). This section builds on analysis of Chapters 2 and 4 of this report to re-assess mitigation and sustainable development in the context of 1.5°C global warming as well as the Sustainable Development Goals (SDGs).

5.4.1 Synergies and Trade-offs between Mitigation Options and Sustainable Development

Adopting stringent climate mitigation options can generate multiple positive non-climate benefits that have the potential to reduce the costs of achieving sustainable development (IPCC, 2014b; Ürge-Vorsatz et al., 2014, 2016; Schaeffer et al., 2015; von Stechow et al., 2015). Understanding the positive impacts (synergies) but also the negative impacts (trade-offs) is key for selecting mitigation options and policy choices that maximise the synergies between mitigation and developmental actions (Hildingsson and Johansson, 2015; Nilsson et al., 2016; Delponte et al., 2017; van Vuuren et al., 2017b; McCollum et al., 2018).
Aligning mitigation response options to sustainable development objectives can ensure public acceptance (IPCC, 2014a), encourage faster action (Lechtenboehmer and Knoop, 2017), and support the design of equitable mitigation (Holz et al., 2017; Winkler et al., 2018) that protect human rights (MRFCJ, 2015b) (Section 5.5.3).

This sub-section assesses available literature on the interactions of individual mitigation options (see Chapter 2, Sections 2.3.1.2, Chapter 4, Sections 4.2 and 4.3) with sustainable development and the SDGs and underlying targets. Table 5.3 (available as a supplementary pdf) presents an assessment of these synergies and trade-offs and the strength of the interaction using an SDG-interaction score (see Glossary) (McCollum et al., 2018), with evidence and agreements levels. Figure 5.3 presents the information of Table 5.3 (available as a supplementary pdf), showing gross (not net) interactions with the SDGs. This detailed assessment of synergies and trade-offs of individual mitigation options with the SDGs (Table 5.3 a–d (available as a supplementary pdf), Figure 5.3) reveals that the number of synergies exceeds that of trade-offs. Mitigation response options in the energy demand sector, AFOLU, and oceans have more positive interactions with a larger number of SDGs compared to those on the energy supply side (*robust evidence, high agreement*).

5.4.1.1 Energy Demand: Mitigation Options to Accelerate Reduction in Energy Use and Fuel Switch

For mitigation options in the energy demand sectors, the number of synergies with all sixteen SDGs exceeds the number of trade-off (Figure 5.3, also Table 5.3 (available as a supplementary pdf)) (*robust evidence, high agreement*). Most of the interactions are of reinforcing nature, hence facilitating the achievement of the goals.

Accelerating energy efficiency in all sectors, which is a necessary condition for a 1.5°C warmer world (see Chapters 2 and 4), has synergies with a large number of SDGs (Figure 5.3, Table 5.3 (available as a supplementary pdf)) (*robust evidence, high agreement*). The diffusion of efficient equipment and appliances across end use sectors has synergies with international partnership (SDG 17) and participatory and transparent institutions (SDG 16) because innovations and deployment of new technologies require trans-national capacity building and knowledge sharing. Resource and energy savings support sustainable production and consumption (SDG 12), energy access (SDG 7), innovation and infrastructure development (SDG 9), and sustainable city development (SDG 11). Energy efficiency supports the creation of decent jobs by new service companies providing services for energy efficiency, but the net employment effect of efficiency improvement remains uncertain due to macro-economic feedback (SDG 8) (McCollum et al., 2018).

In the buildings sector, accelerating energy efficiency by way of, for example, enhancing the use of efficient appliances, refrigerant transition, insulation, retrofitting, and low- or zero-energy buildings generates benefits across multiple SDG targets. For example, improved cook stoves make fuel endowments last longer and hence reduce deforestation (SDG 15), support equal opportunity by reducing school absences due to asthma among children (SDGs 3 and 4), and empower rural and indigenous women by reducing drudgery (SDG 5) (Derbez et al., 2014; Lucon et al., 2014; Maidment et al., 2014; Scott et al., 2014; Cameron et al., 2015; Fay et al., 2015; Liddell and Guiney, 2015; Shah et al., 2015; Sharpe et al., 2015; Wells et al., 2015; Willand et al., 2015; Hallegatte et al., 2016; Kusumaningtyas and Aldrian, 2016; Berrueta et al., 2017; McCollum et al., 2017) (*robust evidence, high agreement*).

In energy-intensive processing industries, 1.5ºC-compatible trajectories require radical technology innovation through maximum electrification, shift to other low-emission energy carriers such as hydrogen or biomass, integration of Carbon Capture and Storage (CCS) and innovations for Carbon Capture and Utilisation (CCU) (see Chapter 4, Section 4.3.4.5). These transformations have strong synergies with innovation and sustainable industrialisation (SDG 9), supranational partnerships (SDGs 16 and 17) and sustainable production (SDG 12). However, possible trade-offs due to risks of CCS-based carbon leakage, increased electricity demands, and associated price impacts affecting energy access and poverty (SDGs 7 and 1) would need careful regulatory attention (Wesseling et al., 2017). In the mining industry, energy efficiency can be synergetic or face trade-offs with sustainable management (SDG 6), depending on the option retained for water management (Nguyen et al., 2014). Substitution and recycling are also an important driver of 1.5ºC-compatible trajectories in industrial systems (see Chapter 4, Section 4.3.4.2). Structural changes and reorganisation of economic activities in industrial park/clusters following the principles of industrial symbiosis (circular economy) improves the overall sustainability by reducing energy and waste (Fan et al., 2017; Preston and Lehne, 2017) and reinforce responsible production and consumption (SDG 12) through recycling, water use efficiency (SDG 6), energy access (SDG 7), and ecosystem service value enhancement (SDG 15) (Karner et al., 2015; Zeng et al., 2017).

In the transport sector, deep electrification may trigger increases of electricity prices and adversely affect poor populations (SDG 1), unless pro-poor redistributive policies are in place (Klausbruckner et al., 2016). In cities, governments can lay the foundations for compact, connected low-carbon cities, which are an important component of 1.5ºC-compatible transformations (see Chapter 4, Section 4.3.3) and show synergies with sustainable cities (SDG 11) (Colenbrander et al., 2016).

Behavioural responses are important determinants of the ultimate outcome of energy efficiency on emission reductions and energy access (SDG 7) and their management requires a detailed understanding of the drivers of consumption and the potential for and barriers to absolute reductions (Fuchs et al., 2016). Notably, the rebound effect tends to offset the benefits of efficiency for emission reductions through growing demand for energy services (Sorrell, 2015; Suffolk and Poortinga, 2016). However, high rebound can help in providing faster access to affordable energy (SDG 7.1) where the goal is to reduce energy poverty and unmet energy demand (Chakravarty et al., 2013)(see Chapter 2, Section 2.4.3). Comprehensive policy design, including rebound supressing policies such as carbon price and policies that encourage awareness building and promotional material design, are needed to tap the full potential of energy savings, as applicable to 1.5°C warming context (Chakravarty and Tavoni, 2013; IPCC, 2014b; Karner et al., 2015; Zhang et al., 2015; Altieri et al., 2016; Santarius et al., 2016) and to address policy-related trade-offs and welfare-enhancing benefits (Chakravarty et al., 2013; Chakravarty and Roy, 2016; Gillingham et al., 2016) (*robust evidence,* *high agreement*).

Other behavioural responses will affect the interplay between energy efficiency and sustainable development. Building occupants reluctant to change their habits may miss out on welfare-enhancing energy efficiency opportunities (Zhao et al., 2017). Preferences for new products and premature obsolescence for appliances is expected to affect sustainable consumption and production adversely (SDG 12) with ramifications for resource use efficiency (Echegaray, 2016). User behaviour change towards increased physical activity, less reliance on motorised travel over short distances, and the use of public transport would help to decarbonise the transport sector in a synergetic manner with SDGs 3, 11, and 12 (Shaw et al., 2014; Ajanovic, 2015; Chakrabarti and Shin, 2017) while reducing inequality in access to basic facilities (SDG 10) (Lucas and Pangbourne, 2014; Kagawa et al., 2015). However, infrastructure design and regulations would need to ensure road safety and address risks of road accidents for pedestrians (Hwang et al., 2017; Khreis et al., 2017) to ensure sustainable infrastructure growth in human settlements (SDGs 9 and 11) (Lin et al., 2015; SLoCaT, 2017).

5.4.1.2 Energy Supply: Accelerated Decarbonisation

Decreasing the share of coal in energy supply in line with 1.5ºC-compatible scenarios (see Chapter 2, Section 2.4.2) reduces adverse impacts of upstream supply-chain activities, in particular air and water pollution, and coal mining accidents, and enhances health by reducing air pollution, notably in cities, showing synergies with SDGs 3, 11 and 12 (Yang et al., 2016; UNEP, 2017).

Fast deployment of renewables like solar and wind, hydro, modern biomass, together with the decrease of fossil fuels in energy supply (see Chapter 2, Section 2.4.2.1), is aligned with the doubling of renewables in the global energy mix (SDG 7.2). Renewables could also support progress on SDGs 1, 10, 11, and 12 and supplement new technology (Chaturvedi and Shukla, 2014; Rose et al., 2014; Smith and Sagar, 2014; Riahi et al., 2015; IEA, 2016; McCollum et al., 2017; van Vuuren et al., 2017a) (*robust evidence, high agreement*). However, some trade-offs with the SDGs can emerge from offshore installations, particularly SDG 14 in local contexts (McCollum et al., 2017). Moreover, trade-offs between renewable energy production and affordability (SDG 7) (Labordena et al., 2017) and other environmental objectives would need to be scrutinised for potential negative social outcomes. Policy interventions through regional cooperation building (SDG 17) and institutional capacity (SDG 16) can enhance affordability (SDG 7) (Labordena et al., 2017).The deployment of small-scale renewables, or off-grid solutions for people in remote areas (Sánchez and Izzo, 2017), has strong potential for synergies with access to energy (SDG 7), but the actualisation of these potentials requires measures to overcome technology and reliability risks associated with large-scale deployment of renewables (Giwa et al., 2017; Heard et al., 2017). Bundling energy-efficient appliances and lighting with off-grid renewables can lead to substantial cost reduction while increasing reliability (IEA, 2017). Low-income populations in industrialised countries are often left out of renewable energy generation schemes, either because of high start-up costs or lack of home ownership (UNRISD, 2016).

Nuclear energy, the share of which increases in most of the 1.5ºC-compatible pathways (see Chapter 2, Section 2.4.2.1), can increase the risks of proliferation (SDG 16), have negative environmental effects (e.g., for water use, SDG 6), and have mixed effects for human health when replacing fossil fuels (SDGs 7 and 3) (see Table 5.2). The use of fossil CCS, which plays an important role in deep mitigation pathways (see Chapter 2, Section 2.4.2.3), implies continued adverse impacts of upstream supply-chain activities in the coal sector, and because of lower efficiency of CCS coal power plants (SDG 12), upstream impacts and local air pollution are likely to be exacerbated (SDG 3). Furthermore, there is a non-negligible risk of carbon dioxide leakage from geological storage and the carbon dioxide transport infrastructure (SDG 3) (Table 5.3 (available as a supplementary pdf)).

Economies dependent upon fossil fuel-based energy generation and/or export revenue are expected to be disproportionally affected by future restrictions on the use of fossil fuels, under stringent climate goals and higher carbon prices; this includes impacts on employment, stranded assets, resources left underground, lower capacity use, and early phasing out of large infrastructure already under construction (Johnson et al., 2015; McGlade and Ekins, 2015; UNEP, 2017; Spencer et al., 2018) (Box 5.2) (*robust evidence, high agreement*). Investment in coal continues to be attractive in many countries as it is a mature technology, provides cheap energy supply, large-scale employment, and energy security (Jakob and Steckel, 2016; Vogt-Schilb and Hallegatte, 2017; Spencer et al., 2018). Hence, accompanying policies and measures would be required to ease job losses and correct for relatively higher prices of alternative energy (Oosterhuis and Ten Brink, 2014; Oei and Mendelevitch, 2016; Garg et al., 2017; HLCCP, 2017; Jordaan et al., 2017; OECD, 2017; UNEP, 2017; Blondeel and van de Graaf, 2018; Green, 2018). Research on historical transitions shows that managing the impacts on workers through retraining programs is essential in order to align the phase down of mining industries with meeting ambitious climate targets, and the objectives of a 'just transition' (Galgóczi, 2014; Caldecott et al., 2017; Healy and Barry, 2017). This aspect is even more important in developing countries where the mining workforce is largely semi- or un-skilled (Altieri et al., 2016; Tung, 2016). Ambitious emission reduction targets can unlock very strong decoupling potentials in industrialised fossil exporting economies (Hatfield-Dodds et al., 2015).

[START BOX 5.2 HERE]

Box 5.2: Challenges and Opportunities of Low-Carbon Pathways in Gulf Cooperative Council (GCC) Countries

The Gulf Cooperative Council (GCC) region (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and United Arab Emirates) is characterised by high dependency on hydrocarbon resources (natural oil and gas), with high risks of socio-economic impacts of policies and response measures to address climate change. The region is also vulnerable to the decrease of the global demand and price of hydrocarbons as a result of climate change response measures. The projected declining use of oil and gas under low emissions pathways creates risks of significant economic losses for the GCC region (e.g., Waisman et al., 2013; Van de Graaf and Verbruggen, 2015; Al-Maamary et al., 2016; Bauer et al., 2016), given that natural gas and oil revenues contributed to ~70% of government budgets and > 35% of the gross domestic product in 2010 (Callen et al., 2014).

The current high energy intensity of the domestic economies (Al-Maamary et al., 2017), triggered mainly by low domestic energy prices (Alshehry and Belloumi, 2015), suggests specific challenges for aligning mitigation towards 1.5°C-consistent trajectories, which would require strong energy efficiency and economic development for the region.

Economies of the region are highly reliant on fossil fuel for their domestic activities. Yet, the renewables deployment potentials are large, deployment is already happening (Cugurullo, 2013; IRENA, 2016), and positive economic benefits can be envisaged (Sgouridis et al., 2016). Nonetheless, the use of renewables is currently limited by economics and structural challenges (Lilliestam and Patt, 2015; Griffiths, 2017a). Carbon Capture and Storage (CCS) is also envisaged with concrete steps towards implementation (Alsheyab, 2017; Ustadi et al., 2017); yet, the real potential of this technology in terms of scale and economic dimensions is still uncertain.

Beyond the above mitigation-related challenges, human societies and fragile ecosystems of the region are highly vulnerable to the impacts of climate change, such as water stress (Evans et al., 2004; Shaffrey et al., 2009), desertification (Bayram and Öztürk, 2014), sea level rise affecting vast low costal lands, and high temperature and humidity with future levels potentially beyond adaptive capacities (Pal and Eltahir, 2016). A low-carbon pathway that manages climate-related risks within the context of sustainable development requires an approach that jointly addresses both types of vulnerabilities (Al Ansari, 2013; Lilliestam and Patt, 2015; Babiker, 2016; Griffiths, 2017b).

The Nationally Determined Contributions (NDCs) for GCC countries identified energy efficiency, deployment of renewables, and technology transfer to enhance agriculture, food security, protection of marine, and management of water and costal zones (Babiker, 2016). Strategic vision documents, such as Saudi Arabia's "Vision 2030", identify emergent opportunities for energy price reforms, energy efficiency, turning emissions in valuable products, and deployment of renewables and other clean technologies, if accompanied with appropriate policies to manage the transition and in the context of economic diversification (Luomi, 2014; Atalay et al., 2016; Griffiths, 2017b; Howarth et al., 2017).

[END BOX 5.2 HERE]

5.4.1.3 Land-based Agriculture, Forestry and Ocean: Mitigation Response Options and Carbon Dioxide Removal

In the AFOLU sector, dietary change towards global healthy diets, that is, a shift from over-consumption of animal-related to plant-related diets, and food waste reduction (see Chapter 4, Section 4.3.2.1) are in synergy with SDGs 2 and 6, and SDG 3 through lower consumption of animal products and reduced losses and waste throughout the food system, contributing to achieving SDGs 12 and 15 (Bajželj et al., 2014; Bustamante et al., 2014; Tilman and Clark, 2014; Hiç et al., 2016).

Power dynamics plays an important role in achieving behavioural change and sustainable consumption (Fuchs et al., 2016). In forest management (see Chapter 4, Section 4.3.2.2), encouraging responsible sourcing of forest products and securing indigenous land tenure has the potential to increase economic benefits by creating decent jobs (SDG 8), maintaining biodiversity (SDG 15), facilitating innovation and upgrading technology (SDG 9), and responsible and just decision making (SDG 16) (Ding et al., 2016; WWF, 2017) (*medium evidence, high agreement*).

Emerging evidence indicates that future mitigation efforts that would be required to reach stringent climate targets, particularly those associated with Carbon Dioxide Removal (CDR) (e.g., Bioenergy with Carbon Capture and Storage (BECCS) and afforestation and reforestation), may also impose significant constraints upon poor and vulnerable communities (SDG 1) via increased food prices and competition for arable land, land appropriation, and dispossession (Cavanagh and Benjaminsen, 2014; Hunsberger et al., 2014; Work, 2015; Muratori et al., 2016; Smith et al., 2016; Burns and Nicholson, 2017; Corbera et al., 2017) with disproportionate negative impacts upon rural poor and indigenous populations (SDG 1) (Grubert et al., 2014; Grill et al., 2015; Zhang and Chen, 2015; Fricko et al., 2016; Johansson et al., 2016; Aha and Ayitey, 2017; De Stefano et al., 2017; Shi et al., 2017) (Section 5.4.2.2, Table 5.3 (available as a supplementary pdf), Figure 5.3) (*robust evidence, high agreement*). Crops for bioenergy may increase irrigation needs and exacerbate water stress with negative associated impacts on SDGs 6 and 10 (Boysen et al., 2017).

Ocean Iron Fertilisation (OIF) and enhanced weathering have two-way interactions with life under water and on land and food security (SDGs 2, 14, and 15) (Table 5.3 (available as a supplementary pdf)). Development of blue carbon resources through coastal (mangrove) and marine (seaweed) vegetative ecosystems encourages integrated water resource management (SDG 6) (Vierros, 2017), promotes life on land (SDG 15) (Potouroglou et al., 2017); poverty reduction (SDG 1) (Schirmer and Bull, 2014; Lamb et al., 2016) and food security (SDG 2) (Ahmed et al., 2017a, b; Duarte et al., 2017; Sondak et al., 2017; Vierros, 2017; Zhang et al., 2017).

[INSERT FIGURE 5.3 HERE]

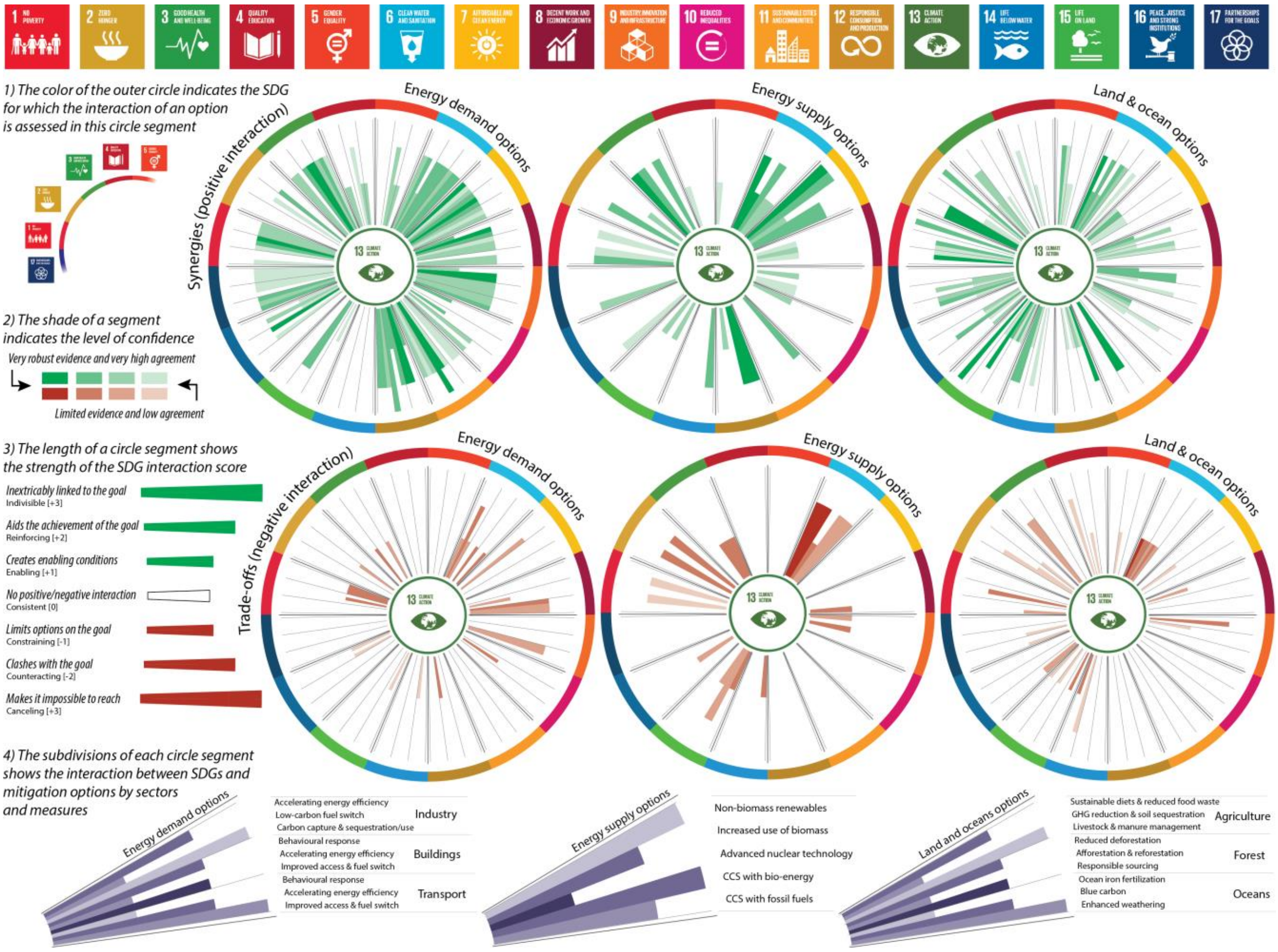

Figure 5.3: Synergies and trade-offs and gross Sustainable Development Goal (SDG)-interaction with individual mitigation options. The top three wheels represent synergies and the bottom three wheels show trade-offs. The colours on the border of the wheels correspond to the SDGs listed above, starting at the 9 o'clock position, with reading guidance in the top-left corner with the quarter circle (Note 1). Mitigation (climate action, SDG 13) is at the centre of the circle. The coloured segments inside the circles can be counted to arrive at the number of synergies (green) and trade-offs (red). The length of the coloured segments shows the strength of the synergies or trade-offs (Note 3) and the shading indicates confidence (Note 2). Various mitigation options within the energy demand sector, energy supply sector, and land and ocean sector, and how to read them within a segment are shown in grey (Note 4). See also Table 5.3 (available as a supplementary pdf).

5.4.2 Sustainable Development Implications of 1.5°C and 2°C Mitigation Pathways

While previous sections have focused on individual mitigation options and their interaction with sustainable development and the SDGs, this section takes a systems perspective. Emphasis is on quantitative pathways depicting path-dependent evolutions of human and natural systems over time. Specifically, the focus is on fundamental transformations and thus stringent mitigation policies consistent with 1.5°C or 2°C, and the differential synergies and trade-offs with respect to the various sustainable development dimensions.

Both 1.5°C and 2°C pathways would require deep cuts in greenhouse gas (GHG) emissions and large-scale changes of energy supply and demand, as well as in agriculture and forestry systems (see Chapter 2, Section 2.4). For the assessment of the sustainable development implications of these pathways, we draw upon studies that show the aggregated impact of mitigation for multiple sustainable development dimensions (Grubler et al., 2018; McCollum et al., 2018; Rogelj et al., 2018) and across multiple Integrated Assessment

Modelling (IAM) frameworks. Often these tools are linked to disciplinary models covering specific SDGs in more detail (Cameron et al., 2016; Rao et al., 2017; Grubler et al., 2018; McCollum et al., 2018). Using multiple IAMs and disciplinary models is important for a robust assessment of the sustainable development implications of different pathways. Emphasis is on multi-regional studies, which can be aggregated to the global scale. The recent literature on 1.5°C mitigation pathways has begun to provide quantifications for a range of sustainable development dimensions, including air pollution and health, food security and hunger, energy access, water security, and multidimensional poverty and equity.

5.4.2.1 Air Pollution and Health

Greenhouse gases and air pollutants are typically emitted by the same sources. Hence, mitigation strategies that reduce GHGs or the use of fossil fuels typically also reduce emissions of pollutants, such as particulate matter (e.g., PM2.5 and PM10), black carbon (BC), sulphur dioxide (SO_2), nitrogen oxides (NO_x), and other harmful species (Clarke et al., 2014) (Figure 5.4), causing adverse health and ecosystem effects at various scales (Kusumaningtyas and Aldrian, 2016).

Mitigation pathways typically show that there are significant synergies for air pollution, and that the synergies increase with the stringency of the mitigation policies (Amann et al., 2011; Rao et al., 2016; Klimont et al., 2017; Shindell et al., 2017; Markandya et al., 2018). Recent multi-model comparisons indicate that mitigation pathways consistent with 1.5°C would result in higher synergies with air pollution compared to pathways that are consistent with 2°C (Figures 5.4 and 5.5). Shindell et al. (2018) indicate that health benefits worldwide over the century of 1.5°C pathways could be in the range of 110 to 190 million fewer premature deaths compared to 2°C pathways. The synergies for air pollution are highest in the developing world, particularly in Asia. In addition to significant health benefits, there are also economic benefits from mitigation, reducing the investment needs in air pollution control technologies by about 35% globally (or about 100 billion US$2015 per year to 2030 in 1.5°C pathways) (McCollum et al., 2018) (Figure 5.5).

5.4.2.2 Food Security and Hunger

Stringent climate mitigation pathways in line with ‘well below 2°C’ or ‘1.5°C’ goals often rely on the deployment of large-scale land-related measures, like afforestation and/or bioenergy supply (Popp et al., 2014; Rose et al., 2014; Creutzig et al., 2015). These land-related measures can compete with food production and hence raise food security concerns (Section 5.4.1.3) (P. Smith et al., 2014). Mitigation studies indicate that so-called ‘single-minded’ climate policy, aiming solely at limiting warming to 1.5°C or 2°C without concurrent measures in the food sector, can have negative impacts for global food security (Hasegawa et al., 2015; McCollum et al., 2018). Impacts of 1.5°C mitigation pathways can be significantly higher than those of 2°C pathways (Figures 5.4 and 5.5). An important driver of the food security impacts in these scenarios is the increase of food prices and the effect of mitigation on disposable income and wealth due to GHG pricing. A recent study indicates that, on aggregate, the price and income effects on food may be bigger than the effect due to competition over land between food and bioenergy (Hasegawa et al., 2015).

In order to address the issue of trade-offs with food security, mitigation policies would need to be designed in a way that shields the population at risk of hunger, including through the adoption of different complementary measures, such as food price support. The investment needs of complementary food price policies are found to be globally relatively much smaller than the associated mitigation investments of 1.5°C pathways (Figure 5.4) (McCollum et al., 2018). Besides food support price, other measures include improving productivity and efficiency of agricultural production systems (FAO and NZAGRC, 2017a, b; Frank et al., 2017) and programs focusing on forest land-use change (Havlík et al., 2014). All these lead to additional benefits of mitigation, improving resilience and livelihoods.

van Vuuren et al. (2018) and Grubler et al. (2018) show that 1.5°C pathways without reliance on BECCS can be achieved through a fundamental transformation of the service sectors which would significantly reduce energy and food demand (see Chapter 2, Sections 2.1.1, 2.3.1, and 2.4.3). Such low energy demand (LED) pathways would result in significantly reduced pressure on food security, lower food prices, and put fewer people at risk of hunger. Importantly, the trade-offs with food security would be reduced by the avoided impacts in the agricultural sector due to the reduced warming associated with the 1.5°C pathways (see Chapter 3, Section 3.5). However, such feedbacks are not comprehensively captured in the studies on mitigation.

5.4.2.3 Lack of Energy Access/Energy Poverty

A lack of access to clean and affordable energy (especially for cooking) is a major policy concern in many countries, especially in those in South Asia and Africa where major parts of the population still rely primarily on solid fuels for cooking (IEA and World Bank, 2017). Scenario studies which quantify the interactions between climate mitigation and energy access indicate that stringent climate policy which would affect energy prices could significantly slow down the transition to clean cooking fuels, such as liquefied petroleum gas (LPG) or electricity (Cameron et al., 2016).

Estimates across six different IAMs (McCollum et al., 2018) indicate that, in the absence of compensatory measures, the number of people without access to clean cooking fuels may increase. Re-distributional measures, such as subsidies on cleaner fuels and stoves, could compensate for the negative effects of mitigation on energy access. Investment costs of the re-distributional measures in 1.5°C pathways (on average around 120 billion per year to 2030; Figure 5.5) are much smaller than the mitigation investments of 1.5°C pathways (McCollum et al., 2018). The recycling of revenues from climate policy might act as a means to help finance the costs of providing energy access to the poor (Cameron et al., 2016).

5.4.2.4 Water Security

Transformations towards low-emissions energy and agricultural systems can have major implications for freshwater demand as well as water pollution. The scaling up of renewables and energy efficiency as depicted by low emissions pathways would, in most instances, lower water demands for thermal energy supply facilities (‘water-for-energy’) compared to fossil energy technologies, and thus reinforce targets related to water access and scarcity (see Chapter 4, Section 4.2.1). However, some low-carbon options such as bioenergy, centralised solar power, nuclear, and hydropower technologies could, if not managed properly, have counteracting effects that compound existing water-related problems in a given locale (Byers et al., 2014; Fricko et al., 2016; IEA, 2016; Fujimori et al., 2017a; McCollum et al., 2017; Wang, 2017).

Under stringent mitigation efforts, the demand for bioenergy can result in a substantial increase of water demand for irrigation, thereby potentially contributing to water scarcity in water-stressed regions (Berger et al., 2015; Bonsch et al., 2016; Jägermeyr et al., 2017). However, this risk can be reduced by prioritising rain-fed production of bioenergy (Hayashi et al., 2015, 2018; Bonsch et al., 2016), but might have adverse effects for food security (Boysen et al., 2017).

Reducing food and energy demand without compromising the needs of the poor emerges as a robust strategy for both water conservation and GHG emissions reductions (von Stechow et al., 2015; IEA, 2016; Parkinson et al., 2016; Grubler et al., 2018). The results underscore the importance of an integrated approach when developing water, energy, and climate policy (IEA, 2016).

Estimates across different models for the impacts of stringent mitigation pathways on energy-related water uses seem ambiguous. Some pathways show synergies (Mouratiadou et al., 2018) while others indicate trade-offs and thus increases of water use due to mitigation (Fricko et al., 2016). The signal depends on the adopted policy implementation or mitigation strategies and technology portfolio. A number of adaptation options exist (e.g., dry cooling), which can effectively reduce electricity-related water trade-offs (Fricko et al., 2016; IEA, 2016). Similarly, irrigation water use will depend on the regions where crops are produced, the sources of bioenergy (e.g., agriculture vs. forestry) and dietary change induced by climate policy. Overall, and also considering other water-related SDGs, including access to safe drinking water and sanitation as well as waste-water treatment, investments into the water sector seem to be only modestly affected by stringent climate policy compatible with 1.5°C (Figure 5.5) (McCollum et al., 2018).

[INSERT FIGURE 5.4 HERE]

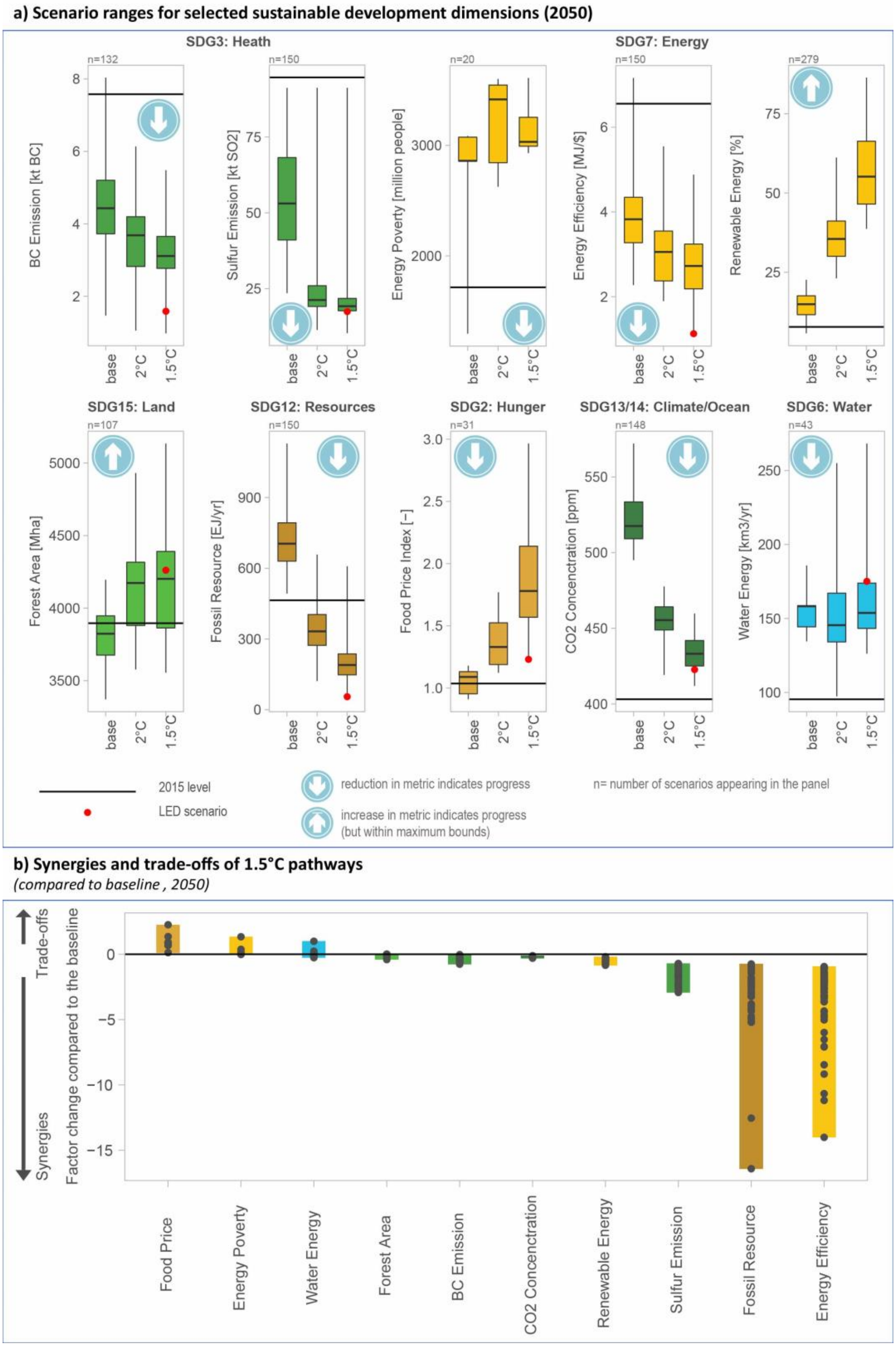

Figure 5.4: **Sustainable development implications of mitigation actions in 1.5°C pathways**. **Panel (a)** shows ranges for 1.5°C pathways for selected sustainable development dimensions compared to the ranges of 2°C pathways and baseline pathways. The panel (a) depicts interquartile and the full range across the scenarios for Sustainable Development Goal (SDG) 2 (hunger), SDG 3 (health), SDG 6 (water), SDG 7 (energy), SDG 13 (climate), and SDG 15 (land). Progress towards achieving the SDGs is denoted by arrow symbols (increase or decrease of indicator). Black horizontal lines show 2015 values for comparison. Note that sustainable development effects are estimated for the effect of mitigation and do not include benefits from avoided impacts (see Chapter 3, Section 3.5). Low energy demand (LED) denotes estimates from a pathway with extremely low energy demand reaching 1.5°C without Bioenergy with Carbon Capture and Storage (BECCS). **Panel (b)** presents the resulting full range for synergies and trade-offs of 1.5°C pathways compared to the corresponding baseline scenarios. The y-axis in panel (b) indicates the factor change in the 1.5°C pathway compared to the baseline. Note that the figure shows gross impacts of mitigation and does not include feedbacks due to avoided impacts. The realisation of the side-effects will critically depend on local circumstances and implementation practice. Trade-offs across many sustainable development dimensions can be reduced through complementary/re-distributional measures. The figure is not comprehensive and focuses on those sustainable development dimensions for which quantifications across models are available. Sources: 1.5°C pathways database of Chapter 2 (Grubler et al., 2018; McCollum et al., 2018).

[INSERT FIGURE 5.5 HERE]

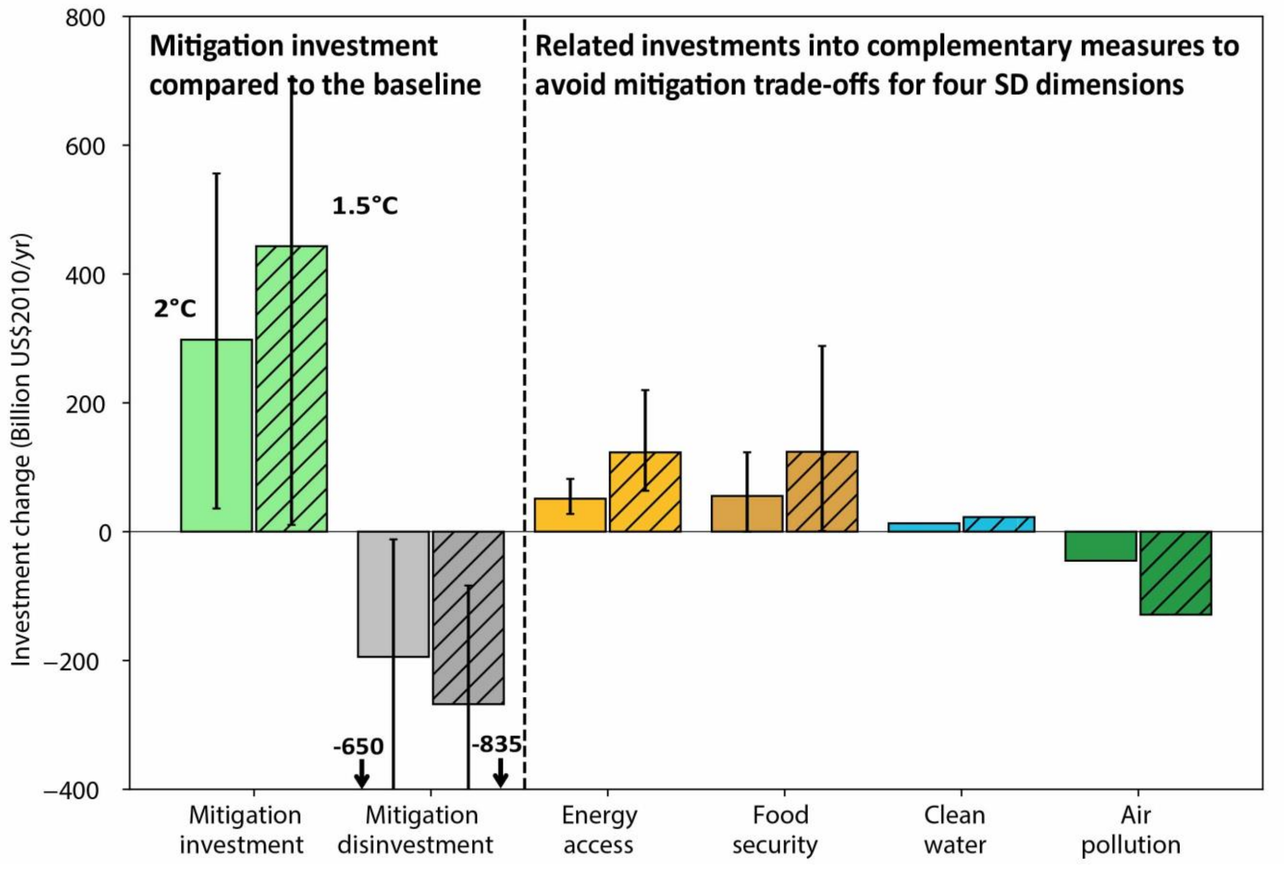

Figure 5.5: **Investment into mitigation up until 2030 and implications for investments for four sustainable development dimensions**. Cross-hatched bars show the median investment in 1.5°C pathways across results from different models, and solid bars for 2°C pathways, respectively. Whiskers on bars represent minima and maxima across estimates from six models. Clean water and air pollution investments are available only from one model. Mitigation investments show the change in investments across mitigation options compared to the baseline. Negative mitigation investments (grey bars) denote disinvestment (reduced investment needs) into fossil fuel sectors compared to the baseline. Investments for different

sustainable development dimensions denote the investment needs for complementary measures in order to avoid trade-offs (negative impacts) of mitigation. Negative sustainable development investments for air pollution indicate cost savings, and thus synergies of mitigation for air pollution control costs. The values compare to about US$(2010) 2 trillion (range of 1.4 to 3 trillion) of total energy-related investments in the 1.5°C pathways. Source: estimates from CD-LINKS scenarios summarised by McCollum et al. (2018).

In summary, the assessment of mitigation pathways shows that, to meet the 1.5°C target, a wide range of mitigation options would need to be deployed (see Chapter 2, Sections 2.3 and 2.4). While pathways aiming at 1.5° C are associated with high synergies for some sustainable development dimensions (such as human health and air pollution, forest preservation), the rapid pace and magnitude of the required changes would also lead to increased risks for trade-offs for other sustainable development dimensions (particularly food security) (Figures 5.4 and 5.5). Synergies and trade-offs are expected to be unevenly distributed between regions and nations (Box 5.2), though little literature has formally examined such distributions under 1.5°C consistent mitigation scenarios. Reducing these risks requires smart policy designs and mechanisms that shield the poor and redistribute the burden so that the most vulnerable are not affected. Recent scenario analyses show that associated investments for reducing the trade-offs for, for example, food, water and energy access to be significantly lower than the required mitigation investments (McCollum et al., 2018). Fundamental transformation of demand, including efficiency and behavioural changes, can help to significantly reduce the reliance on risky technologies, such as BECCS, and thus reduce the risk of potential trade-offs between mitigation and other sustainable development dimensions (von Stechow et al., 2015; Grubler et al., 2018; van Vuuren et al., 2018). Reliance on demand-side measures only, however, would not be sufficient for meeting stringent targets, such as 1.5°C and 2°C (Clarke et al., 2014).

5.5 Sustainable Development Pathways to 1.5°C

This section assesses what is known in the literature on development pathways that are sustainable and climate-resilient and relevant to a 1.5°C warmer world. Pathways, transitions from today's world to achieving a set of future goals (see Chapter 1, Section 1.2.3, Cross-Chapter Box 1), follow broadly two main traditions: first, as integrated pathways describing the required societal and systems transformations, combining quantitative modelling and qualitative narratives at multiple spatial scales (global to sub-national); and second, as country- and community-level, solution-oriented trajectories and decision-making processes about context- and place-specific opportunities, challenges, and trade-offs. These two notions of pathways offer different, though complementary, insights into the nature of 1.5°C-relevant trajectories and the short-term actions that enable long-term goals. Both highlight to varying degrees the urgency, ethics, and equity dimensions of possible trajectories and society- and system-wide transformations, yet at different scales, building on Chapter 2 (see Section 2.4) and Chapter 4 (see Section 4.5).

5.5.1 Integration of Adaptation, Mitigation, and Sustainable Development

Insights into climate-compatible development (see Glossary) illustrate how integration between adaptation, mitigation, and sustainable development works in context-specific projects, how synergies are achieved, and what challenges are encountered during implementation (Stringer et al., 2014; Suckall et al., 2014; Antwi-Agyei et al., 2017a; Bickersteth et al., 2017; Kalafatis, 2017; Nunan, 2017). The operationalisation of climate-compatible development, including climate-smart agriculture and carbon-forestry projects (Lipper et al., 2014; Campbell et al., 2016; Quan et al., 2017), shows multi-level and multi-sector trade-offs involving 'winners' and 'losers' across governance levels (Kongsager and Corbera, 2015; Naess et al., 2015; Ficklin et al., 2017; Karlsson et al., 2017; Tanner et al., 2017; Taylor, 2017; Wood, 2017) (*high confidence*). Issues of power, participation, values, equity, inequality, and justice transcend case study examples of attempted integrated approaches (Nunan, 2017; Phillips et al., 2017; Stringer et al., 2017; Wood, 2017), also reflected in policy frameworks for integrated outcomes (Stringer et al., 2014; Di Gregorio et al., 2017; Few et al., 2017; Tanner et al., 2017).

Ultimately, reconciling trade-offs between development needs and emission reductions towards a 1.5°C warmer world requires a dynamic view of the interlinkages between adaptation, mitigation, and sustainable development (Nunan, 2017). This entails recognition of the ways in which development contexts shape the choice and effectiveness of interventions, limit the range of responses afforded to communities and governments, and potentially impose injustices upon vulnerable groups (UNRISD, 2016; Thornton and Comberti, 2017). A variety of approaches, both quantitative and qualitative, exist to examine possible sustainable development pathways under which climate and sustainable development goals can be achieved, and synergies and trade-offs for transformation identified (Sections 5.3 and 5.4).

5.5.2 Pathways for Adaptation, Mitigation, and Sustainable Development

This section focuses on the growing body of pathways literature describing the dynamic and systemic integration of mitigation and adaptation with sustainable development in the context of a 1.5°C warmer world. These studies are critically important for the identification of 'enabling' conditions under which climate and the SDGs can be achieved, and thus help the design of transformation strategies that maximise synergies and avoid potential trade-offs (Sections 5.3 and 5.4). Full integration of sustainable development dimensions is, however, challenging, given their diversity and the need for high temporal, spatial, and social resolution to address local effects, including heterogeneity related to poverty and equity (von Stechow et al., 2015). Research on long-term climate change mitigation and adaptation pathways has covered individual SDGs to different degrees. Interactions between climate and other SDGs have been explored for SDGs 2, 3, 4, 6, 7, 8, 12, 14, and 15 (Clarke et al., 2014; Abel et al., 2016; von Stechow et al., 2016; Rao et al., 2017) while interactions with SDGs 1, 5, 11, and 16 remain largely underexplored in integrated long-term scenarios (Zimm et al., 2018).

Quantitative pathways studies now better represent 'nexus' approaches to assess sustainable development dimensions. In such approaches (see Chapter 4, Section 4.3.3.8), a sub-set of sustainable development dimensions are investigated together because of their close relationships (Welsch et al., 2014; Conway et al., 2015; Keairns et al., 2016; Parkinson et al., 2016; Rasul and Sharma, 2016; Howarth and Monasterolo, 2017). Compared to single objective climate-SDG assessments (Section 5.4.2), nexus solutions attempt to integrate complex interdependencies across diverse sectors in a systems approach for consistent analysis. Recent pathways studies show how water, energy, and climate (SDGs 6, 7 and 13) interact (Parkinson et al., 2016; McCollum et al., 2018), calling for integrated water-energy investment decisions to manage systemic risks. For instance, the provision of bioenergy, important in many 1.5°C-consistent pathways, can help resolve 'nexus challenges' by alleviating energy security concerns, but can also have adverse 'nexus impacts' on food security, water use, and biodiversity (Lotze-Campen et al., 2014; Bonsch et al., 2016). Policies that improve the resource use efficiency across sectors can maximise synergies for sustainable development (Bartos and Chester, 2014; McCollum et al., 2018; van Vuuren et al., 2018). Mitigation compatible with 1.5°C can significantly reduce impacts and adaptation needs in the nexus sectors compared to 2°C (Byers et al., 2018), In order to avoid trade-offs due to high carbon pricing of 1.5°C pathways, regulation in specific areas may complement price-based instruments. Such combined policies generally lead also to more early action maximizing synergies and avoiding some of the adverse climate effects for sustainable development (Bertram et al., 2018).

The comprehensive analysis of climate change in the context of sustainable development requires suitable reference scenarios that lend themselves to broader sustainable development analyses. The Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017a; Riahi et al., 2017) (Chapter 1, Cross-Chapter Box 1 in Chapter 1) constitute an important first step in providing a framework for the integrated assessment of adaptation and mitigation and their climate-development linkages (Ebi et al., 2014). The five underlying SSP narratives (O'Neill et al., 2017a) map well into some of the key SDG dimensions, with one of the pathways (SSP1) explicitly depicting sustainability as the main theme (van Vuuren et al., 2017b).

To date, no pathway in the literature proves to achieve all 17 SDGs because several targets are not met or not sufficiently covered in the analysis, hence resulting in a sustainability gap (Zimm et al., 2018). The SSPs facilitate the systematic exploration of different sustainable dimensions under ambitious climate objectives. SSP1 proves to be in line with eight SDGs (3, 7, 8, 9, 10, 11, 13, and 15) and several of their targets in a 2°C warmer world (van Vuuren et al., 2017b; Zimm et al., 2018). But, important targets for SDGs 1, 2, and 4 (i.e., people living in extreme poverty, people living at the risk of hunger, and gender gap in years of schooling) are not met in this scenario.

The SSPs show that sustainable socio-economic conditions will play a key role in reaching stringent climate targets (Riahi et al., 2017; Rogelj et al., 2018). Recent modelling work has examined 1.5°C-consistent, stringent mitigation scenarios for 2100 applied to the SSPs, using six different Integrated Assessment Models (IAMs). Despite limitations of these models which are coarse approximations of reality, robust trends can be identified (Rogelj et al., 2018). SSP1 - which depicts broader “sustainability” as well as enhancing equity and poverty reductions - is the only pathway where all models could reach 1.5°C and is associated with the lowest mitigation costs across all SSPs. A decreasing number of models was successful for SSP2, SSP4, and SSP5, respectively, indicating distinctly higher risks of failure due to high growth and energy intensity as well as geographical and social inequalities and uneven regional development. And reaching 1.5°C has even been found infeasible in the less sustainable SSP3 - “regional rivalry” (Fujimori et al., 2017b; Riahi et al., 2017). All these conclusions hold true if a 2°C objective is considered (Calvin et al., 2017; Fujimori et al., 2017b; Popp et al., 2017; Riahi et al., 2017). Rogelj et al. (2018) also show that fewer scenarios are, however, feasible across different SSPs in case of 1.5°C, and mitigation costs substantially increase in 1.5°C pathways compared to 2°C pathways.

There is a wide range of SSP-based studies focusing on the connections between adaptation/impacts and different sustainable development dimensions (Hasegawa et al., 2014; Ishida et al., 2014; Arnell et al., 2015; Bowyer et al., 2015; Burke et al., 2015; Lemoine and Kapnick, 2016; Rozenberg and Hallegatte, 2016; Blanco et al., 2017; Hallegatte and Rozenberg, 2017; O'Neill et al., 2017a; Rutledge et al., 2017; Byers et al., 2018).

New methods for projecting inequality and poverty (downscaled to sub-national rural and urban levels as well as spatially-explicit levels) have enabled advanced SSP-based assessments of locally sustainable development implications of avoided impacts and related adaptation needs. For instance, Byers et al. (2018) find that, in a 1.5°C warmer world, a focus on sustainable development can reduce the climate risk exposure of populations vulnerable to poverty by more than an order of magnitude (Section 5.2.2). Moreover, aggressive reductions in between-country inequality may decrease the emissions intensity of global economic growth (Rao and Min, 2018). This is due to the higher potential for decoupling of energy from income growth in lower-income countries, due to high potential for technological advancements that reduce the energy intensity of growth of poor countries - critical also for reaching 1.5°C in a socially and economically equitable way. Participatory downscaling of SSPs in several European Union countries and in Central Asia shows numerous possible pathways of solutions to the 2-1.5°C goal, depending on differential visions (Tàbara et al., 2018). Other participatory applications of the SSPs, for example in West Africa (Palazzo et al., 2017) and the south-eastern United States (Absar and Preston, 2015), illustrate the potentially large differences in adaptive capacity within regions and between sectors.

Harnessing the full potential of the SSP framework to inform sustainable development requires (1) further elaboration and extension of the current SSPs to cover sustainable development objectives explicitly; (2) the development of new or variants of current narratives that would facilitate more SDG-focused analyses with climate as one objective (among other SDGs) (Riahi et al., 2017); (3) scenarios with high regional resolution (Fujimori et al., 2017b); (4) a more explicit representation of institutional and governance change associated with the SSPs (Zimm et al., 2018); and (5) a scale-up of localised and spatially-explicit vulnerability, poverty and inequality estimates, which have emerged in recent publications based on the SSPs (Byers et al., 2018) and are essential to investigate equity dimensions (Klinsky and Winkler, 2018).

5.5.3 Climate-Resilient Development Pathways

This section assesses the literature on pathways as solution-oriented trajectories and decision-making processes for attaining transformative visions for a 1.5°C warmer world. It builds on climate-resilient development pathways (CRDPs) introduced in the AR5 (Olsson et al., 2014) (Section 5.1.2) as well as growing, literature (e.g., Eriksen et al., 2017; Johnson, 2017; Orindi et al., 2017; Kirby and O'Mahony, 2018; Solecki et al., 2018) that uses CRDPs as a conceptual and aspirational idea for steering societies towards low-carbon, prosperous, and ecologically safe futures. Such a notion of pathways foregrounds decision-making processes at local to national levels to situate transformation, resilience, equity, and well-being in the complex reality of specific places, nations, and communities (Harris et al., 2017; Ziervogel et al., 2017; Fazey et al., 2018; Gajjar et al., 2018; Klinsky and Winkler, 2018; Patterson et al., 2018; Tàbara et al., 2018).

Pathways compatible with 1.5°C warming are not merely scenarios to envision possible futures but processes of deliberation and implementation that address societal values, local priorities, and inevitable trade-offs. This includes attention to politics and power that perpetuate business-as-usual trajectories (K. O’Brien, 2016; Harris et al., 2017), the politics that shape sustainability and capabilities of everyday life (Agyeman et al., 2016; Schlosberg et al., 2017), and ingredients for community resilience and transformative change (Fazey et al., 2018). Chartering CRDPs encourages locally-situated and problem-solving processes to negotiate and operationalise resilience ‘on the ground’ (Beilin and Wilkinson, 2015; Harris et al., 2017; Ziervogel et al., 2017). This entails contestation, inclusive governance, and iterative engagement of diverse populations with varied needs, aspirations, agency, and rights claims, including those most affected, to deliberate trade-offs in a multiplicity of possible pathways (see Figure 5.6) (Stirling, 2014; Vale, 2014; Walsh-Dilley and Wolford, 2015; Biermann et al., 2016; J.R.A. Butler et al., 2016; K.L. O’Brien, 2016; Harris et al., 2017; Jones and Tanner, 2017; Mapfumo et al., 2017; Rosenbloom, 2017; Gajjar et al., 2018; Klinsky and Winkler, 2018; Lyon, 2018; O’Brien, 2018; Tàbara et al., 2018) (*high confidence*).

[INSERT FIGURE 5.6 HERE]

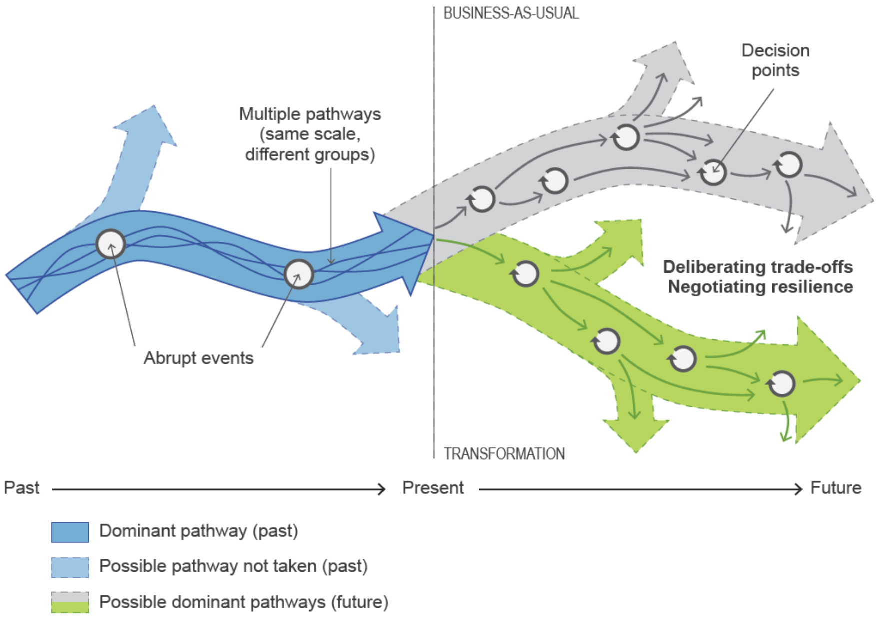

Figure 5.6: Pathways into the future, with path dependencies and iterative problem-solving and decision-making (after Fazey et al. (2016).

5.5.3.1 *Transformations, Equity, and Well-being*

Most literature related to CRDPs invokes the concept of transformation, underscoring the need for urgent and far-reaching changes in practices, institutions, and social relations in society. Transformations toward a 1.5°C warmer world would need to address considerations for equity and well-being, including in trade-off decisions (see Figure 5.1).

To attain the anticipated *transformations*, all countries as well as non-state actors would need to strengthen their contributions, through bolder and more committed cooperation and equitable effort-sharing (Rao, 2014; Frumhoff et al., 2015; Ekwurzel et al., 2017; Holz et al., 2017; Millar et al., 2017; Shue, 2017; Robinson and Shine, 2018) (*medium evidence, high agreement*). Sustaining decarbonisation rates at a 1.5°C-compatible level would be unprecedented and not possible without rapid transformations to a net-zero-emissions global economy by mid-century or the later half of the century (see Chapters 2 and 4). Such efforts would entail overcoming technical, infrastructural, institutional, and behavioural barriers across all sectors and levels of society (Pfeiffer et al., 2016; Seto et al., 2016) and defeating path dependencies, including poverty traps (Boonstra et al., 2016; Enqvist et al., 2016; Haider et al., 2017; Lade et al., 2017). Transformation also entails ensuring that 1.5°C-compatible pathways are inclusive and desirable, build solidarity and alliances, and protect vulnerable groups, including against disruptions of transformation (Patterson et al., 2018).

There is growing emphasis on the role of *equity, fairness*, and *justice* (see Glossary) regarding context-specific transformations and pathways to a 1.5°C warmer world (Shue, 2014; Thorp, 2014; Dennig et al., 2015; Moellendorf, 2015; Klinsky et al., 2017b; Roser and Seidel, 2017; Sealey-Huggins, 2017; Klinsky and Winkler, 2018; Robinson and Shine, 2018) (*medium evidence, high agreement*). Consideration for what is equitable and fair suggests the need for stringent decarbonisation and up-scaled adaptation that do not exacerbate social injustices, locally and at national levels (Okereke and Coventry, 2016), uphold human rights (Robinson and Shine, 2018), are socially desirable and acceptable (von Stechow et al., 2016; Rosenbloom, 2017), address values and beliefs (O’Brien, 2018), and overcome vested interests (Normann, 2015; Patterson et al., 2016). Attention is often drawn to huge disparities in the cost, benefits, opportunities, and challenges involved in transformation within and between countries, and the fact that the suffering of already poor, vulnerable, and disadvantaged populations may be worsened, if care to protect them is not taken (Holden et al., 2017; Klinsky and Winkler, 2018; Patterson et al., 2018).

Well-being for all (Dearing et al., 2014; Raworth, 2017) is at the core of an ecologically safe and socially just space for humanity, including health and housing to peace and justice, social equity, gender equality, and political voices (Raworth, 2017). It is in alignment with transformative social development (UNRISD, 2016) and the 2030 Agenda of ‘leaving no one behind’. The social conditions to enable well-being for all are to reduce entrenched inequalities within and between countries (Klinsky and Winkler, 2018), rethink prevailing values, ethics and behaviours (Holden et al., 2017), allow people to live a life in dignity while avoiding actions that undermine capabilities (Klinsky and Golub, 2016), transform economies (Popescu and Ciurlau, 2016; Tàbara et al., 2018), overcome uneven consumption and production patterns (Dearing et al., 2014; Häyhä et al., 2016; Raworth, 2017) and conceptualise development as well-being rather than mere economic growth (Gupta and Pouw, 2017) (*medium evidence, high agreement*).

5.5.3.2 Development Trajectories, Sharing of Efforts, and Cooperation

The potential for pursuing sustainable and climate-resilient development pathways toward a 1.5°C warmer world differs between and within nations, due to differential development achievements and trajectories, and opportunities and challenges (Figure 5.1) (*very high confidence*). There are clear differences between high-income countries where social achievements are high, albeit often with negative effects on the environment, and most developing nations where vulnerabilities to climate change are high and social support and life satisfaction are low, especially in the Least Developed Countries (Sachs et al., 2017; O’Neill et al., 2018). Differential starting points for CRDPs between and within countries, including path dependencies (Figure 5.6), call for sensitivity to context (Klinsky and Winkler, 2018). For the developing world, limiting warming to 1.5°C also means potentially severely curtailed development prospects (Okereke and Coventry, 2016) and risks to human rights from both climate action and inaction to achieve this goal (Robinson and Shine, 2018) (Section 5.2). Within-country development differences remain, despite efforts to ensure inclusive societies (Gupta and Arts, 2017; Gupta and Pouw, 2017). Cole et al. (2017), for instance, show how differences between provinces in South Africa constitute barriers to sustainable development trajectories and for operationalising nation-level SDGs, across various dimensions of social deprivation and environmental stress, reflecting historic disadvantages.

Moreover, various equity and effort- or burden-sharing approaches to climate stabilisation in the literature allow to sketch national potentials for a 1.5°C warmer world (e.g., CSO Review, 2015; Meinshausen et al., 2015; Okereke and Coventry, 2016; Anand, 2017; Bexell and Jönsson, 2017; Holz et al., 2017; Otto et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017; Kartha et al., 2018; Winkler et al., 2018). Many approaches build on the AR5 'responsibility-capacity-need' assessment (Clarke et al., 2014), complement other proposed national-level metrics for capabilities, equity, and fairness (Heyward and Roser, 2016; Klinsky et al., 2017a), or fall under the wider umbrella of fair share debates on responsibility, capability, and right to development in climate policy (Fuglestvedt and Kallbekken, 2016). Importantly, different principles and methodologies generate different calculated contributions, responsibilities, and capacities (Skeie et al., 2017).

The notion of nation-level fair shares is now also discussed in the context of limiting global warming to 1.5°C, and the Nationally Determined Contributions (NDCs) (see Chapter 4, Cross-Chapter Box 11 in Chapter 4) (CSO Review, 2015; Mace, 2016; Holz et al., 2017; Pan et al., 2017; Robiou du Pont et al., 2017; Kartha et al., 2018; Winkler et al., 2018). A study by Pan et al. (2017) concluded that all countries would need to contribute to ambitious emission reduction and that current pledges for 2030 by seven out of eight high-emitting countries would be insufficient to meet 1.5°C. Emerging literature on justice-centred pathways to 1.5°C points toward ambitious emission reductions domestically and committed cooperation internationally whereby wealthier countries support poorer ones, technologically, financially, and otherwise to enhance capacities (Okereke and Coventry, 2016; Holz et al., 2017; Robinson and Shine, 2018; Shue, 2018). These findings suggest that equitable and 1.5°C-compatible pathways would require fast action across all countries at all levels of development rather than late accession of developing countries (as assumed under SSP3, see Chapter 2), with external support for prompt mitigation and resilience-building efforts in the latter (*medium evidence, medium agreement*).

Scientific advances since the AR5 now also allow to determine contributions to climate change for non-state actors (see Chapter 4, Section 4.4.1) and their potential to contribute to CRDPs (*medium evidence, medium agreement*). This includes cities (Bulkeley et al., 2013, 2014; Byrne et al., 2016), businesses (Heede, 2014; Frumhoff et al., 2015; Shue, 2017), transnational initiatives (Castro, 2016; Andonova et al., 2017), and industries. Recent work demonstrates the contributions of 90 industrial carbon producers to global temperature and sea level rise, and their responsibilities to contribute to investments in and support for mitigation and adaptation (Heede, 2014; Ekwurzel et al., 2017; Shue, 2017) (Sections 5.6.1 and 5.6.2).

At the level of groups and individuals, equity in pursuing climate resilience for a 1.5°C warmer world means addressing disadvantage, inequities, and empowerment that shape transformative processes and pathways (Fazey et al., 2018), and deliberate efforts to strengthen the capabilities, capacities, and well-being of poor, marginalised, and vulnerable people (Byrnes, 2014; Tokar, 2014; Harris et al., 2017; Klinsky et al., 2017a; Klinsky and Winkler, 2018). Community-driven CRDPs can flag potential negative impacts of national trajectories on disadvantaged groups, such as low-income families and communities of colour (Rao, 2014). They emphasise social equity, participatory governance, social inclusion, and human rights, as well as innovation, experimentation, and social learning (see Glossary) (*medium evidence, high agreement*) (Sections 5.5.3.3 and 5.6).

5.5.3.3 Country and Community Strategies and Experiences

There are many possible pathways toward climate-resilient futures (O'Brien, 2018; Tàbara et al., 2018). Literature depicting different sustainable development trajectories in line with CRDPs is growing with some specific to 1.5°C global warming. Most experiences to date are at local and sub-national levels (Cross-Chapter Box 13 in this Chapter) while state-level efforts align largely with green economy trajectories or planning for climate resilience (Box 5.3). Due to the fact that these strategies are context-specific, the literature is scarce on comparisons, efforts to scale up, and systematic monitoring.

States can play an enabling or hindering role in transitions to 1.5°C warmer worlds (Patterson et al., 2018). The literature on strategies to reconcile low-carbon trajectories with sustainable development and ecological sustainability through green growth, inclusive growth, de-growth, post-growth, and development as well-being shows *low agreement* (see Chapter 4, Section 4.5). Efforts that align best with CRDPs are described as ‘transformational’ and ‘strong’ (Ferguson, 2015). Some view ‘thick green’ perspectives as enabling equity, democracy, and agency building (Lorek and Spangenberg, 2014; Stirling, 2014; Ehresman and Okereke, 2015; Buch-Hansen, 2018), others show how green economy and sustainable development pathways can align (Brown et al., 2014; Georgeson et al., 2017b), and how a green economy can help link the SDGs with NDCs, for instance in Mongolia, Kenya, and Sweden (Shine, 2017). Others still critique the continuous reliance on market mechanisms (Wanner, 2014; Brockington and Ponte, 2015), and disregard for equity and distributional and procedural justice (Stirling, 2014; Bell, 2015).

Country-level pathways and achievements vary significantly (*robust evidence*, *medium agreement*). For instance, the Scandinavian countries rank top in the Global Green Economy Index (Dual Citizen LLC, 2016), although they also tend to show high spill-over effects (Holz et al., 2017) and transgress their biophysical boundaries (O’Neill et al., 2018). State-driven efforts in non-member countries of the Organisation for Economic Co-operation and Development include Ethiopia’s ‘Climate-resilient Green Economy Strategy’, Mozambique’s ‘Green Economy Action Plan’, and Costa Rica’s ecosystem- and conservation-driven green transition paths. China and India have adopted technology and renewables pathways (Brown et al., 2014; Death, 2014, 2015, 2016; Khanna et al., 2014; Chen et al., 2015; Kim and Thurbon, 2015; Wang et al., 2015; Weng et al., 2015). Brazil promotes low per-capita GHG emissions, clean energy sources, green jobs, renewables, and sustainable transportation while slowing rates of deforestation (Brown et al., 2014; La Rovere, 2017) (see Chapter 4, Box 4.7). Yet, concerns remain regarding persistent inequalities, ecosystem monetisation, lack of participation in green-style projects (Brown et al., 2014), and labour conditions and risk of displacement in the sugarcane ethanol sector (McKay et al., 2016). Experiences with low-carbon development pathways in Least Developed Countries (LDCs) highlight the crucial role of identifying synergies across scale, removing institutional barriers, and ensuring equity and fairness in distributing benefits as part of the right to development (Rai and Fisher, 2017).

In small islands states, for many of which climate change hazards and impacts at 1.5°C pose significant risks to sustainable development (see Chapter 3 Box 3.5, Chapter 4 Box 4.3, Box 5.3), examples of CRDPs have emerged since the AR5. This includes the SAMOA Pathway: SIDS Accelerated Modalities of Action (see Chapter 4, Box 4.3) (UN, 2014a; Government of Kiribati, 2016; Steering Committee on Partnerships for SIDS and UNDESA, 2016; Lefale et al., 2017) and the Framework for Resilient Development in the Pacific, a leading example of integrated regional climate change adaptation planning for mitigation and sustainable development, disaster risk management and low carbon economies (FRDP, 2016). Small islands of the Pacific vary significantly in their capacity and resources to support effective integrated planning (McCubbin et al., 2015; Barnett and Walters, 2016; Cvitanovic et al., 2016; Hemstock, 2017; Robinson and Dornan, 2017). Vanuatu (Box 5.3) has developed a significant coordinated national adaptation plan to advance the 2030 Agenda for Sustainable Development, respond to the Paris Agreement, and reduce the risk of disasters in line with the Sendai targets (UNDP, 2016; Republic of Vanuatu, 2017).

[START BOX 5.3 HERE]

Box 5.3: Republic of Vanuatu – National Planning for Development and Climate Resilience

The Republic of Vanuatu is leading Pacific Small Island Developing States (SIDS)to develop a nationally coordinated plan for climate-resilient development in the context of high exposure to hazard risk (MCCA, 2016; UNU-EHS, 2016). The majority of the population depends on subsistence, rain-fed agriculture and coastal fisheries for food security (Sovacool et al., 2017). Sea level rise, increased prolonged drought, water shortages, intense storms, cyclone events, and degraded coral reef environments threaten human security in a 1.5°C warmer world (see Chapter 3, Box 3.5) (SPC, 2015; Aipira et al., 2017). Given Vanuatu’s long history of disasters, local adaptive capacity is relatively high, despite barriers to the use of local knowledge and technology, and low rates of literacy and women’s participation (McNamara and Prasad, 2014; Aipira et al., 2017; Granderson, 2017). However, the adaptive capacity of Vanuatu and other SIDS is increasingly constrained due to more frequent severe weather events (see Chapter 3 Box 3.5, Chapter 4, Cross-Chapter Box 9 in Chapter 4) (Gero et al., 2013; Kuruppu and Willie, 2015; SPC, 2015; Sovacool et al., 2017).

Vanuatu has developed a national sustainable development plan for 2016-2030: the People’s Plan (Republic of Vanuatu, 2016). This coordinated, inclusive plan of action on economy, environment, and society aims to strengthen adaptive capacity and resilience to climate change and disasters. It emphasises rights of all Ni-Vanuatu, including women, youth, the elderly, and vulnerable groups (Nalau et al., 2016). Vanuatu has also developed a Coastal Adaptation Plan (Republic of Vanuatu, 2016), an integrated Climate Change and Disaster Risk Reduction Policy (2016–2030) (SPC, 2015), and the first South Pacific National Advisory Board on Climate Change & Disaster Risk Reduction (SPC, 2015; UNDP, 2016).

Vanuatu aims to integrate planning at multiple scales, and increase climate resilience by supporting local coping capacities and iterative processes of planning for sustainable development and integrated risk assessment (Aipira et al., 2017; Eriksson et al., 2017; Granderson, 2017). Climate-resilient development is also supported by non-state partnerships, for example, the ‘Yumi stap redi long climate change’– or the Vanuatu non-governmental organisation Climate Change Adaptation Program (Maclellan, 2015). This programme focuses on equitable governance, with particular attention to supporting women’s voices in decision making through allied programs addressing domestic violence, and rights-based education to reduce social marginalisation; alongside institutional reforms for greater transparency, accountability, and community participation in decision-making (Davies, 2015; Maclellan, 2015; Sterrett, 2015; Ensor, 2016; UN Women, 2016).

Power imbalances embedded in the political economy of development (Nunn et al., 2014), gender discrimination (Aipira et al., 2017), and the priorities of climate finance (Cabezon et al., 2016) may marginalise the priorities of local communities and influence how local risks are understood, prioritised, and managed (Kuruppu and Willie, 2015; Baldacchino, 2017; Sovacool et al., 2017). However, the experience of the low death toll after Cyclone Pam suggests effective use of local knowledge in planning and early warning may support resilience at least in the absence of storm surge flooding (Handmer and Iveson, 2017; Nalau et al., 2017). Nevertheless, the very severe infrastructure damage of Cyclone Pam 2015 highlights the limits of individual Pacific SIDS efforts and the need for global and regional responses to a 1.5°C warmer world (Dilling et al., 2015; Ensor, 2016; Shultz et al., 2016; Rey et al., 2017) (see Chapter 3 Box 3.5, Chapter 4 Box 4.3).

[END BOX 5.3 HERE]

Communities, towns, and cities also contribute to low-carbon pathways, sustainable development and fair and equitable climate resilience, often focused on processes of power, learning, and contestation as entry points to more localised CRDPs (*medium evidence, high agreement*) (Cross-Chapter Box 13 in this Chapter, Box 5.2). In the Scottish Borders Climate Resilient Communities Project (United Kingdom), local flood management is linked with national policies to foster cross-scalar and inclusive governance, with attention to systemic disadvantages, shocks and stressors, capacity building, learning for change, and climate narratives to inspire hope and action, all of which are essential for community resilience in a 1.5°C warmer world (Fazey et al., 2018). Narratives and storytelling are vital for realising place-based 1.5°C futures as they create space for agency, deliberation, co-constructing meaning, imagination, and desirable and dignified pathways (Veland et al., 2018). Engagement with possible futures, identity, and self-reliance is also documented for Alaska where 1.5°C warming has already been exceeded and indigenous communities invest in renewable energy, greenhouses for food security, and new fishing practices to overcome loss of sea ice, flooding, and erosion (Chapin et al., 2016; Fazey et al., 2018). The Asian Cities Climate Change Resilience Network (ACCRN) facilitates shared learning dialogues, risk-to-resilience workshops, and iterative, consultative planning in flood-prone cities in India; vulnerable communities, municipal governmental agents, entrepreneurs, and technical experts negotiate different visions, trade-offs, and local politics to identify desirable pathways (Harris et al., 2017).

Transforming our societies and systems to limit global warming to 1.5°C and ensuring equity and well-being for human populations and ecosystems in a 1.5°C warmer world would require ambitious and well-integrated adaptation-mitigation-development pathways that deviate fundamentally from high-carbon, business-as-usual futures (Okereke and Coventry, 2016; Arts, 2017; Gupta and Arts, 2017; Sealey-Huggins, 2017). Identifying and negotiating socially acceptable, inclusive, and equitable pathways toward climate-resilient futures is a challenging, yet important, endeavour, fraught with complex moral, practical, and political difficulties and inevitable trade-offs (*very high confidence*). The ultimate questions are: what futures do we want (Bai et al., 2016; Tàbara et al., 2017; Klinsky and Winkler, 2018; O'Brien, 2018; Veland et al., 2018), whose resilience matters, for what, where, when and why (Meerow and Newell, 2016), and 'whose vision … is being pursued and along which pathways' (Gillard et al., 2016).

[START CROSS-CHAPTER BOX 13 HERE]

Cross-Chapter Box 13: Cities and Urban Transformation

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Global Urbanisation in a 1.5°C Warmer World

The concentration of economic activity, dense social networks, human resource capacity, investment in infrastructure and buildings, relatively nimble local governments, close connection to surrounding rural and natural environments, and a tradition of innovation provide urban areas with transformational potential (Castán Broto, 2017) (see Chapter 4, Section 4.3.3). In this sense, the urbanisation mega-trend that will take place over the next three decades, and add approximately 2 billion people to the global urban population (UN, 2014b), offers opportunities for efforts to limit warming to 1.5°C.

Cities can also, however, concentrate the risks of flooding, landslides, fire, and infectious and parasitic disease that are expected to heighten in a 1.5°C warmer world (Chapter 3). In African and Asian countries where urbanisation rates are highest, these risks could expose and amplify pre-existing stresses related to poverty, exclusion, and governance (Gore, 2015; Dodman et al., 2017; Jiang and O'Neill, 2017; Pelling et al., 2018; Solecki et al., 2018). Through its impact on economic development and investment, urbanisation often leads to increased consumption and environmental degradation and enhanced vulnerability, risk, and impacts (Rosenzweig et al., 2018). In the absence of innovation, the combination of urbanisation and urban economic development could contribute 226 $GtCO_2$ in emissions by 2050 (Bai et al., 2018). At the same time, some new urban developments are demonstrating combined carbon and Sustainable Development Goals (SDG) benefits (Wiktorowicz et al., 2018), and it is in towns and cities that building renovation rates can be most easily accelerated to support the transition to 1.5°C pathways (Kuramochi et al., 2018), including through voluntary programs (Van der Heijden, 2018).

Urban Transformations and Emerging Climate-Resilient Development Pathways

1.5°C pathways require action in all cities and urban contexts. Recent literature emphasises the need to deliberate and negotiate how resilience and climate-resilient pathways can be fostered in the context of people's daily lives, including the failings of everyday development such as unemployment, inadequate housing, and growing informality, in order to acknowledge local priorities and foster transformative learning (Vale, 2014; Shi et al., 2016; Harris et al., 2017; Ziervogel et al., 2017; Fazey et al., 2018; Macintyre et al., 2018). Enhancing deliberate transformative capacities in urban contexts also entails new and relational forms of envisioning agency, equity, resilience, social cohesion, and well-being (Gillard et al., 2016; Ziervogel et al., 2016) (Section 5.5.3). Two examples of urban transformation are explored here.

The built environment, spatial planning, infrastructure, energy services, mobility, and urban-rural linkages necessary in **rapidly growing cities in South Asia and Africa** in the next three decades present mitigation, adaptation and development opportunities that are crucial for a 1.5°C world (Newman et al., 2017; Lwasa et al., 2018; Teferi and Newman, 2018). Realising these opportunities would require the structural challenges of poverty, weak and contested local governance, and low levels of local government investment to be addressed on an unprecedented scale (Wachsmuth et al., 2016; Chu et al., 2017; van Noorloos and Kloosterboer, 2017; Pelling et al., 2018).

Urban governance is critical to ensuring that the necessary urban transitions deliver economic growth and equity (Hughes et al., 2018). The proximity of local governments to citizens and their needs can make them powerful agents of climate action (Melica et al., 2018), but urban governance is enhanced when it involves multiple actors (Ziervogel et al., 2016; Pelling et al., 2018), supportive national governments (Tait and Euston-Brown, 2017) and sub-national climate networks (see Chapter 4, Section 4.4.1). Governance is complicated for the urban population currently living in what is termed ‘informality’. This population is expected to triple, to three billion, by 2050 (Satterthwaite et al., 2018), placing a significant portion of the world’s population beyond the direct reach of formal climate mitigation and adaptation policies (Revi et al., 2014). How to address the co-evolved and structural conditions that lead to urban informality and associated vulnerability to 1.5°C of warming is a central question for this report. Brown and McGranahan (2016) cite evidence that the informal urban “green economy” that has emerged out of necessity in the absence of formal service provisions is frequently low-carbon and resource-efficient.

Realising the potential for low carbon transitions in informal urban settlements would require an express recognition of the unpaid-for contributions of women in the informal economy, and new partnerships between the state and communities (Ziervogel et al., 2017; Pelling et al., 2018; Satterthwaite et al., 2018). There is no guarantee that these partnerships will evolve or cohere into the type of service delivery and climate governance system that could steer the change on a scale required to limit to warming to 1.5°C (Jaglin, 2014). However, transnational networks such as Shack/Slum Dwellers International, C40, the Global Covenant of Mayors, and International Council for Local Environmental Initiatives (ICLEI), as well as efforts to combine in-country planning for Nationally Determined Contributions (NDCs) (Andonova et al., 2017; Fuhr et al., 2018) with those taking place to support the New Urban Agenda and National Urban Policies, represent one step towards realising the potential (Tait and Euston-Brown, 2017). So too do “old urban agendas” such as slum upgrading and universal water and sanitation provision (McGranahan et al., 2016; Satterthwaite, 2016; Satterthwaite et al., 2018).

Transition Towns (TTs) is a type of urban transformation mainly in high-income countries. The grassroots TT movement (origin in the United Kingdom) combines adaptation, mitigation, and just transitions, mainly at the level of communities and small towns. It now has >1,300 registered local initiatives in >40 countries (Grossmann and Creamer, 2017), many of them in the United Kingdom, the United States, and other high-income countries. TTs are described as ‘progressive localism’ (Cretney et al., 2016), aiming to foster a ‘communitarian ecological citizenship’ that goes beyond changes in consumption and lifestyle (Kenis, 2016). They aspire to promote equitable communities resilient to the impacts of climate change, peak oil, and unstable global markets; re-localisation of production and consumption; and transition pathways to a post-carbon future (Feola and Nunes, 2014; Evans and Phelan, 2016; Grossmann and Creamer, 2017).

TT initiatives typically pursue lifestyle-related low-carbon living and economies, food self-sufficiency, energy efficiency through renewables, construction with locally-sourced material, and cottage industries (Barnes, 2015; Staggenborg and Ogrodnik, 2015; Taylor Aiken, 2016). Social and iterative learning through the collective involves dialogue, deliberation, capacity building, citizen science engagements, technical re-skilling to increase self-reliance, for example canning and preserving food and permaculture, future visioning, and emotional training to share difficulties and loss (Feola and Nunes, 2014; Barnes, 2015; Boke, 2015; Taylor Aiken, 2015; Kenis, 2016; Mehmood, 2016; Grossmann and Creamer, 2017).

Important conditions for successful transition groups include flexibility, participatory democracy, care ethics, inclusiveness, and consensus-building, assuming bridging or brokering roles, and community alliances and partnerships (Feola and Nunes, 2014; Mehmood, 2016; Taylor Aiken, 2016; Grossmann and Creamer, 2017). Smaller scale rural initiatives allow for more experimentation (Cretney et al., 2016) while those in urban centres benefit from stronger networks and proximity to power structures (North and Longhurst, 2013; Nicolosi and Feola, 2016). Increasingly, TTs recognise the need to participate in policy making (Kenis and Mathijs, 2014; Barnes, 2015).

Despite high self-ratings of success, some TT initiatives are too inwardly focused and geographically isolated (Feola and Nunes, 2014) while others have difficulties in engaging marginalised, non-white, non-middle-class community members (Evans and Phelan, 2016; Nicolosi and Feola, 2016; Grossmann and Creamer, 2017). In the United Kingdom, expectations of innovations growing in scale (Taylor Aiken, 2015) and carbon accounting methods required by funding bodies (Taylor Aiken, 2016) undermine local resilience building. Tension between explicit engagements with climate change action and efforts to appeal to more people have resulted in difficult trade-offs and strained member relations (Grossmann and Creamer, 2017) though the contribution to changing an urban culture that prioritises climate change can be underestimated (Wiktorowicz et al., 2018).

Urban actions that can highlight the 1.5°C agenda include individual actions within homes (Werfel, 2017; Buntaine and Prather, 2018), demonstration zero carbon developments (Wiktorowicz et al., 2018), new partnerships between communities, government and business to build mass transit and electrify transport (Glazebrook and Newman, 2018), city plans to include climate outcomes (Millard-Ball, 2013), and support for transformative change across political, professional, and sectoral divides (Bai et al., 2018).

[END CROSS-CHAPTER BOX 13 HERE]

5.6 Conditions for Achieving Sustainable Development, Eradicating Poverty and Reducing Inequalities in 1.5°C Warmer Worlds

This chapter has described the fundamental, urgent, and systemic transformations that would be needed to achieve sustainable development, eradicate poverty, and reduce inequalities in a 1.5°C warmer world, in various contexts and across scales. In particular, it has highlighted the societal dimensions, putting at the centre people's needs and aspirations in their specific contexts. Here, we synthesise some of the most pertinent enabling conditions (see Glossary) to support these profound transformations. These conditions are closely interlinked and connected by the overarching concept of governance, which broadly includes institutional, socioeconomic, cultural, and technological elements (see Chapter 1, Cross-Chapter Box 4 in Chapter 1).

5.6.1 Finance and Technology Aligned with Local Needs

Significant gaps in green investment constrain transitions to a low-carbon economy aligned with development objectives (Volz et al., 2015; Campiglio, 2016). Hence, unlocking new forms of public, private, and public-private financing is essential to support environmental sustainability of the economic system (Croce et al., 2011; Blyth et al., 2015; Falcone et al., 2018) (see Chapter 4, Section 4.4.5). To avoid risks of undesirable trade-offs with the SDGs caused by national budget constraints, improved access to international climate finance is essential for supporting adaptation, mitigation, and sustainable development, especially for Least Developed Countries (LDCs) and Small Island Developing States (SIDS) (Shine and Campillo, 2016; Wood, 2017) (*medium evidence, high agreement*). Care needs to be taken when international donors or partnership arrangements influence project financing structures (Kongsager and Corbera, 2015; Purdon, 2015; Ficklin et al., 2017; Phillips et al., 2017). Conventional climate funding schemes, especially the Clean Development Mechanism (CDM), have shown positive effects on sustainable development but also adverse consequences, for example on adaptive capacities of rural households and uneven distribution of costs and benefits, often exacerbating inequalities (Aggarwal, 2014; Brohé, 2014; He et al., 2014; Schade and Obergassel, 2014; Smits and Middleton, 2014; Wood et al., 2016a; Horstmann and Hein, 2017; Kreibich et al., 2017) (*robust evidence, high agreement*). Close consideration of recipients' context-specific needs when designing financial support helps to overcome these limitations as it better aligns community needs, national policy objectives, and donors' priorities, puts the emphasis on the increase of transparency and predictability of support, and fosters local capacity building (Barrett, 2013; Boyle et al., 2013; Shine and Campillo, 2016; Ley, 2017; Sánchez and Izzo, 2017) (*medium evidence, high agreement*).

The development and transfer of technologies is another enabler for developing countries to contribute to the requirements of the 1.5°C objective while achieving climate resilience and their socioeconomic development goals (see Chapter 4, Section 4.4.4). International-level governance would be needed to boost domestic innovation and the deployment of new technologies such as Negative Emission Technologies toward the 1.5°C objective (see Chapter 4, Section 4.3.7), but the alignment with local needs depends on close consideration of the specificities of the domestic context in countries at all levels of development (de Coninck and Sagar, 2015; IEA, 2015; Parikh et al., 2018). Technology transfer supporting development in developing countries would require an understanding of local and national actors and institutions (de Coninck and Puig, 2015; de Coninck and Sagar, 2017; Michaelowa et al., 2018), careful attention to the capacities in the entire innovation chain (Khosla et al., 2017; Olawuyi, 2017), and transfer of not only equipment but also knowledge (Murphy et al., 2015) (*medium evidence, high agreement*).

5.6.2 Integration of Institutions

Multi-level governance in climate change has emerged as a key enabler for systemic transformation and effective governance (see Chapter 4, Section 4.4.1). On the one hand, low-carbon and climate-resilient development actions are often well aligned at the lowest scale possible (Suckall et al., 2015; Sánchez and Izzo, 2017), and informal, local institutions are critical in enhancing the adaptive capacity of countries and marginalised communities (Yaro et al., 2015). On the other hand, international and national institutions can provide incentives for projects to harness synergies and avoid trade-offs (Kongsager et al., 2016).

Governance approaches that coordinate and monitor multi-scale policy actions and trade-offs across sectoral, local, national, regional, and international levels are therefore best suited to implement goals toward 1.5°C warmer conditions and sustainable development (Ayers et al., 2014; Stringer et al., 2014; von Stechow et al., 2016; Gwimbi, 2017; Hayward, 2017; Maor et al., 2017; Roger et al., 2017; Michaelowa et al., 2018). Vertical and horizontal policy integration and coordination is essential to take into account the interplay and trade-offs between sectors and spatial scales (Duguma et al., 2014; Naess et al., 2015; von Stechow et al., 2015; Antwi-Agyei et al., 2017a; Di Gregorio et al., 2017; Runhaar et al., 2018), enable the dialogue between local communities and institutional bodies (Colenbrander et al., 2016), and involve non-state actors such as business, local governments, and civil society operating across different scales (Hajer et al., 2015; Labriet et al., 2015; Hale, 2016; Pelling et al., 2016; Kalafatis, 2017; Lyon, 2018) (*robust evidence, high agreement*).

5.6.3 Inclusive Processes

Inclusive governance processes are critical for preparing for a 1.5°C warmer world (Fazey et al., 2018; O'Brien, 2018; Patterson et al., 2018). These processes have been shown to serve the interests of diverse groups of people and enhance empowerment of often excluded stakeholders, notably women and youth, (MRFCJ, 2015a; Dumont et al., 2017). They also enhance social and co-learning which, in turn, facilitates accelerated and adaptive management and the scaling up of capacities for resilience building (Ensor and Harvey, 2015; Reij and Winterbottom, 2015; Tschakert et al., 2016; Binam et al., 2017; Dumont et al., 2017; Fazey et al., 2018; Lyon, 2018; O'Brien, 2018), and provides opportunities to blend indigenous, local, and scientific knowledge (Antwi-Agyei et al., 2017a; Coe et al., 2017; Thornton and Comberti, 2017) (see Chapter 4, Section 4.3.5.5, Box 4.3; Section 5.3) (*robust evidence, high agreement*). Such co-learning has been effective in improving deliberative decision-making processes that incorporate different values and world views (Cundill et al., 2014; C. Butler et al., 2016; Ensor, 2016; Fazey et al., 2016; Gorddard et al., 2016; Aipira et al., 2017; Fook, 2017; Maor et al., 2017), and create space for negotiating diverse interests and preferences (O'Brien et al., 2015; Gillard et al., 2016; DeCaro et al., 2017; Harris et al., 2017; Lahn, 2017) (*robust evidence, high agreement*).

5.6.4 Attention to Issues of Power and Inequality

Societal transformations to limit global warming to 1.5°C and strive for equity and well-being for all are not power neutral (Section 5.5.3). Development preferences are often shaped by powerful interests that determine the direction and pace of change, anticipated benefits and beneficiaries, and acceptable and unacceptable trade-offs (Newell et al., 2014; Fazey et al., 2016; Tschakert et al., 2016; Winkler and Dubash, 2016; Wood et al., 2016b; Karlsson et al., 2017; Quan et al., 2017; Tanner et al., 2017). Each development pathway, including legacies and path dependencies, creates its own set of opportunities and challenges and winners and losers, both within and across countries (Figure 5.6) (Mathur et al., 2014; Ficklin et al., 2017; Phillips et al., 2017; Stringer et al., 2017; Wood, 2017; Gajjar et al., 2018) (*robust evidence, high agreement*).

Addressing the uneven distribution of power is critical to ensure that societal transformation toward a 1.5°C warmer world does not exacerbate poverty and vulnerability or create new injustices but rather encourages equitable transformational change (Patterson et al., 2018). Equitable outcomes are enhanced when they pay attention to just outcomes for those negatively affected by change (Newell et al., 2014; Dilling et al., 2015; Naess et al., 2015; Sovacool et al., 2015; Cervigni and Morris, 2016; Keohane and Victor, 2016) and promote human rights, increase equality, and reduce power asymmetries within societies (UNRISD, 2016; Robinson and Shine, 2018) (*robust evidence, high agreement*).

5.6.5 Reconsidering Values

The profound transformations that would be needed to integrate sustainable development and 1.5°C-compatible pathways call for examining the values, ethics, attitudes, and behaviours that underpin societies (Hartzell-Nichols, 2017; O'Brien, 2018; Patterson et al., 2018). Infusing values that promote sustainable development (Holden et al., 2017), overcome individual economic interests and go beyond economic growth (Hackmann, 2016), encourage desirable and transformative visions (Tàbara et al., 2018), and care for the less fortunate (Howell and Allen, 2017) is part and parcel of climate-resilient and sustainable development pathways. This entails helping societies and individuals to strive for sufficiency in resource consumption within planetary boundaries alongside sustainable and equitable well-being (O'Neill et al., 2018). Navigating 1.5°C societal transformations, characterised by action from local to global, stresses the core commitment to social justice, solidarity, and cooperation, particularly regarding the distribution of responsibilities, rights, and mutual obligations between nations (Patterson et al., 2018; Robinson and Shine, 2018) (*medium evidence, high agreement*).

5.7 Synthesis and Research Gaps

The assessment in Chapter 5 illustrates that limiting global warming to 1.5°C is fundamentally connected with achieving sustainable development, poverty eradication, and reducing inequalities. It shows that avoided impacts between 1.5°C and 2°C temperature stabilisation would make it easier to achieve many aspects of sustainable development, although important risks would remain at 1.5°C (Section 5.2). Synergies between adaptation and mitigation response measures with sustainable development and the Sustainable Development Goals (SDGs) can often be enhanced when attention is paid to well-being and equity while, when unaddressed, poverty and inequalities may be exacerbated (Section 5.3 and 5.4). Climate-resilient development pathways (CRDPs) open up routes toward socially desirable futures that are sustainable and liveable, but concrete evidence reveals complex trade-offs along a continuum of different pathways, highlighting the role of societal values, internal contestations, and political dynamics (Section 5.5). The transformations towards sustainable development in a 1.5°C warmer world, in all contexts, involve fundamental societal and systemic changes over time and across scale, and a set of enabling conditions without which the dual goal is difficult if not impossible to achieve (Sections 5.5 and 5.6).

This assessment is supported by growing knowledge on the linkages between a 1.5°C warmer world and different dimensions of sustainable development. However, several gaps in the literature remain:

Limited evidence exists that explicitly examines the real-world implications of a 1.5°C warmer world (and overshoots) as well as avoided impacts between 1.5°C versus 2°C for the SDGs and sustainable development more broadly. Few projections are available for households, livelihoods, and communities. And literature on differential localised impacts and their cross-sector interacting and cascading effects with multidimensional patterns of societal vulnerability, poverty, and inequalities remains scarce. Hence, caution is needed when global-level conclusions about adaptation and mitigation measures in a 1.5°C warmer world are applied to sustainable development in local, national, and regional settings.

Limited literature has systematically evaluated context-specific synergies and trade-offs between and across adaptation and mitigation response measures in 1.5°C-compatible pathways and the SDGs. This hampers the ability to inform decision-making and fair and robust policy packages adapted to different local, regional, or national circumstances. More research is required to understand how trade-offs and synergies will intensify or decrease, differentially across geographic regions and time, in a 1.5ºC warmer world and as compared to higher temperatures.

Limited availability of interdisciplinary studies also poses a challenge for connecting the socio-economic transformations and the governance aspects of low-emission, climate-resilient transformations. For example, it remains unclear how governance structures enable or hinder different groups of people and countries to negotiate pathway options, values, and priorities.

The literature does not demonstrate the existence of 1.5°C-compatible pathways achieving the "universal and indivisible" agenda of the 17 SDGs, and hence does not show whether and how the nature and pace of changes that would be required to meet 1.5°C climate stabilisation could be fully synergetic with all the SDGs.

The literature on low-emission and climate-resilient development pathways in local, regional, and national contexts is growing. Yet, the lack of standard indicators to monitor such pathways makes it difficult to compare evidence grounded in specific contexts with differential circumstances and therefore to derive generic lessons on the outcome of decisions on specific indicators. This knowledge gap poses a challenge for connecting local-level visions with global-level trajectories to better understand key conditions for societal and systems transformations that reconcile urgent climate action with well-being for all.

Frequently Asked Questions

FAQ 5.1: What are the connections between sustainable development and limiting global warming to 1.5°C?

Summary: *Sustainable development seeks to meet the needs of people living today without compromising the needs of future generations, while balancing social, economic and environmental considerations. The 17 UN Sustainable Development Goals (SDGs) include targets for eradicating poverty; ensuring health, energy and food security; reducing inequality; protecting ecosystems; pursuing sustainable cities and economies; and a goal for climate action (SDG13). Climate change affects the ability to achieve sustainable development goals and limiting warming to 1.5°C will help meet some sustainable development targets. Pursuing sustainable development will influence emissions, impacts and vulnerabilities. Responses to climate change in the form of adaptation and mitigation will also interact with sustainable development with positive effects, known as synergies, or negative effects, known as trade-offs. Responses to climate change can be planned to maximize synergies and limit trade-offs with sustainable development.*

For more than 25 years, the United Nations (UN) and other international organizations have embraced the concept of sustainable development to promote wellbeing and meet the needs of today’s population without compromising the needs of future generations. This concept spans economic, social and environmental objectives including poverty and hunger alleviation, equitable economic growth, access to resources, and the protection of water, air and ecosystems. Between 1990 and 2015, the UN monitored a set of eight Millennium Development Goals (MDGs). They reported progress in reducing poverty, easing hunger and child mortality, and improving access to clean water and sanitation. But with millions remaining in poor health, living in poverty, and facing serious problems associated with climate change, pollution and land use change, the UN decided that more needed to be done. In 2015, the UN *Sustainable Development Goals* (SDGs) were endorsed as part of the 2030 Agenda for Sustainable Development. The 17 SDGs (Figure FAQ 5.1) apply to all countries and have a timeline for success by 2030. The SDGs seek to eliminate extreme poverty and hunger; ensure health, education, peace, safe water, and clean energy for all; promote inclusive and sustainable consumption, cities, infrastructure and economic growth; reduce inequality including gender inequality; combat climate change and protect oceans and terrestrial ecosystems.

Climate change and sustainable development are fundamentally connected. Previous IPCC reports found that climate change can undermine sustainable development, and that well-designed mitigation and adaptation responses can support poverty alleviation, food security, healthy ecosystems, equality and other dimensions of sustainable development. Limiting global warming to 1.5°C would require mitigation actions and adaptation measures to be taken at all levels. These adaptation and mitigation actions would include reducing emissions and increasing resilience through technology and infrastructure choices, as well as changing behaviour and policy. These actions can interact with sustainable development objectives in positive ways that strengthen sustainable development, known as *synergies*. Or negative ways, where sustainable development is hindered or reversed, known as *trade-offs*.

An example of a synergy is sustainable forest management, which can prevent emissions from deforestation and take up carbon to reduce warming at reasonable cost. It can work synergistically with other dimensions of sustainable development by providing food (SDG 2), cleaning water (SDG 6) and protecting ecosystems (SDG 15). Other examples of synergies are when climate adaptation measures, such as coastal or agricultural projects, empower women and benefit local incomes, health and ecosystems.

An example of a trade-off can occur if ambitious climate change mitigation compatible with 1.5°C changes land use in ways that have negative impacts on sustainable development. An example could be turning natural forests, agricultural areas, or land under indigenous or local ownership to plantations for bioenergy production. If not managed carefully, such changes could undermine dimensions of sustainable development by threatening food and water security, creating conflict over land rights, and causing biodiversity loss. Another trade-off could occur for some countries, assets, workers, and infrastructure already in place if a switch is made from fossil fuels to other energy sources without adequate planning for such a transition. Trade-offs can be minimised if effectively managed as when care is taken to improve bioenergy crop yields to reduce harmful land-use change or where workers are retrained for employment in lower carbon sectors.

Limiting temperatures to 1.5°C can make it much easier to achieve the SDGs, but it is also possible that pursuing the SDGs could result in trade-offs with efforts to limit climate change. There are trade-offs when people escaping from poverty and hunger consume more energy or land and thus increase emissions, or if goals for economic growth and industrialization increase fossil fuel consumption and greenhouse gas emissions. Conversely, efforts to reduce poverty and gender inequalities, and to enhance food, health and water security can reduce vulnerability to climate change. Other synergies can occur when coastal and ocean ecosystem protection reduces the impacts of climate change on these systems. The sustainable development goal of affordable and clean energy (SDG 7) specifically targets access to renewable energy and energy efficiency, important to ambitious mitigation and limiting warming to 1.5°C.

The link between sustainable development and limiting global warming to 1.5°C is recognized by the Sustainable Development Goal for climate action (SDG 13) which seeks to combat climate change and its impacts while acknowledging that the UNFCCC is the primary international, intergovernmental forum for negotiating the global response to climate change.

The challenge is to put in place sustainable development policies and actions that reduce deprivation, alleviate poverty and ease ecosystem degradation while also lowering emissions, reducing climate change impacts and facilitating adaptation. It is important to strengthen synergies and minimize trade-offs when planning climate change adaptation and mitigation actions. Unfortunately, not all trade-offs can be avoided or minimised, but careful planning and implementation can build the enabling conditions for long-term sustainable development.


FAQ5.1: **The United Nations Sustainable Development Goals (SDGs)**

The link between sustainable development and limiting global warming to 1.5°C is recognised by the Sustainable Development Goal for climate action (SDG 13)

FAQ 5.1, Figure 1: Climate change action is one of the United Nations Sustainable Development Goals (SDGs) and is connected to sustainable development more broadly. Actions to reduce climate risk can interact with other sustainable development objectives in positive ways (synergies) and negative ways (trade-offs).

FAQ 5.2: What are the pathways to achieving poverty reduction and reducing inequalities while reaching the 1.5°C world?

Summary: *There are ways to limit global warming to 1.5°C above pre-industrial levels. Of the pathways that exist, some simultaneously achieve sustainable development. They entail a mix of measures that lower emissions and reduce the impacts of climate change, while contributing to poverty eradication and reducing inequalities. Which pathways are possible and desirable will differ between and within regions and nations. This is due to the fact that development progress to date has been uneven and climate-related risks are unevenly distributed. Flexible governance would be needed to ensure that such pathways are inclusive, fair, and equitable to avoid poor and disadvantaged populations becoming worse off. 'Climate-Resilient Development Pathways' (CRDPs) offer possibilities to achieve both equitable and low-carbon futures.*

Issues of equity and fairness have long been central to climate change and sustainable development. Equity, like equality, aims to promote justness and fairness for all. This is not necessarily the same as treating everyone equally, since not everyone comes from the same starting point. Often used interchangeably with fairness and justice, equity implies implementing different actions in different places, all with a view to creating an equal world that is fair for all and where no one is left behind.

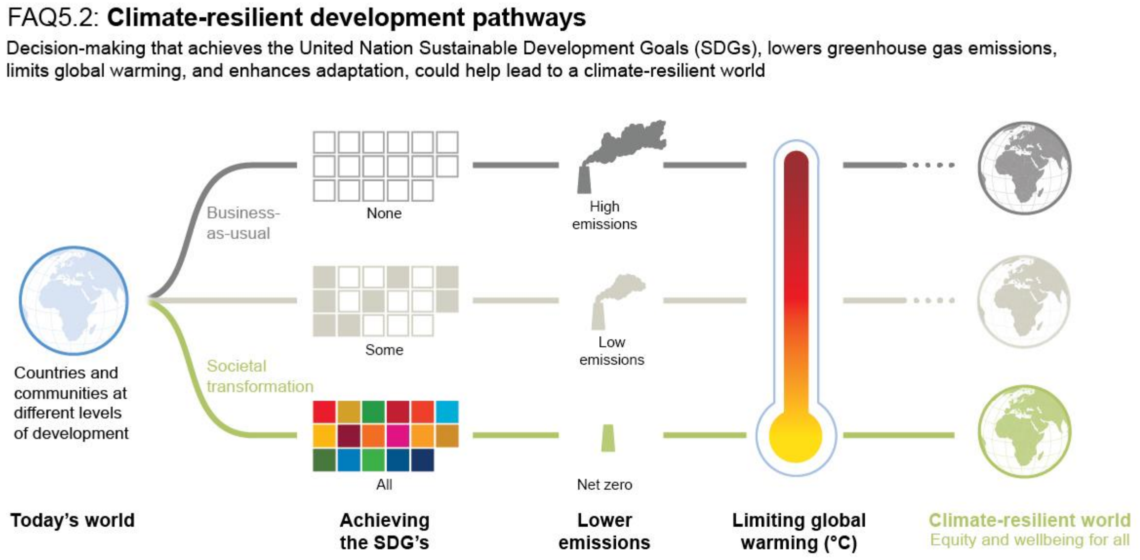
The Paris Agreement states that it "will be implemented to reflect equity… in the light of different national circumstances" and calls for "rapid reductions" of greenhouse gases to be achieved "on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty". Similarly, the United Nations Sustainable Development Goals (SDGs) include targets to reduce poverty and inequalities, and to ensure equitable and affordable access to health, water, and energy for all.

The principles of equity and fairness are important for considering pathways that limit warming to 1.5°C in a way that is liveable for every person and species. They recognise the uneven development status between richer and poorer nations, the uneven distribution of climate impacts (including on future generations), and the uneven capacity of different nations and people to respond to climate risks. This is particularly true for those who are highly vulnerable to climate change such as indigenous communities in the Arctic, people whose livelihoods depend on agriculture or coastal and marine ecosystems, and inhabitants of small-island developing states. The poorest people will continue to experience climate change through the loss of income and livelihood opportunities, hunger, adverse health effects, and displacement.

Well-planned adaptation and mitigation measures are essential to avoid exacerbating inequalities or creating new injustices. Pathways that are compatible with limiting warming to 1.5°C and aligned with the SDGs consider mitigation and adaptation options that reduce inequalities in terms of who benefits, who pays the costs, and who is affected by possible negative consequences. Attention to equity ensures that disadvantaged people can secure their livelihoods and live in dignity, and that those who experience mitigation or adaptation costs have financial and technical support to enable fair transitions.

Climate-resilient development pathways (CRDPs) describe trajectories that pursue the dual goal of limiting warming to 1.5°C while strengthening sustainable development. This includes eradicating poverty as well as reducing vulnerabilities and inequalities for regions, countries, communities, businesses, and cities. These trajectories entail a mix of adaptation and mitigation measures consistent with profound societal and systems transformations. The goals are to meet the short-term SDGs, achieve longer-term sustainable development, reduce emissions toward net zero around the middle of the century, build resilience and enhance human capacities to adapt, all while paying close attention to equity and well-being for all.

The characteristics of CRDPs will differ across communities and nations, and will be based on deliberations with a diverse range of people, including those most affected by climate change and by possible routes toward transformation. For this reason, there are no standard methods for designing CRDPs or for monitoring their progress toward climate-resilient futures. However, examples from around the world demonstrate that flexible and inclusive governance structures and broad participation often help support iterative decision-making, continuous learning, and experimentation. Such inclusive processes can also help to overcome weak institutional arrangements and power structures that may further exacerbate inequalities.



FAQ 5.2, Figure 1: Climate-resilient development pathways (CRDPs) describe trajectories that pursue the dual goal of limiting warming to 1.5°C while strengthening sustainable development. Decision-making that achieves the SDGs, lowers greenhouse gas emissions and limits global warming could help lead to a climate-resilient world, within the context of enhancing adaptation.

Ambitious actions already underway around the world can offer insight into CRDPs for limiting warming to 1.5°C. For example, some countries have adopted clean energy and sustainable transport while creating environmentally friendly jobs and supporting social welfare programs to reduce domestic poverty. Other examples teach us about different ways to promote development through practices inspired by community values. For instance, *Buen Vivir*, a Latin American concept based on indigenous ideas of communities living in harmony with nature, is aligned with peace, diversity, solidarity, rights to education, health, and safe food, water, and energy, and well-being and justice for all. The Transition Movement, with origins in Europe, promotes equitable and resilient communities through low-carbon living, food self-sufficiency, and citizen science. Such examples indicate that pathways that reduce poverty and inequalities while limiting warming to 1.5°C are possible and that they can provide guidance on pathways towards socially desirable, equitable, and low-carbon futures.

References

Abel, G.J., B. Barakat, S. KC, and W. Lutz, 2016: Meeting the Sustainable Development Goals leads to lower world population growth. *Proceedings of the National Academy of Sciences*, **113(50)**, 14294-14299, doi:10.1073/pnas.1611386113.

Absar, S.M. and B.L. Preston, 2015: Extending the Shared Socioeconomic Pathways for sub-national impacts, adaptation, and vulnerability studies. *Global Environmental Change*, **33**, 83-96, doi:10.1016/j.gloenvcha.2015.04.004.

Adam, H.N., 2015: Mainstreaming adaptation in India - the Mahatma Gandhi National Rural Employment Guarantee Act and climate change. *Climate and Development*, **7(2)**, 142-152, doi:10.1080/17565529.2014.934772.

Adger, W.N. et al., 2014: Human security. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 755-791.

Aggarwal, A., 2014: How sustainable are forestry clean development mechanism projects? A review of the selected projects from India. *Mitigation and Adaptation Strategies for Global Change*, **19(1)**, 73-91, doi:10.1007/s11027-012-9427-x.

Agoramoorthy, G. and M.J. Hsu, 2016: Small dams revive dry rivers and mitigate local climate change in India's drylands. *International Journal of Climate Change Strategies and Management*, **8(2)**, 271-285, doi:10.1108/IJCCSM-12-2014-0141.

Agyeman, J., D. Schlosberg, L. Craven, and C. Matthews, 2016: Trends and directions in environmental justice: from inequity to everyday life, community, and just sustainabilities. *Annual Review of Environment and Resources*, **41**, 321-340, doi:10.1146/annurev-environ-110615-090052.

Aha, B. and J.Z. Ayitey, 2017: Biofuels and the hazards of land grabbing: tenure (in)security and indigenous farmers' investment decisions in Ghana. *Land Use Policy*, **60**, 48-59, doi:10.1016/j.landusepol.2016.10.012.

Ahmed, N., W.W.L. Cheung, S. Thompson, and M. Glaser, 2017a: Solutions to blue carbon emissions: Shrimp cultivation, mangrove deforestation and climate change in coastal Bangladesh. *Marine Policy*, **82(May)**, 68-75, doi:10.1016/j.marpol.2017.05.007.

Ahmed, N., S.W. Bunting, M. Glaser, M.S. Flaherty, and J.S. Diana, 2017b: Can greening of aquaculture sequester blue carbon? *Ambio*, **46(4)**, 468-477, doi:10.1007/s13280-016-0849-7.

Aipira, C., A. Kidd, and K. Morioka, 2017: Climate change adaptation in Pacific countries: fostering resilience through gender equality. In: *Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life* [Leal Filho, W. (ed.)]. Springer International Publishing AG, Cham, Switzerland, pp. 225-239.

Ajanovic, A., 2015: The future of electric vehicles: prospects and impediments. *Wiley Interdisciplinary Reviews: Energy and Environment*, **4(6)**, 521-536, doi:10.1002/wene.160.

Al Ansari, M.S., 2013: Climate change policies and the potential for energy efficiency in the Gulf Cooperation Council (GCC) Economy. *Environment and Natural Resources Research*, **3(4)**, 106-117, doi:10.5539/enrr.v3n4p106.

Albert, S. et al., 2017: Heading for the hills: climate-driven community relocations in the Solomon Islands and Alaska provide insight for a 1.5°C future. *Regional Environmental Change*, 1-12, doi:10.1007/s10113-017-1256-8.

Ali, A. and O. Erenstein, 2017: Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Climate Risk Management*, **16**, 183-194, doi:10.1016/j.crm.2016.12.001.

Al-Maamary, H.M.S., H.A. Kazem, and M.T. Chaichan, 2016: Changing the energy profile of the GCC states: a review. *International Journal of Applied Engineering Research*, **11(3)**, 1980-1988.

Al-Maamary, H.M.S., H.A. Kazem, and M.T. Chaichan, 2017: The impact of oil price fluctuations on common renewable energies in GCC countries. *Renewable and Sustainable Energy Reviews*, **75**, 989-1007, doi:10.1016/j.rser.2016.11.079.

Alshehry, A.S. and M. Belloumi, 2015: Energy consumption, carbon dioxide emissions and economic growth: the case of Saudi Arabia. *Renewable and Sustainable Energy Reviews*, **41**, 237-247, doi:10.1016/j.rser.2014.08.004.

Alsheyab, M.A.T., 2017: Qatar's effort for the deployment of Carbon Capture and Storage. *Global Nest Journal*, **19(3)**, 453-457.

Altieri, K.E. et al., 2016: Achieving development and mitigation objectives through a decarbonization development pathway in South Africa. *Climate Policy*, **16(sup1)**, S78-S91, doi:10.1080/14693062.2016.1150250.

Amann, M. et al., 2011: Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling & Software*, **26(12)**, 1489-1501, doi:http://dx.doi.org/10.1016/j.envsoft.2011.07.012.

Anand, R., 2017: International environmental justice: a North-South dimension. .

Andonova, L.B., T.N. Hale, and C.B. Roger, 2017: National policy and transnational governance of climate change:

substitutes or complements? *International Studies Quarterly*, **61(2)**, 253-268, doi:10.1093/isq/sqx014.

Ansuategi, A. et al., 2015: *The impact of climate change on the achievement of the post-2015 sustainable development goals*. Metroeconomica, HR Wallingford and CDKN, 84 pp.

Antwi-Agyei, P., A.J. Dougill, and L.C. Stringer, 2015: Impacts of land tenure arrangements on the adaptive capacity of marginalized groups: The case of Ghana's Ejura Sekyedumase and Bongo districts. *Land Use Policy*, **49**, 203-212, doi:10.1016/j.landusepol.2015.08.007.

Antwi-Agyei, P., A. Dougill, and L. Stringer, 2017a: Assessing Coherence between Sector Policies and Climate Compatible Development: Opportunities for Triple Wins. *Sustainability*, **9(11)**, 2130, doi:10.3390/su9112130.

Antwi-Agyei, P., A.J. Dougill, L.C. Stringer, and S.N.A. Codjoe, 2018: Adaptation opportunities and maladaptive outcomes in climate vulnerability hotspots of northern Ghana. *Climate Risk Management*, **19(April 2017)**, 83-93, doi:10.1016/j.crm.2017.11.003.

Antwi-Agyei, P. et al., 2017b: Perceived stressors of climate vulnerability across scales in the Savannah zone of Ghana: a participatory approach. *Regional Environmental Change*, **17(1)**, 213-227, doi:10.1007/s10113-016-0993-4.

Apgar, M.J., W. Allen, K. Moore, and J. Ataria, 2015: Understanding adaptation and transformation through indigenous practice: the case of the Guna of Panama. *Ecology and Society*, **20(1)**.

Arakelyan, I., D. Moran, and A. Wreford, 2017: Climate smart agriculture: a critical review. In: *Making climate compatible development happen* [Nunan, F. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 66-86.

Arbuthnott, K., S. Hajat, C. Heaviside, and S. Vardoulakis, 2016: Changes in population susceptibility to heat and cold over time: assessing adaptation to climate change. *Environmental Health*, **15(S1)**, S33, doi:10.1186/s12940-016-0102-7.

Archer, D. et al., 2014: Moving towards inclusive urban adaptation: approaches to integrating community-based adaptation to climate change at city and national scale. *Climate and Development*, **6(4)**, 345-356, doi:10.1080/17565529.2014.918868.

Armitage, D.R., 2015: Social-ecological change in Canada's Arctic: coping, adapting, learning for an uncertain future. In: *Climate Change and the Coast: Building Resilient Communities* [Glavovic, B., M. Kelly, R. Kay, and A. Travers (eds.)]. CRC Press, Boca Raton, FL, USA, pp. 103-124.

Arnell, N.W. and S.N. Gosling, 2016: The impacts of climate change on river flood risk at the global scale. *Climatic Change*, **134(3)**, 387-401, doi:10.1007/s10584-014-1084-5.

Arnell, N.W. et al., 2015: *The global impacts of climate change under pathways that reach 2°, 3° and 4°C above pre-industrial levels*. Report from AVOID2 project to the Committee on Climate Change, 34 pp.

Arriagada, R.A., E.O. Sills, P.J. Ferraro, and S.K. Pattanayak, 2015: Do payments pay off? Evidence from participation in Costa Rica's PES program. *PLOS ONE*, **10(7)**, 1-17, doi:10.1371/journal.pone.0131544.

Arthurson, K. and S. Baum, 2015: Making space for social inclusion in conceptualising climate change vulnerability. *Local Environment*, **20(1)**, 1-17, doi:10.1080/13549839.2013.818951.

Arts, K., 2017: Inclusive sustainable development: a human rights perspective. *Current Opinion in Environmental Sustainability*, **24**, 58-62, doi:10.1016/j.cosust.2017.02.001.

Atalay, Y., F. Biermann, and A. Kalfagianni, 2016: Adoption of renewable energy technologies in oil-rich countries: explaining policy variation in the Gulf Cooperation Council states. *Renewable Energy*, **85**, 206-214, doi:10.1016/j.renene.2015.06.045.

Ayers, J.M., S. Huq, H. Wright, A.M. Faisal, and S.T. Hussain, 2014: Mainstreaming climate change adaptation into development in Bangladesh. *Climate and Development*, **6(4)**, 293-305, doi:10.1002/wcc.226.

Babiker, M.H., 2016: Options for climate change policy in MENA countries after Paris. .

Bado, B.V., P. Savadogo, and M.L.S. Manzo, 2016: *Restoration of Degraded Lands in West Africa Sahel: Review of experiences in Burkina Faso and Niger*. 16 pp.

Bai, X. et al., 2016: Plausible and desirable futures in the Anthropocene: A new research agenda. *Global Environmental Change*, **39**, 351-362, doi:10.1016/j.gloenvcha.2015.09.017.

Bai, X. et al., 2018: Six Research Priorities for Cities and Climate Change. *Nature*, **555**, 23-25, doi:10.1038/d41586-018-02409-z.

Bajželj, B. et al., 2014: Importance of food-demand management for climate mitigation. *Nature Climate Change*, **4(10)**, 924-929.

Baldacchino, G., 2017: Seizing history: development and non-climate change in Small Island Developing States. *International Journal of Climate Change Strategies and Management*, IJCCSM-02-2017-0037, doi:10.1108/IJCCSM-02-2017-0037.

Banda, M.L. and S. Fulton, 2017: Litigating Climate Change in National Courts: Recent Trends and Developments in Global Climate Law. *Environmental Law Rep. News & Analysis*, **47(10121)**, 10121-10134.

Barnes, P., 2015: The political economy of localization in the transition movement. *Community Development Journal*, **50(2)**, 312-326, doi:10.1093/cdj/bsu042.

Barnett, J. and E. Walters, 2016: Rethinking the vulnerability of small island states: climate change and development in the Pacific Islands. *The Palgrave Handbook of International Development*, doi:10.1057/978-1-137-42724-3_40.

Barnett, J., P. Tschakert, L. Head, and W.N. Adger, 2016: A science of loss. *Nature Climate Change***, 6(November)**, 976-978, doi:10.1038/nclimate3140.

Barnett, J. et al., 2014: A local coastal adaptation pathway. *Nature Climate Change***, 4(12)**, 1103-1108, doi:10.1038/nclimate2383.

Barrett, S., 2013: Local level climate justice? Adaptation finance and vulnerability reduction. *Global Environmental Change***, 23(6)**, 1819-1829, doi:10.1016/j.gloenvcha.2013.07.015.

Barrington-Leigh, C., 2016: Sustainability and Well-Being: A Happy Synergy. *Development***, 59**, 292-298, doi:10.1057/s41301-017-0113-x.

Bartos, M.D. and M. Chester, 2014: The conservation nexus: Valuing interdependent water and energy savings in Arizona. *Environmental science & technology***, 48(4)**, 2139-2149.

Bathiany, S., V. Dakos, M. Scheffer, and T.M. Lenton, 2018: Climate models predict increasing temperature variability in poor countries. *Science Advances***, 4(5)**, eaar5809, doi:10.1126/sciadv.aar5809.

Bauer, N. et al., 2016: Global fossil energy markets and climate change mitigation - an analysis with REMIND. *Climatic Change***, 136(1)**, 69-82, doi:10.1007/s10584-013-0901-6.

Bayram, H. and A.B. Öztürk, 2014: Global climate change, desertification, and its consequences in Turkey and the Middle East. In: *Global Climate Change and Public Health* [Pinkerton, K.E. and W.N. Rom (eds.)]. Springer, New York, NY, USA, pp. 293-305.

Bebbington, J. and C. Larrinaga, 2014: Accounting and sustainable development: an exploration. *Accounting, Organizations and Society***, 39(6)**, 395-413, doi:10.1016/j.aos.2014.01.003.

Beilin, R. and C. Wilkinson, 2015: Introduction: Governing for urban resilience. *Urban Studies***, 52(7)**, 1205-1217, doi:10.1177/0042098015574955.

Bell, K., 2015: Can the capitalist economic system deliver environmental justice? *Environmental Research Letters***, 10(12)**, doi:10.1088/1748-9326/10/12/125017.

Berger, M., S. Pfister, V. Bach, and M. Finkbeiner, 2015: Saving the planet's climate or water resources? The trade-off between carbon and water footprints of European biofuels. *Sustainability***, 7(6)**, 6665-6683, doi:10.3390/su7066665.

Berner, J. et al., 2016: Adaptation in Arctic circumpolar communities: food and water security in a changing climate. *International Journal of Circumpolar Health***, 3982(May 2017)**, 1-8, doi:10.3402/ijch.v75.33820.

Berrueta, V.M., M. Serrano-Medrano, C. Garcia-Bustamante, M. Astier, and O.R. Masera, 2017: Promoting sustainable local development of rural communities and mitigating climate change: the case of Mexico's Patsari improved cookstove project. *Climatic Change***, 140(1)**, 63-77, doi:10.1007/s10584-015-1523-y.

Bertram, C. et al., 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environmental Research Letters* (in press).

Betts, R.A. et al., 2018: Changes in climate extremes, fresh water availability and vulnerability to food insecurity projected at 1.5°C and 2°C global warming with a higher-resolution global climate model. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences***, 376(2119)**, 20160452, doi:10.1098/rsta.2016.0452.

Betzold, C. and F. Weiler, 2017: Allocation of aid for adaptation to climate change: do vulnerable countries receive more support? *International Environmental Agreements: Politics, Law and Economics***, 17**, 17-36.

Bexell, M. and K. Jönsson, 2017: Responsibility and the United Nations' Sustainable Development Goals. *Forum for Development Studies***, 44(1)**, 13-29, doi:10.1080/08039410.2016.1252424.

Bickersteth, S. et al., 2017: *Mainstreaming climate compatible development: Insights from CDKN's first seven years*.

Biermann, F. and I. Boas, 2017: Towards a global governance system to protect climate migrants: taking stock. In: *Research Handbook on Climate Change, Migration and the Law* [Mayer, B. and F. Crepeau (eds.)]. Edward Elgar Publishing, Cheltenham, UK ; Northampton, MA, USA, pp. 405-419.

Biermann, M., K. Hillmer-Pegram, C.N. Knapp, and R.E. Hum, 2016: Approaching a critical turn? A content analysis of the politics of resilience in key bodies of resilience literature. *Resilience***, 4(2)**, 59-78, doi:10.1080/21693293.2015.1094170.

Binam, J.N., F. Place, A.A. Djalal, and A. Kalinganire, 2017: Effects of local institutions on the adoption of agroforestry innovations: evidence of farmer managed natural regeneration and its implications for rural livelihoods in the Sahel. *Agricultural and Food Economics***, 5(1)**, 2, doi:10.1186/s40100-017-0072-2.

Blanco, V., C. Brown, S. Holzhauer, G. Vulturius, and M.D.A. Rounsevell, 2017: The importance of socio-ecological system dynamics in understanding adaptation to global change in the forestry sector. *Journal of Environmental Management***, 196**, 36-47, doi:10.1016/j.jenvman.2017.02.066.

Blondeel, M. and T. van de Graaf, 2018: Toward a global coal mining moratorium? A comparative analysis of coal mining policies in the USA, China, India and Australia. *Climatic Change*, 1-13, doi:10.1007/s10584-017-2135-5.

Blyth, W., R. McCarthy, and R. Gross, 2015: Financing the UK power sector: is the money available? *Energy Policy*, **87**, 607-622, doi:https://doi.org/10.1016/j.enpol.2015.08.028.

Boke, C., 2015: Resilience's problem of the present: reconciling social justice and future-oriented resilience planning in the Transition Town movement. *Resilience*, **3(3)**, 207-220, doi:10.1080/21693293.2015.1072313.

Bonsch, M. et al., 2016: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy*, **8(1)**, 11-24.

Boonstra, W.J., E. Björkvik, L.J. Haider, and V. Masterson, 2016: Human responses to social-ecological traps. *Sustainability Science*, **11(6)**, 877-889, doi:10.1007/s11625-016-0397-x.

Bosomworth, K., P. Leith, A. Harwood, and P.J. Wallis, 2017: What's the problem in adaptation pathways planning? The potential of a diagnostic problem-structuring approach. *Environmental Science and Policy*, **76(January)**, 23-28, doi:10.1016/j.envsci.2017.06.007.

Bowyer, P., M. Schaller, S. Bender, and D. Jacob, 2015: Adaptation as climate risk management: methods and approaches. *Handbook of Climate Change Adaptation*, 71-92.

Boyd, E., R.A. James, R.G. Jones, H.R. Young, and F.E.L. Otto, 2017: A typology of loss and damage perspectives. *Nature Climate Change*, **7(10)**, 723-729, doi:10.1038/nclimate3389.

Boyle, J. et al., 2013: *Exploring trends in low-carbon, climate-resilient development*. 37 pp.

Boysen, L.R., W. Lucht, and D. Gerten, 2017: Trade-offs for food production, nature conservation and climate limit the terrestrial carbon dioxide removal potential. *Global Change Biology*, **23(10)**, 4303-4317, doi:10.1111/gcb.13745.

Brink, E. et al., 2016: Cascades of green: A review of ecosystem-based adaptation in urban areas. *Global Environmental Change*, **36**, 111-123, doi:10.1016/j.gloenvcha.2015.11.003.

Brockington, D. and S. Ponte, 2015: The Green Economy in the global South: experiences, redistributions and resistance. *Third World Quarterly*, **36(12)**, 2197-2206, doi:10.1080/01436597.2015.1086639.

Brohé, A., 2014: Whither the CDM? Investment outcomes and future prospects. *Environment, Development and Sustainability*, **16(2)**, 305-322, doi:10.1007/s10668-013-9478-5.

Brown, D. and G. McGranahan, 2016: The urban informal economy, local inclusion and achieving a global green transformation. *Habitat International*, **53**, 97-105.

Brown, E., J. Cloke, D. Gent, P.H. Johnson, and C. Hill, 2014: Green growth or ecological commodification: debating the green economy in the global south. *Geografiska Annaler, Series B: Human Geography*, **96(3)**, 245-259, doi:10.1111/geob.12049.

Bryan, E., Q. Bernier, M. Espinal, and C. Ringler, 2017: Making climate change adaptation programmes in sub-Saharan Africa more gender responsive: insights from implementing organizations on the barriers and opportunities. *Climate and Development*, 1-15, doi:10.1080/17565529.2017.1301870.

Buch-Hansen, H., 2018: The Prerequisites for a Degrowth Paradigm Shift: Insights from Critical Political Economy. *Ecological Economics*, **146(October 2017)**, 157-163, doi:10.1016/j.ecolecon.2017.10.021.

Bulkeley, H., G.A.S. Edwards, and S. Fuller, 2014: Contesting climate justice in the city: examining politics and practice in urban climate change experiments. *Global Environmental Change*, **25(1)**, 31-40, doi:10.1016/j.gloenvcha.2014.01.009.

Bulkeley, H., J.A. Carmin, V. Castán Broto, G.A.S. Edwards, and S. Fuller, 2013: Climate justice and global cities: mapping the emerging discourses. *Global Environmental Change*, **23(5)**, 914-925, doi:10.1016/j.gloenvcha.2013.05.010.

Buntaine, M.T. and L. Prather, 2018: Preferences for Domestic Action Over International Transfers in Global Climate Policy. *Journal of Experimental Political Science*, 1-15, doi:10.1017/XPS.2017.34.

Burke, M., S.M. Hsiang, and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature*, **527(7577)**, 235-239, doi:10.1038/nature15725.

Burns, W. and S. Nicholson, 2017: Bioenergy and carbon capture with storage (BECCS): the prospects and challenges of an emerging climate policy response. *Journal of Environmental Studies and Sciences*, **7(4)**, 527-534, doi:10.1007/s13412-017-0445-6.

Bustamante, M. et al., 2014: Co-benefits, trade-offs, barriers and policies for greenhouse gas mitigation in the agriculture, forestry and other land use (AFOLU) sector. *Global Change Biology*, **20(10)**, 3270-3290, doi:10.1111/gcb.12591.

Butler, C., K.A. Parkhill, and N.F. Pidgeon, 2016: Energy consumption and everyday life: choice, values and agency through a practice theoretical lens. *Journal of Consumer Culture*, **16(3)**, 887-907, doi:10.1177/1469540514553691.

Butler, J.R.A. et al., 2016: Scenario planning to leap-frog the Sustainable Development Goals: an adaptation pathways approach. *Climate Risk Management*, **12**, 83-99, doi:10.1016/j.crm.2015.11.003.

Butt, N. et al., 2016: Challenges in assessing the vulnerability of species to climate change to inform conservation actions. *Biological Conservation*, **199**, 10-15, doi:10.1016/j.biocon.2016.04.020.

Byers, E. et al., 2018: Global exposure and vulnerability to multi-sector climate change hotspots. *Environmental*

Research Letters (in press), doi:10.1088/1748-9326/aabf45.

Byers, E.A., J.W. Hall, and J.M. Amezaga, 2014: Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, **25**, 16-30, doi:10.1016/j.gloenvcha.2014.01.005.

Byrne, J. et al., 2016: Could urban greening mitigate suburban thermal inequity?: the role of residents' dispositions and household practices. *Environmental Research Letters*, **11(9)**, 095014, doi:10.1088/1748-9326/11/9/095014.

Byrnes, W.M., 2014: Climate justice, Hurricane Katrina, and African American environmentalism. *Journal of African American Studies*, **18(3)**, 305-314, doi:10.1007/s12111-013-9270-5.

Cabezon, E., L. Hunter, P. Tumbarello, K. Washimi, and Yiqun Wu, 2016: Strengthening Macro-Fiscal Resilience to Natural Disasters and Climate Change in the Small States of the Pacific. In: *Resilience and Growth in the Small States of the Pacific* [Khor, H.E., R.P. Kronenberg, and P. Tumbarello (eds.)]. pp. 71-94.

Caldecott, B., O. Sartor, and T. Spencer, 2017: *Lessons from previous 'coal transitions': High-level summary for decision-makers*. 24 pp.

Callen, T., R. Cherif, F. Hasanov, A. Hegazy, and P. Khandelwal, 2014: Economic diversification in the GCC: past, present, and future.

Calliari, E., 2016: Loss and damage: a critical discourse analysis of Parties' positions in climate change negotiations. *Journal of Risk Research*, **9877**, 1-23, doi:10.1080/13669877.2016.1240706.

Calvet-Mir, L., E. Corbera, A. Martin, J. Fisher, and N. Gross-Camp, 2015: Payments for ecosystem services in the tropics: a closer look at effectiveness and equity. *Current Opinion in Environmental Sustainability*, **14(May)**, 150-162, doi:10.1016/j.cosust.2015.06.001.

Calvin, K. et al., 2017: The SSP4: A world of deepening inequality. *Global Environmental Change*, **42**, 284-296, doi:10.1016/j.gloenvcha.2016.06.010.

Cameron, C. et al., 2016: Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nature Energy*, **1**, 1-5, doi:10.1038/nenergy.2015.10.

Cameron, R.W.F., J. Taylor, and M. Emmett, 2015: A Hedera green facade - energy performance and saving under different maritime-temperate, winter weather conditions. *Building and Environment*, **92**, 111-121, doi:10.1016/j.buildenv.2015.04.011.

Campbell, B.M. et al., 2016: Reducing risks to food security from climate change. *Global Food Security*, **11**, 34-43, doi:10.1016/j.gfs.2016.06.002.

Câmpeanu, C.N. and I. Fazey, 2014: Adaptation and pathways of change and response: a case study from Eastern Europe. *Global Environmental Change*, **28**, 351-367, doi:10.1016/j.gloenvcha.2014.04.010.

Campiglio, E., 2016: Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecological Economics*, **121**, 220-230, doi:10.1016/j.ecolecon.2015.03.020.

Carr, E.R. and M.C. Thompson, 2014: Gender and climate change adaptation in agrarian settings. *Geography Compass*, **8/3(October)**, 182-197, doi:10.1111/gec3.12121.

Carr, E.R. and K.N. Owusu-Daaku, 2015: The shifting epistemologies of vulnerability in climate services for development: The case of Mali's agrometeorological advisory programme. *Area*, 7-17, doi:10.1111/area.12179.

Carr, E.R. and S.N. Onzere, 2017: Really effective (for 15% of the men): lessons in understanding and addressing user needs in climate services from Mali. *Climate Risk Management* (in press), doi:10.1016/j.crm.2017.03.002.

Carter, T.R. et al., 2016: Characterising vulnerability of the elderly to climate change in the Nordic region. *Regional Environmental Change*, **16(1)**, 43-58, doi:10.1007/s10113-014-0688-7.

Castán Broto, V., 2017: Urban Governance and the Politics of Climate change. *World Development*, **93**, 1-15, doi:10.1016/j.worlddev.2016.12.031.

Castro, P., 2016: Common but differentiated responsibilities beyond the nation state: how is differential treatment addressed in transnational Climate governance initiatives? *Transnational Environmental Law*, **5(02)**, 379-400, doi:10.1017/S2047102516000224.

Cavanagh, C. and T.A. Benjaminsen, 2014: Virtual nature, violent accumulation: The 'spectacular failure' of carbon offsetting at a Ugandan National Park. *Geoforum*, **56**, 55-65, doi:10.1016/j.geoforum.2014.06.013.

Cervigni, R. and M. Morris (eds.), 2016: *Confronting drought in Africa's drylands: opportunities for enhancing resilience*. World Bank, Washington DC, USA.

Chakrabarti, S. and E.J. Shin, 2017: Automobile dependence and physical inactivity: insights from the California Household Travel Survey. *Journal of Transport and Health*, **6(April)**, 262-271, doi:10.1016/j.jth.2017.05.002.

Chakravarty, D. and M. Tavoni, 2013: Energy poverty alleviation and climate change mitigation: Is there a trade off? *Energy Economics*, **40**, S67-S73.

Chakravarty, D. and J. Roy, 2016: The Global South: new estimates and insights from urban India. In: *Rethinking climate and energy policies: new perspectives on the rebound phenomenon* [Santarius, T., H.J. Walnum, and A. Carlo (eds.)]. Springer, pp. 55-72.

Chakravarty, D., S. Dasgupta, and J. Roy, 2013: Rebound effect: how much to worry? *Current Opinion in Environmental Sustainability*, **5(2)**, 216-228, doi:10.1016/j.cosust.2013.03.001.

Chan, K.M.A., E. Anderson, M. Chapman, K. Jespersen, and P. Olmsted, 2017: Payments for ecosystem services: rife with problems and potential-for transformation towards sustainability. *Ecological Economics***, 140**, 110-122, doi:10.1016/j.ecolecon.2017.04.029.

Chancel, L. and T. Picketty, 2015: *Carbon and inequality: from Kyoto to Paris. Trends in the global inequality of carbon emissions (1998-2013) & prospects for an equitable adaptation fund*. 50 pp.

Chapin, F.S., C.N. Knapp, T.J. Brinkman, R. Bronen, and P. Cochran, 2016: Community-empowered adaptation for self-reliance. *Current Opinion in Environmental Sustainability***, 19**, 67-75, doi:10.1016/j.cosust.2015.12.008.

Chaturvedi, V. and P.R. Shukla, 2014: Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Climatic Change***, 123(3)**, 597-609, doi:10.1007/s10584-013-0898-x.

Chelleri, L., G. Minucci, and E. Skrimizea, 2016: Does community resilience decrease social-ecological vulnerability? Adaptation pathways trade-off in the Bolivian Altiplano. *Regional Environmental Change***, 16(8)**, 2229-2241, doi:10.1007/s10113-016-1046-8.

Chen, X., X. Liu, and D. Hu, 2015: Assessment of sustainable development: A case study of Wuhan as a pilot city in China. *Ecological Indicators***, 50**, 206-214, doi:10.1016/j.ecolind.2014.11.002.

Cheung, W.W.L., G. Reygondeau, and T.L. Frölicher, 2016: Large benefits to marine fisheries of meeting the 1.5°C global warming target. *Science***, 354(6319)**, 1591-1594, doi:10.1126/science.aag2331.

Chief, K., A. Meadow, and K. Whyte, 2016: Engaging southwestern tribes in sustainable water resources topics and management. *Water***, 8(8)**, 1-21, doi:10.3390/w8080350.

Chong, J., 2014: Ecosystem-based approaches to climate change adaptation: progress and challenges. *International Environmental Agreements: Politics, Law and Economics***, 14(4)**, 391-405, doi:10.1007/s10784-014-9242-9.

Chu, E., I. Anguelovski, and D. Roberts, 2017: Climate adaptation as strategic urbanism: assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities***, 60**, 378-387, doi:10.1016/j.cities.2016.10.016.

Clarke, L.E. et al., 2014: Assessing transformation pathways. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 413-510.

Clements, R., 2009: *The Economic Cost of Climate Change in Africa*. 52 pp.

Cobbinah, P.B. and G.K. Anane, 2016: Climate change adaptation in rural Ghana: indigenous perceptions and strategies. *Climate and Development***, 8(2)**, 169-178, doi:10.1080/17565529.2015.1034228.

Coe, R., F. Sinclair, and E. Barrios, 2014: Scaling up agroforestry requires research 'in' rather than 'for' development. *Current Opinion in Environmental Sustainability***, 6(1)**, 73-77, doi:10.1016/j.cosust.2013.10.013.

Coe, R., J. Njoloma, and F. Sinclair, 2017: To control or not to control: how do we learn more about how agronomic innovations perform on farms? *Experimental Agriculture*, 1-7, doi:10.1017/S0014479717000102.

Cohen, M.G. (ed.), 2017: *Climate change and gender in rich countries: work, public policy and action*. Routledge, Abingdon, UK and New York, NY, USA, 322 pp.

Cole, M.J., R.M. Bailey, and M.G. New, 2017: Spatial variability in sustainable development trajectories in South Africa: provincial level safe and just operating spaces. *Sustainability Science***, 12(5)**, 829-848, doi:10.1007/s11625-016-0418-9.

Colenbrander, S., D. Dodman, and D. Mitlin, 2017: Using climate finance to advance climate justice: the politics and practice of channelling resources to the local level. *Climate Policy*, 1-14, doi:10.1080/14693062.2017.1388212.

Colenbrander, S. et al., 2016: Can low-carbon urban development be pro-poor? The case of Kolkata, India. *Environment and Urbanization***, 29(1)**, 139-158, doi:10.1177/0956247816677775.

Colloff, M.J. et al., 2017: An integrative research framework for enabling transformative adaptation. *Environmental Science and Policy***, 68**, 87-96, doi:10.1016/j.envsci.2016.11.007.

Conservation International, 2016: *Ecosystem Based Adaptation: Essential for Achieving the Sustainable Development Goals*. 4 pp.

Conway, D. et al., 2015: Climate and southern Africa's water-energy-food nexus. *Nature Climate Change***, 5(9)**, 837-846, doi:10.1038/Nclimate2735.

Corbera, E., C. Hunsberger, and C. Vaddhanaphuti, 2017: Climate change policies, land grabbing and conflict: perspectives from Southeast Asia. *Canadian Journal of Development Studies***, 38(3)**, 297-304, doi:10.1080/02255189.2017.1343413.

Cretney, R.M., A.C. Thomas, and S. Bond, 2016: Maintaining grassroots activism: Transition Towns in Aotearoa New Zealand. *New Zealand Geographer***, 72(2)**, 81-91.

Creutzig, F. et al., 2015: Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy***, 7(5)**, 916-944, doi:10.1111/gcbb.12205.

Croce, D., C. Kaminker, and F. Stewart, 2011: The role of pension funds in financing green growth initiatives. OECD Working Papers on Finance, Insurance and Private Pensions.

Crosland, T., A. Meyer, and M. Wewerinke-singh, 2016: The Paris Agreement Implementation Blueprint: a practical guide to bridging the gap between actions and goal and closing the accountability deficit (Part 1). *Environmental liability*, **25(2)**, 114-125.

CSO Review, 2015: Fair shares: a civil society equity review of INDCs. , doi:10.6084/m9.figshare.5917399.

Cugurullo, F., 2013: How to build a sandcastle: an analysis of the genesis and development of Masdar City. *Journal of Urban Technology*, **20(1)**, 23-37, doi:10.1080/10630732.2012.735105.

Cundill, G. et al., 2014: *Social learning for adaptation: a descriptive handbook for practitioners and action researchers*. 118 pp.

Cutter, S.L., 2016: Resilience to What? Resilience for Whom? *Geographical Journal*, **182(2)**, 110-113, doi:10.1111/geoj.12174.

Cvitanovic, C. et al., 2016: Linking adaptation science to action to build food secure Pacific Island communities. *Climate Risk Management*, **11**, 53-62, doi:10.1016/j.crm.2016.01.003.

Daigneault, A., P. Brown, and D. Gawith, 2016: Dredging versus hedging: Comparing hard infrastructure to ecosystem-based adaptation to flooding. *Ecological Economics*, **122**, 25-35, doi:10.1016/j.ecolecon.2015.11.023.

Dasgupta, P., 2016: *Climate Sensitive Adaptation in Health: Imperatives for India in a Developing Economy Context*. Springer India, 194 pp.

Dasgupta, P., K. Ebi, and I. Sachdeva, 2016: Health sector preparedness for adaptation planning in India. *Climatic Change*, **138(3-4)**, 551-566, doi:10.1007/s10584-016-1745-7.

Dasgupta, S., M. Huq, M.G. Mustafa, M.I. Sobhan, and D. Wheeler, 2017: The impact of aquatic salinization on fish habitats and poor communities in a changing climate: evidence from southwest coastal Bangladesh. *Ecological Economics*, **139**, 128-139, doi:10.1016/j.ecolecon.2017.04.009.

Datta, N., 2015: Evaluating impacts of watershed development program on agricultural productivity, income, and livelihood in bhalki watershed of Bardhaman District, West Bengal. *World Development*, **66**, 443-456, doi:10.1016/j.worlddev.2014.08.024.

Davies, K., 2015: Kastom, climate change and intergenerational democracy: experiences from Vanuatu. In: *Climate change in the Asia-Pacific region* [Leal Filho, W. (ed.)]. Springer, pp. 49-66.

Davies, T.E., N. Pettorelli, W. Cresswill, and I.R. Fazey, 2014: Who are the poor? Measuring wealth inequality to aid understanding of socioeconomic contexts for conservation: a case-study from the Solomon Islands. *Environmental Conservation*, **41(04)**, 357-366, doi:10.1017/S0376892914000058.

de Coninck, H.C. and D. Puig, 2015: Assessing climate change mitigation technology interventions by international institutions. *Climatic Change*, **131(3)**, 417-433, doi:10.1007/s10584-015-1344-z.

de Coninck, H.C. and A. Sagar, 2015: Making sense of policy for climate technology development and transfer. *Climate Policy*, **15(1)**, 1-11, doi:10.1080/14693062.2014.953909.

de Coninck, H.C. and A. Sagar, 2017: Technology development and transfer (Article 10). *The Paris Agreement on Climate Change*, 258-276.

De Stefano, L., J.D. Petersen-Perlman, E.A. Sproles, J. Eynard, and A.T. Wolf, 2017: Assessment of transboundary river basins for potential hydro-political tensions. *Global Environmental Change*, **45**, 35-46.

Dearing, J.A. et al., 2014: Safe and just operating spaces for regional social-ecological systems. *Global Environmental Change*, **28(1)**, 227-238, doi:10.1016/j.gloenvcha.2014.06.012.

Death, C., 2014: The Green Economy in South Africa: Global Discourses and Local Politics. *Politikon*, **41(1)**, 1-22, doi:10.1080/02589346.2014.885668.

Death, C., 2015: Four discourses of the green economy in the global South. *Third World Quarterly*, **36(12)**, 2207-2224, doi:10.1080/01436597.2015.1068110.

Death, C., 2016: Green states in Africa: beyond the usual suspects. *Environmental Politics*, **25:1**, 116-135, doi:10.1080/09644016.2015.1074380.

DeCaro, D.A., C. Anthony, T. Arnold, E.F. Boamah, and A.S. Garmestani, 2017: Understanding and applying principles of social cognition and decision making in adaptive environmental governance. *Ecology and Society*, **22(1)**, 33, doi:doi.org/10.5751/ES-09154-220133.

DeClerck, F.A.J. et al., 2016: Agricultural ecosystems and their services: the vanguard of sustainability? *Current Opinion in Environmental Sustainability*, **23**, 92-99, doi:10.1016/j.cosust.2016.11.016.

Delponte, I., I. Pittaluga, and C. Schenone, 2017: Monitoring and evaluation of Sustainable Energy Action Plan: practice and perspective. *Energy Policy*, **100**, 9-17, doi:10.1016/j.enpol.2016.10.003.

Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112(52)**, 15827-15832, doi:10.1073/pnas.1513967112.

Denton, F. et al., 2014: Climate-resilient pathways: adaptation, mitigation, and sustainable development. In: *Climate*

Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1101-1131.

Derbez, M. et al., 2014: Indoor air quality and comfort in seven newly built, energy-efficient houses in France. *Building and Environment*, **72**, 173-187, doi:10.1016/j.buildenv.2013.10.017.

Di Gregorio, M. et al., 2017: Climate policy integration in the land use sector: Mitigation, adaptation and sustainable development linkages. *Environmental Science & Policy*, **67**, 35-43, doi:10.1016/j.envsci.2016.11.004.

Dilling, L., M.E. Daly, W.R. Travis, O. Wilhelmi, and R.A. Klein, 2015: The dynamics of vulnerability: why adapting to climate variability will not always prepare us for climate change. *Wiley Interdisciplinary Reviews: Climate Change*, **6(4)**, 413-425, doi:10.1002/wcc.341.

Ding, H. et al., 2016: *Climate Benefits, Tenure Costs: The Economic Case For Securing Indigenous Land Rights in the Amazon*. 98 pp.

Dinku, T. et al., 2014: Bridging critical gaps in climate services and applications in Africa. *Earth Perspectives*, **1(1)**, 15, doi:10.1186/2194-6434-1-15.

Dodman, D., H. Leck, M. Rusca, and S. Colenbrander, 2017: African urbanisation and urbanism: implications for risk accumulation and reduction. *International Journal of Disaster Risk Reduction*, **26(January)**, 7-15, doi:10.1016/j.ijdrr.2017.06.029.

Doswald, N. et al., 2014: Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. *Climate and Development*, **6(2)**, 185-201, doi:10.1080/17565529.2013.867247.

Douxchamps, S. et al., 2016: Linking agricultural adaptation strategies, food security and vulnerability: evidence from West Africa. *Regional Environmental Change*, **16(5)**, 1305-1317, doi:10.1007/s10113-015-0838-6.

Dovie, D.B.K., M. Dzodzomenyo, and O.A. Ogunseitan, 2017: Sensitivity of health sector indicators' response to climate change in Ghana. *Science of the Total Environment*, **574**, 837-846, doi:10.1016/j.scitotenv.2016.09.066.

Dow, K. et al., 2013: Limits to adaptation. *Nature Climate Change*, **3(4)**, 305-307, doi:10.1038/nclimate1847.

Dual Citizen LLC, 2016: *The Global Green Economy Index - GGEI 2016: Measuring National Performance in the Green Economy*. Dual Citizen LLC, Washington DC, USA and New York, NY, USA, 58 pp.

Duarte, C.M., J. Wu, X. Xiao, A. Bruhn, and D. Krause-Jensen, 2017: Can seaweed farming play a role in climate change mitigation and adaptation? *Frontiers in Marine Science*, **4(April)**, doi:10.3389/fmars.2017.00100.

Duguma, L.A., P.A. Minang, and M. Van Noordwijk, 2014: Climate change mitigation and adaptation in the land use sector: from complementarity to synergy. *Environmental Management*, **54(3)**, 420-432, doi:10.1007/s00267-014-0331-x.

Dumont, E.S., S. Bonhomme, T.F. Pagella, and F.L. Sinclair, 2017: Structured stakeholder engagement leads to development of more diverse and inclusive agroforestry options. *Experimental Agriculture*, 1-23, doi:10.1017/S0014479716000788.

Eakin, H.C., M.C. Lemos, and D.R. Nelson, 2014: Differentiating capacities as a means to sustainable climate change adaptation. *Global Environmental Change*, **27(27)**, 1-8, doi:10.1016/j.gloenvcha.2014.04.013.

Ebi, K.L. and M.O. Del Barrio, 2017: Lessons learned on health adaptation to climate variability and change: Experiences across low- and middle-income countries. *Environmental Health Perspectives*, **125(6)**, doi:10.1289/EHP405.

Ebi, K.L. et al., 2014: A new scenario framework for climate change research: background, process, and future directions. *Climatic Change*, **122(3)**, 363-372, doi:10.1007/s10584-013-0912-3.

Echegaray, F., 2016: Consumers' reactions to product obsolescence in emerging markets: the case of Brazil. *Journal of Cleaner Production*, **134**, 191-203, doi:10.1016/j.jclepro.2015.08.119.

Ehresman, T.G. and C. Okereke, 2015: Environmental justice and conceptions of the green economy. *International Environmental Agreements: Politics, Law and Economics*, **15(1)**, 13-27, doi:10.1007/s10784-014-9265-2.

Ekwurzel, B. et al., 2017: The rise in global atmospheric CO2, surface temperature, and sea level from emissions traced to major carbon producers. *Climatic Change*, 1-12, doi:10.1007/s10584-017-1978-0.

Enqvist, J., M. Tengö, and W.J. Boonstra, 2016: Against the current: rewiring rigidity trap dynamics in urban water governance through civic engagement. *Sustainability Science*, **11(6)**, 919-933, doi:10.1007/s11625-016-0377-1.

Ensor, J., 2016: Adaptation and resilience in Vanuatu: Interpreting community perceptions of vulnerability, knowledge and power for community-based adaptation programming. 32 pp.

Ensor, J. and B. Harvey, 2015: Social learning and climate change adaptation: evidence for international development practice. *Wiley Interdisciplinary Reviews: Climate Change*, **6(5)**, 509-522, doi:10.1002/wcc.348.

Entzinger, H. and P. Scholten, 2016: *Adapting to Climate Change through Migration. A case study of the Vietnamese Mekong River Delta*. 62 pp.

Epule, T.E., J.D. Ford, S. Lwasa, and L. Lepage, 2017: Climate change adaptation in the Sahel. *Environmental Science & Policy*, **75(May)**, 121-137, doi:10.1016/j.envsci.2017.05.018.

Eriksen, S., L.O. Naess, R. Haug, L. Lenaerts, and A. Bhonagiri, 2017: Courting catastrophe? Can humanitarian actions contribute to climate change adaptation? *IDS Bulletin*, **48(4)**, doi:10.19088/1968-2017.149.

Eriksson, H. et al., 2017: The role of fish and fisheries in recovering from natural hazards: lessons learned from Vanuatu. *Environmental Science & Policy*, **76(March)**, 50-58, doi:10.1016/j.envsci.2017.06.012.

Estrella, M., F.G. Renaud, K. Sudmeier-Rieux, and U. Nehren, 2016: Defining New Pathways for Ecosystem-Based Disaster Risk Reduction and Adaptation in the Post-2015 Sustainable Development Agenda. In: *Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice* [Renaud, F.G., K. Sudmeier-Rieux, M. Estrella, and U. Nehren (eds.)]. Springer International Publishing Switzerland, pp. 553-591.

Evans, G. and L. Phelan, 2016: Transition to a post-carbon society: linking environmental justice and just transition discourses. *Energy Policy*, **99**, 329-339, doi:10.1016/j.enpol.2016.05.003.

Evans, J.P., R.B. Smith, and R.J. Oglesby, 2004: Middle East climate simulation and dominant precipitation processes. *International Journal of Climatology*, **24(13)**, 1671-1694, doi:10.1002/joc.1084.

Falcone, P.M., P. Morone, and E. Sica, 2018: Greening of the financial system and fuelling a sustainability transition: a discursive approach to assess landscape pressures on the Italian financial system. *Technological Forecasting and Social Change*, **127**, 23-37, doi:https://doi.org/10.1016/j.techfore.2017.05.020.

Fan, Y., Q. Qiao, L. Fang, and Y. Yao, 2017: Energy analysis on industrial symbiosis of an industrial park: a case study of Hefei economic and technological development area. *Journal of Cleaner Production*, **141**, 791-798, doi:10.1016/j.jclepro.2016.09.159.

Fankhauser, S. and T.K.J. McDermott, 2014: Understanding the adaptation deficit: Why are poor countries more vulnerable to climate events than rich countries? *Global Environmental Change*, **27**, 9-18, doi:10.1016/j.gloenvcha.2014.04.014.

Fankhauser, S. and N. Stern, 2016: Climate change, development, poverty and economics. Grantham Research Institute on Climate Change and the Environment Working Paper, 1-30 pp.

FAO, 2015: Adaptation to climate risk and food security: evidence from smallholder farmers in Ethiopia. .

FAO and NZAGRC, 2017a: Low emissions development of the beef cattle sector in Uruguay - reducing enteric methane for food security and livelihoods. .

FAO and NZAGRC, 2017b: Supporting low emissions development in the Ethiopian dairy cattle sector - reducing enteric methane for food security and livelihoods. .

Fatima, R., A.J. Wadud, and S. Coelho, 2014: Human rights, climate change, environmental degradation: a new paradigm. *IOM, MPI, Issue in Brief*.

Fay, M. et al., 2015: *Decarbonizing Development: Three Steps to a Zero-Carbon Future*. World Bank, Washington, DC, USA, 185 pp.

Fazey, I. et al., 2016: Past and future adaptation pathways. *Climate and Development*, **8(1)**, 26-44, doi:10.1080/17565529.2014.989192.

Fazey, I. et al., 2018: Community resilience for a 1.5°C world. *Current Opinion in Environmental Sustainability*, **31**, 30-40, doi:10.1016/j.cosust.2017.12.006.

Feola, G. and R. Nunes, 2014: Success and failure of grassroots innovations for addressing climate change: the case of the Transition Movement. *Global Environmental Change*, **24**, 232-250.

Ferguson, P., 2015: The green economy agenda: business as usual or transformational discourse? *Environmental Politics*, **24(1)**, 17-37, doi:10.1080/09644016.2014.919748.

Fernandes-Jesus, M., A. Carvalho, L. Fernandes, and S. Bento, 2017: Community engagement in the Transition movement: views and practices in Portuguese initiatives. *Local Environment*, **22(12)**, 1546-1562, doi:10.1080/13549839.2017.1379477.

Few, R., A. Martin, and N. Gross-Camp, 2017: Trade-offs in linking adaptation and mitigation in the forests of the Congo Basin. *Regional Environmental Change*, **17(3)**, 851-863, doi:10.1007/s10113-016-1080-6.

Ficklin, L., L.C. Stringer, A.J. Dougill, and S.M. Sallu, 2017: Climate compatible development reconsidered: calling for a critical perspective. *Climate and Development*, doi:10.1080/17565529.2017.1372260.

Field, C.B. et al., 2014: Technical Summary. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94.

Filho, L. and J. Nalau, 2018: Limits to climate change adaptation. , doi:10.1007/978-3-319-64599-5.

Fincher, R., J. Barnett, S. Graham, and A. Hurlimann, 2014: Time stories: making sense of futures in anticipation of sea-level rise. *Geoforum*, **56**, 201-210, doi:10.1016/j.geoforum.2014.07.010.

Fleurbaey, M. et al., 2014: Sustainable development and equity. In: *Climate Change 2014: Mitigation of Climate*

Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 283-350.

Fook, T.C.T., 2017: Transformational processes for community-focused adaptation and social change: a synthesis. *Climate and Development*, **5529(October)**, 1-17, doi:10.1080/17565529.2015.1086294.

Ford, J.D. et al., 2016: Community-based adaptation research in the Canadian Arctic. *Wiley Interdisciplinary Reviews: Climate Change*, **7(2)**, 175-191, doi:10.1002/wcc.376.

Francis, R., P. Weston, and J. Birch, 2015: *The social, environmental and economics benefits of Farmer Managed Natural Regeneration (FMNR)*.

Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, doi:10.1088/1748-9326/aa8c83.

FRDP, 2016: *Framework for resilient development in the Pacific: an integrated approach to address climate change and disaster risk management (FRDP) 2017-2030*. Framework for Resilient Development in the Pacific.

Fricko, O. et al., 2016: Energy sector water use implications of a 2°C degree climate policy. *Environmental Research Letters*, **11(3)**, 34011, doi:10.1088/1748-9326/11/3/034011.

Frumhoff, P.C., R. Heede, and N. Oreskes, 2015: The climate responsibilities of industrial carbon producers. *Climatic Change*, **132(2)**, 157-171, doi:10.1007/s10584-015-1472-5.

Fuchs, D. et al., 2016: Power: the missing element in sustainable consumption and absolute reductions research and action. *Journal of Cleaner Production*, **132**, 298-307, doi:10.1016/j.jclepro.2015.02.006.

Fuglestvedt, J.S. and S. Kallbekken, 2016: Climate responsibility: fair shares? *Nature Climate Change*, **6(1)**, 19-20, doi:10.1038/nclimate2791.

Fuhr, H., T. Hickmann, and K. Kern, 2018: The role of cities in multi-level climate governance: local climate policies and the 1.5 °C target. *Current Opinion in Environmental Sustainability*, **30**, 1-6, doi:10.1016/j.cosust.2017.10.006.

Fujimori, S., N. Hanasaki, and T. Masui, 2017a: Projections of industrial water withdrawal under shared socioeconomic pathways and climate mitigation scenarios. *Sustainability Science*, **12**, 275-292, doi:10.1007/s11625-016-0392-2.

Fujimori, S. et al., 2017b: SSP3: AIM implementation of Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 268-283, doi:10.1016/j.gloenvcha.2016.06.009.

Fukuda-Parr, S., A.E. Yamin, and J. Greenstein, 2014: The power of numbers: a critical review of Millennium Development Goal targets for human development and human rights. *Journal of Human Development and Capabilities*, **15(2-3)**, 105-117, doi:10.1080/19452829.2013.864622.

Fuller, R. and J. Lain, 2017: Building resilience: a meta-analysis of Oxfam's resilience Effectiveness Reviews. .

Gajjar, S.P., C. Singh, and T. Deshpande, 2018: Tracing back to move ahead: a review of development pathways that constrain adaptation futures. *Climate and Development*, 1-15, doi:10.1080/17565529.2018.1442793.

Galgóczi, B., 2014: The Long and Winding Road from Black to Green: Decades of Structural Change in the Ruhr Region. *International Journal of Labour Research*, **6(2)**, 217-240.

Garg, A., P. Mohan, S. Shukla, B. Kankal, and S.S. Vishwanathan, 2017: *High impact opportunities for energy efficiency in India*. UNEP DTU Partnerhsip, Copenhagen, 49 pp.

Gebrehaweria, G., A. Dereje Assefa, G. Girmay, M. Giordano, and L. Simon, 2016: An assessment of integrated watershed management in Ethiopia. IWMI Working Paper 170.

Georgeson, L., M. Maslin, and M. Poessinouw, 2017a: Global disparity in the supply of commercial weather and climate information services. *Science Advances*, **3**, e1602632.

Georgeson, L., M. Maslin, and M. Poessinouw, 2017b: The global green economy: a review of concepts, definitions, measurement methodologies and their interactions. *Geo: Geography and Environment*, **4(1)**, e00036, doi:10.1002/geo2.36.

Gero, A. et al., 2013: *Understanding the Pacific's adaptive capacity to emergencies in the context of climate change: Country Report - Vanuatu*. Report prepared for NCCARF by the Institute for Sustainable Futures, and WHO Collaborating Centre, University of Technology, Sydney, Australia.

Gillard, R., A. Gouldson, J. Paavola, and J. Van Alstine, 2016: Transformational responses to climate change: beyond a systems perspective of social change in mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change*, **7(2)**, 251-265, doi:10.1002/wcc.384.

Gillingham, K., D. Rapson, and G. Wagner, 2016: The rebound effect and energy efficiency policy. *Review of Environmental Economics and Policy*, **10(1)**, 68-88, doi:10.1093/reep/rev017.

Giwa, A., A. Alabi, A. Yusuf, and T. Olukan, 2017: A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. *Renewable and Sustainable Energy Reviews*, **69(November 2016)**, 620-641, doi:10.1016/j.rser.2016.11.160.

Glazebrook, G. and P. Newman, 2018: The City of the Future. *Urban Planning*, **3(2)**, 1, doi:10.17645/up.v3i2.1247.

Godfrey-Wood, R. and L.O. Naess, 2016: Adapting to Climate Change: Transforming Development? *IDS Bulletin*, **47(2)**, doi:10.19088/1968-2016.131.

Gomez-Echeverri, L., 2018: Climate and development: enhancing impact through stronger linkages in the implementation of the Paris Agreement and the Sustainable Development Goals (SDGs). *Philosophical Transactions of the Royal Society A*, **376**, doi:10.1098/rsta.2016.0444.

Gorddard, R., M.J. Colloff, R.M. Wise, D. Ware, and M. Dunlop, 2016: Values, rules and knowledge: Adaptation as change in the decision context. *Environmental Science and Policy*, **57**, 60-69, doi:10.1016/j.envsci.2015.12.004.

Gore, C., 2015: Climate change adaptation and African cities: understanding the impact of government and governance on future action.. *Rethinking the role of cities in the global climate regime*, 205-226.

Government of Kiribati, 2016: *Kiribati development plan 2016-19*. Government of Kiribati.

Granderson, A.A., 2017: Value conflicts and the politics of risk: challenges in assessing climate change impacts and risk priorities in rural Vanuatu. *Climate and Development*, 1-14, doi:10.1080/17565529.2017.1318743.

Grantham, R.W. and M.A. Rudd, 2017: Household susceptibility to hydrological change in the Lower Mekong Basin. *Natural Resources Forum*, **41(1)**, 3-17, doi:10.1111/1477-8947.12113.

Gray, E., N. Henninger, C. Reij, R. Winterbottom, and P. Agostini, 2016: *Integrated landscape approaches for Africa's drylands*.

Green, F., 2018: Anti-fossil fuel norms. *Climatic Change*, 1-14, doi:10.1007/s10584-017-2134-6.

Griffiths, S., 2017a: A review and assessment of energy policy in the Middle East and North Africa region. *Energy Policy*, **102(September 2016)**, 249-269, doi:10.1016/j.enpol.2016.12.023.

Griffiths, S., 2017b: Renewable energy policy trends and recommendations for GCC countries. *Energy Transitions*, **1(1)**, 3, doi:10.1007/s41825-017-0003-6.

Grill, G. et al., 2015: An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environmental Research Letters*, **10(1)**, 15001.

Grist, N. et al., 2017: Framing innovations for climate resilience for farmers in Sahel. *Resilience Intel*, **9**.

Grossmann, M. and E. Creamer, 2017: Assessing diversity and inclusivity within the Transition Movement: an urban case study. *Environmental Politics*, **26(1)**, 161-182, doi:10.1080/09644016.2016.1232522.

Grubert, E.A., A.S. Stillwell, and M.E. Webber, 2014: Where does solar-aided seawater desalination make sense? A method for identifying sustainable sites. *Desalination*, **339**, 10-17.

Grubler, A. et al., 2018: A global scenario of low energy demand for sustainable development below 1.5°C without negative emission technologies. *Nature Energy* (in press), doi:10.1038/s41560-018-0172-6.

Gupta, J. and K. Arts, 2017: Achieving the 1.5 °C objective: just implementation through a right to (sustainable) development approach. *International Environmental Agreements: Politics, Law and Economics*, doi:10.1007/s10784-017-9376-7.

Gupta, J. and N. Pouw, 2017: Towards a trans-disciplinary conceptualization of inclusive development. *Current Opinion in Environmental Sustainability*, **24**, 96-103, doi:10.1016/j.cosust.2017.03.004.

Gustafson, S. et al., 2017: Merging science into community adaptation planning processes: a cross-site comparison of four distinct areas of the Lower Mekong Basin. *Climatic Change*, 1-16, doi:10.1007/s10584-016-1887-7.

Gwimbi, P., 2017: Mainstreaming national adaptation programmes of action into national development plans in Lesotho: lessons and needs. *International Journal of Climate Change Strategies and Management*, **9(3)**, 299-315, doi:10.1108/IJCCSM-11-2015-0164.

Hackmann, B., 2016: Regime learning in global environmental governance. *Environmental Values*, **25(6)**, doi:10.3197/096327116X14736981715625.

Haider, L.J., W.J. Boonstra, G.D. Peterson, and M. Schlüter, 2017: Traps and sustainable development in rural areas: a review. *World Development*, **xx(2013)**, doi:10.1016/j.worlddev.2017.05.038.

Hajer, M. et al., 2015: Beyond cockpit-ism: Four insights to enhance the transformative potential of the sustainable development goals. *Sustainability*, **7(2)**, doi:10.3390/su7021651.

Hale, T., 2016: "All hands on deck": the Paris Agreements and nonstate climate action. *Global Environmental Politics*, **16(3)**, doi:10.1162/GLEP_a_00362.

Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7(4)**, 250-256, doi:10.1038/nclimate3253.

Hallegatte, S. et al., 2014: Climate change and poverty: an analytical framework. , doi:10.1596/1813-9450-7126.

Hallegatte, S. et al., 2016: *Shock Waves: Managing the Impacts of Climate Change on Poverty*. The World Bank, Washington, DC, USA, 227 pp.

Halonen, M. et al., 2017: *Mobilizing climate finance flows: Nordic approaches and opportunities*. TemaNord 2017:519, Nordic Council of Ministers, 151 pp.

Hammill, B.A. and H. Price-Kelly, 2017: *Using NDCs , NAPs and the SDGs to Advance Climate-Resilient Development*. 1-10 pp.

Handmer, J. and H. Iveson, 2017: Cyclone Pam in Vanuatu: Learning from the low death toll. *Australian jouranl of Emergency Management*, **22(2)**.

Hanna, R. and P. Oliva, 2016: Implications of climate change for children in developing countries. *The Future of Children*, **26(1)**, 115-132.

Hansen, G. and D. Stone, 2016: Assessing the observed impact of anthropogenic climate change. *Nature Climate Change*, **6(5)**, 532-537, doi:10.1038/nclimate2896.

Harris, L.M., E.K. Chu, and G. Ziervogel, 2017: Negotiated resilience. *Resilience*, **3293**, 1-19, doi:10.1080/21693293.2017.1353196.

Hartzell-Nichols, L., 2017: *A climate of risk: precautionary principles, catastrophes and climate change*. Routledge, Abingdon, Oxon, UK and New York, NY, USA.

Hasegawa, T. et al., 2014: Climate change impact and adaptation assessment on food consumption utilizing a new scenario framework. *Environmental Science and Technology*, **48(1)**, 438-445, doi:10.1021/es4034149.

Hasegawa, T. et al., 2015: Consequence of climate mitigation on the risk of hunger. *Environmental Science & Technology*, **49(12)**, 7245-7253, doi:10.1021/es5051748.

Hashemi, S., A. Bagheri, and N. Marshall, 2017: Toward sustainable adaptation to future climate change: insights from vulnerability and resilience approaches analyzing agrarian system of Iran. *Environment, Development and Sustainability*, **19(1)**, 1-25.

Hatfield-Dodds, S. et al., 2015: Australia is 'free to choose' economic growth and falling environmental pressures. *Nature*, **527(7576)**, 49-53, doi:10.1038/nature16065.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **111(10)**, 3709-14, doi:10.1073/pnas.1308044111.

Hayashi, A., F. Akimoto, F. Sano, and T. Tomoda, 2015: Evaluation of global energy crop production potential up to 2100 under socioeconomic development and climate change scenarios. *Journal of the Japan Institute of Energy*, **94(6)**, 548-554, doi:doi.org/10.3775/jie.94.548.

Hayashi, A., F. Sano, Y. Nakagami, and K. Akimoto, 2018: Changes in terrestrial water stress and contributions of major factors under temperature rise constraint scenarios. *Mitigation and Adaptation Strategies for Global Change*, 1-27, doi:10.1007/s11027-018-9780-5.

Häyhä, T., P.L. Lucas, D.P. van Vuuren, S.E. Cornell, and H. Hoff, 2016: From Planetary Boundaries to national fair shares of the global safe operating space - How can the scales be bridged? *Global Environmental Change*, **40**, 60-72, doi:10.1016/j.gloenvcha.2016.06.008.

Hayward, B., 2017: *Sea change: climate politics and New Zealand*. Bridget Williams Books, Wellington, NZ.

He, J., Y. Huang, and F. Tarp, 2014: Has the clean development mechanism assisted sustainable development? *Natural Resources Forum*, **38(4)**, 248-260, doi:10.1111/1477-8947.12055.

Healy, N. and J. Barry, 2017: Politicizing energy justice and energy system transitions: Fossil fuel divestment and a "just transition". *Energy Policy*, **108**, 451-459, doi:10.1016/j.enpol.2017.06.014.

Heard, B.P., B.W. Brook, T.M.L. Wigley, and C.J.A. Bradshaw, 2017: Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. *Renewable and Sustainable Energy Reviews*, **76**, 1122-1133, doi:10.1016/J.RSER.2017.03.114.

Heede, R., 2014: Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854-2010. *Climatic Change*, **122(1-2)**, 229-241, doi:10.1007/s10584-013-0986-y.

Helliwell, J., R. Layard, and J. Sachs, 2018: *World Happiness Report*.

Hemstock, S., 2017: A case for formal education in technical vocational education and training for climate change adapatation and disaster risk reduction in the Pacific Islands region. In: *Climate Change Adaptation in Pacific Countries: fostering Resilience and Improving the quality of life* [Filho, W. (ed.)]. Springer Nature, Cham, Switzerland, pp. 309-324.

Hess, J.J. and K.L. Ebi, 2016: Iterative management of heat early warning systems in a changing climate. *Annals of the New York Academy of Sciences*, **1382(1)**, 21-30, doi:10.1111/nyas.13258.

Heyward, C. and D. Roser, 2016: Climate justice in a non-ideal world. .

Hildingsson, R. and B. Johansson, 2015: Governing low-carbon energy transitions in sustainable ways: potential synergies and conflicts between climate and environmental policy objectives. *Energy Policy*, **88**, 245-252, doi:10.1016/j.enpol.2015.10.029.

HLCCP, 2017: *Report of the high-level commission on carbon prices*. High-Level Commission on Carbon Prices (HLCCP). World Bank, Washington DC, USA.

Holden, E., K. Linnerud, and D. Banister, 2017: The imperatives of sustainable development. *Sustainable Development*, **25(3)**, 213-226, doi:10.1002/sd.1647.

Holz, C., S. Kartha, and T. Athanasiou, 2017: Fairly sharing 1.5: national fair shares of a 1.5 °C-compliant global mitigation effort. *International Environmental Agreements: Politics, Law and Economics*, doi:10.1007/s10784-017-9371-z.

Horstmann, B. and J. Hein, 2017: *Aligning climate change mitigation and sustainable development under the*

UNFCCC: A critical assessment of the Clean Development Mechanism, the Green Climate Fund and REDD+. German Development Institute, Bonn.

Howarth, C. and I. Monasterolo, 2017: Opportunities for knowledge co-production across the energy-food-water nexus: making interdisciplinary approaches work for better climate decision making. *Environmental Science and Policy*, **75(June)**, 103-110, doi:10.1016/j.envsci.2017.05.019.

Howarth, N., M. Galeotti, A. Lanza, and K. Dubey, 2017: Economic development and energy consumption in the GCC: an international sectoral analysis. *Energy Transitions*, **1(2)**, 6, doi:10.1007/s41825-017-0006-3.

Howell, R. and S. Allen, 2017: People and Planet: values, motivations and formative influences of individuals acting to mitigate climate change. *Environmental Values*, **26(2)**, 131-155, doi:10.3197/096327117X14847335385436.

Hubacek, K., G. Baiocchi, K. Feng, and A. Patwardhan, 2017: Poverty eradication in a carbon constrained world. *Nature Communications*, **8(1)**, 1-8, doi:10.1038/s41467-017-00919-4.

Huggel, C., I. Wallimann-Helmer, D. Stone, and W. Cramer, 2016: Reconciling justice and attribution research to advance climate policy. *Nature Climate Change*, **6(10)**, 901-908, doi:10.1038/nclimate3104.

Hughes, S., E.K. Chu, and S.G. Mason, 2018: *Climate Change in Cities: Innovations in Multi-Level Governance*. Springer, Cham.

Hunsberger, C., S. Bolwig, E. Corbera, and F. Creutzig, 2014: Livelihood impacts of biofuel crop production: implications for governance. *Geoforum*, **54**, 248-260, doi:10.1016/j.geoforum.2013.09.022.

Huq, N., A. Bruns, L. Ribbe, and S. Huq, 2017: Mainstreaming ecosystem services based climate change adaptation (EbA) in bangladesh: status, challenges and opportunities. *Sustainability*, **9(6)**, 926, doi:10.3390/su9060926.

Hwang, J., K. Joh, and A. Woo, 2017: Social inequalities in child pedestrian traffic injuries: Differences in neighborhood built environments near schools in Austin, TX, USA. *Journal of Transport and Health*, **6(May)**, 40-49, doi:10.1016/j.jth.2017.05.003.

ICSU, 2017: *A Guide to SDG interactions: From Science to Implementation*. 239 pp.

IEA, 2015: *India Energy Outlook*. International Energy Agency (IEA), 1-191 pp.

IEA, 2016: *World Energy Outlook Special Report: Energy and Air Pollution*. International Energy Agency (IEA), Paris, France, 266 pp.

IEA, 2017: *Energy access outlook 2017: from poverty to prosperity*. 144 pp.

IEA and World Bank, 2017: *Sustainable Energy for All 2017 - Progress towards Sustainable Energy*. International Energy Agency (IEA) and International Bank for Reconstruction and Development / The World Bank, Washington DC, USA, 208 pp.

INC, 1991: Vanuatu: Draft annex relating to Article 23 (Insurance) for inclusion in the revised single text on elements relating to mechanisms (A/AC.237/WG.II/Misc.13) submitted by the Co-Chairmen of Working Group II. .

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge Univeristy Press, Cambride, MA, USA and New York, NY, USA.

IPCC, 2014a: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (eds.)]. 1454 pp.

IPCC, 2014b: Summary for Policymakers. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-30.

IRENA, 2016: *Renewable energy market analysis: the GCC region*. IRENA, Abu Dhabi.

Ishida, H. et al., 2014: Global-scale projection and its sensitivity analysis of the health burden attributable to childhood undernutrition under the latest scenario framework for climate change research. *Environmental Research Letters*, **9(6)**, doi:10.1088/1748-9326/9/6/064014.

Islam, M.R. and M. Shamsuddoha, 2017: Socioeconomic consequences of climate induced human displacement and migration in Bangladesh. *International Sociology*, **32(3)**, 277-298, doi:10.1177/0268580917693173.

Jägermeyr, J., A. Pastor, H. Biemans, and D. Gerten, 2017: Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. *Nature Communications*, **8(May)**, 1-9, doi:10.1038/ncomms15900.

Jaglin, S., 2014: Regulating service delivery in southern cities: rethinking urban heterogeneity. *The Routledge handbook on cities of the global South*.

Jakob, M. and J.C.J.C. Steckel, 2016: Implications of climate change mitigation for sustainable development. *Environmental Research Letters*, **11(10)**, 104010, doi:10.1088/1748-9326/11/10/104010.

Janetos, A.C., E. Malone, E. Mastrangelo, K. Hardee, and A. de Bremond, 2012: Linking climate change and development goals: framing, integrating, and measuring. *Climate and Development*, **4(2)**, 141-156, doi:10.1080/17565529.2012.726195.

Jha, C.K., V. Gupta, U. Chattopadhyay, and B. Amarayil Sreeraman, 2017: Migration as adaptation strategy to cope with climate change. *International Journal of Climate Change Strategies and Management*, IJCCSM-03-2017-0059, doi:10.1108/IJCCSM-03-2017-0059.

Jiang, L. and B.C. O'Neill, 2017: Global urbanization projections for the Shared Socioeconomic Pathways. *Global Environmental Change*, **42**, 193-199, doi:10.1016/j.gloenvcha.2015.03.008.

Johansson, E.L., M. Fader, J.W. Seaquist, and K.A. Nicholas, 2016: Green and blue water demand from large-scale land acquisitions in Africa. *Proceedings of the National Academy of Sciences of the United States of America*, **113(41)**, 11471-11476, doi:10.1073/pnas.1524741113.

Johnson, C.A., 2017: Resilient cities? The global politics of urban climate adaptation. In: *The Power of Cities in Global Climate Politics* [Johnson, C.A. (ed.)]. Palgrave Macmillan, London, UK, pp. 91-146.

Johnson, N. et al., 2015: Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants. *Technological Forecasting and Social Change*, **90(PA)**, 89-102, doi:10.1016/j.techfore.2014.02.028.

Jones, L. and T. Tanner, 2017: Subjective resilience': using perceptions to quantify household resilience to climate extremes and disasters. *Regional Environmental Change*, **17(1)**, 229-243, doi:10.1007/s10113-016-0995-2.

Jordaan, S.M. et al., 2017: The role of energy technology innovation in reducing greenhouse gas emissions: a case study of Canada. *Renewable and Sustainable Energy Reviews*, **78(May)**, 1397-1409, doi:10.1016/j.rser.2017.05.162.

Kagawa, S. et al., 2015: CO2 emission clusters within global supply chain networks: Implications for climate change mitigation. *Global Environmental Change*, **35**, 486-496, doi:10.1016/j.gloenvcha.2015.04.003.

Kaijser, A. and A. Kronsell, 2014: Climate change through the lens of intersectionality. *Environmental Politics*, **23(3)**, 417-433, doi:10.1080/09644016.2013.835203.

Kalafatis, S., 2017: Identifying the Potential for Climate Compatible Development Efforts and the Missing Links. *Sustainability*, **9(9)**, 1642, doi:10.3390/su9091642.

Karlsson, L., A. Nightingale, L.O. Naess, and J. Thompson, 2017: Triple wins' or 'triple faults'? Analysing policy discourse on climate-smart agriculture (CSA). Working Paper no.197, CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), Copenhagen, Denmark, 43 pp.

Karner, K., M. Theissing, and T. Kienberger, 2015: Energy efficiency for industries through synergies with urban areas. *Journal of Cleaner Production*, **2020**, 1-11, doi:10.1016/j.jclepro.2016.02.010.

Kartha, S. et al., 2018: Inequitable mitigation: cascading biases against poorer countries. *Nature Climate Change*, **8**, 348-349, doi:10.1038/s41558-018-0152-7.

Kassie, M., H. Teklewold, M. Jaleta, P. Marenya, and O. Erenstein, 2015: Understanding the adoption of a portfolio of sustainable intensification practices in eastern and southern Africa. *Land Use Policy*, **42**, 400-411, doi:10.1016/j.landusepol.2014.08.016.

Keairns, D.L., R.C. Darton, and A. Irabien, 2016: The energy-water-food nexus. *Annual Review of Chemical and Biomolecular Engineering*, **7(1)**, 239-262, doi:10.1146/annurev-chembioeng-080615-033539.

Kelman, I., 2017: Linking disaster risk reduction, climate change, and the sustainable development goals. *Disaster Prevention and Management: An International Journal*, **26(3)**, 254-258, doi:10.1108/DPM-02-2017-0043.

Kenis, A., 2016: Ecological citizenship and democracy: Communitarian versus agonistic perspectives. *Environmental Politics*, **4016(August)**, 1-22, doi:10.1080/09644016.2016.1203524.

Kenis, A. and E. Mathijs, 2014: (De)politicising the local: The case of the Transition Towns movement in Flanders (Belgium). *Journal of Rural Studies*, **34**, 172-183, doi:10.1016/j.jrurstud.2014.01.013.

Keohane, R.O. and D.G. Victor, 2016: Cooperation and discord in global climate policy. *Nature Climate Change*, **6(6)**, doi:10.1038/nclimate2937.

Khanna, N., D. Fridley, and L. Hong, 2014: China's pilot low-carbon city initiative: A comparative assessment of national goals and local plans. *Sustainable Cities and Society*, **12**, 110-121, doi:10.1016/j.scs.2014.03.005.

Khosla, R., A. Sagar, and A. Mathur, 2017: Deploying Low-carbon Technologies in Developing Countries: A view from India's buildings sector. *Environmental Policy and Governance*, **27(2)**, 149-162, doi:10.1002/eet.1750.

Khreis, H., A.D. May, and M.J. Nieuwenhuijsen, 2017: Health impacts of urban transport policy measures: a guidance note for practice. *Journal of Transport & Health*, **6(June)**, 209-227, doi:10.1016/j.jth.2017.06.003.

Kim, S.–Y. and E. Thurbon, 2015: Developmental Environmentalism. *Politics & Society*, **43(2)**, 213-240, doi:10.1177/0032329215571287.

Kim, Y. et al., 2017: A perspective on climate-resilient development and national adaptation planning based on USAID's experience. *Climate and Development*, **9(2)**, 141-151, doi:10.1080/17565529.2015.1124037.

King, A.D., D.J. Karoly, and B.J. Henley, 2017: Australian climate extremes at 1.5 °C and 2 °C of global warming. *Nature Clim. Change*, **7**, 412-416, doi:10.1038/nclimate3296.

Kirby, P. and T. O'Mahony, 2018: Development models: lessons from international development. In: *The political economy of the low-carbon transition: pathways beyond techno-optimism* [Kirby, P. and O'Mahony (eds.)].

Palgrave Macmillan, Cham, Switzerland, pp. 89-114.

Klausbruckner, C., H. Annegarn, L.R.F. Henneman, and P. Rafaj, 2016: A policy review of synergies and trade-offs in South African climate change mitigation and air pollution control strategies. *Environmental Science & Policy*, **57**, 70-78, doi:10.1016/j.envsci.2015.12.001.

Klein, R.J.T. et al., 2014: Adaptation opportunities, constraints, and limits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S.M.C. and L.L.W. P.R. Mastrandrea (eds.)]. Cambridge University Press, Cambride, MA, USA and New York, NY, USA, pp. 899-943.

Klimont, Z. et al., 2017: Bridging the gap - the role of short-lived climate pollutants. In: *The Emissions Gap Report 2017: A UN Environmental Synethesis Report*. United Nations Environment Programme, Nairobi, Kenya, pp. 48-57.

Klinsky, S. and A. Golub, 2016: Justice and Sustainability. In: *Sustainability Science: An introduction* [Heinrichs, H., P. Martens, G. Michelsen, and A. Wiek (eds.)]. Springer Netherlands, Dordrecht, Netherlands, pp. 161-173.

Klinsky, S. and H. Winkler, 2018: Building equity in: strategies for integrating equity into modelling for a 1.5°C world. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160461, doi:10.1098/rsta.2016.0461.

Klinsky, S., D. Waskow, E. Northrop, and W. Bevins, 2017a: Operationalizing equity and supporting ambition: identifying a more robust approach to 'respective capabilities'. *Climate and Development*, **9(4)**, 1-11, doi:10.1080/17565529.2016.1146121.

Klinsky, S. et al., 2017b: Why equity is fundamental in climate change policy research. *Global Environmental Change*, **44**, 170-173, doi:10.1016/j.gloenvcha.2016.08.002.

Kongsager, R. and E. Corbera, 2015: Linking mitigation and adaptation in carbon forestry projects: Evidence from Belize. *World Development*, **76**, 132-146, doi:10.1016/j.worlddev.2015.07.003.

Kongsager, R., B. Locatelli, and F. Chazarin, 2016: Addressing climate change mitigation and adaptation together: a global assessment of agriculture and forestry projects. *Environmental Management*, **57(2)**, 271-282, doi:10.1007/s00267-015-0605-y.

Kreibich, N., L. Hermwille, C. Warnecke, and C. Arens, 2017: An update on the Clean Development Mechanism in Africa in times of market crisis. *Climate and Development*, **9(2)**, 178-190, doi:10.1080/17565529.2016.1145102.

Kumar, N.S. et al., 2014: *Climate risks and strategizing agricultural adaptation in climatically challenged regions*. Indian Agriculture Research Institute, New Delhi, India.

Kuramochi, T. et al., 2018: Ten key short-term sectoral benchmarks to limit warming to 1.5°C. *Climate Policy*, **18(3)**, 287-305, doi:10.1080/14693062.2017.1397495.

Kuruppu, N. and R. Willie, 2015: Barriers to reducing climate enhanced disaster risks in least developed country-small islands through anticipatory adaptation. *Weather and Climate Extremes*, **7**, 72-83, doi:10.1016/j.wace.2014.06.001.

Kusumaningtyas, S.D.A. and E. Aldrian, 2016: Impact of the June 2013 Riau province Sumatera smoke haze event on regional air pollution. *Environmental Research Letters*, **11(7)**, doi:10.1088/1748-9326/11/7/075007.

La Rovere, E.L., 2017: Low-carbon development pathways in Brazil and 'Climate Clubs'. *Wiley Interdisciplinary Reviews: Climate Change*, **8(1)**, 1-7, doi:10.1002/wcc.439.

Labordena, M., A. Patt, M. Bazilian, M. Howells, and J. Lilliestam, 2017: Impact of political and economical barriers for concentrating solar power in Sub-Saharan Africa. *Energy Policy*, **102(April 2016)**, 52-72, doi:10.1016/j.enpol.2016.12.008.

Labriet, M., C. Fiebig, and M. Labrousse, 2015: Inside stories on climate compatible development. .

Lade, S.J., L.J. Haider, G. Engström, and M. Schlüter, 2017: Resilience offers escape from trapped thinking on poverty alleviation. *Science Advances*, **3(5)**, e1603043, doi:10.1126/sciadv.1603043.

Lahn, B., 2017: In the light of equity and science: scientific expertise and climate justice after Paris. *International Environmental Agreements: Politics, Law and Economics*, doi:10.1007/s10784-017-9375-8.

Lamb, A. et al., 2016: The potential for land sparing to offset greenhouse gas emissions from agriculture. *Nature Climate Change*, **6**, 488-492, doi:10.1038/nclimate2910.

Langford, M., A. Sumner, and A.E. Yamin (eds.), 2013: *The Millennium Development Goals and Human Rights: Past, Present and Future*. Cambridge University Press, New York, NY, USA, 571 pp.

Lasage, R. et al., 2015: A Stepwise, participatory approach to design and implement community based adaptation to drought in the Peruvian Andes. *Sustainability*, **7(2)**, 1742-1773, doi:10.3390/su7021742.

Lawrence, J. and M. Haasnoot, 2017: What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. *Environmental Science and Policy*, **68**, 47-57, doi:10.1016/j.envsci.2016.12.003.

Lechtenboehmer, S. and K. Knoop (eds.), 2017: *Realising long-term transitions towards low carbon societies. Impulses* *from the 8th Annual Meeting of the International Research Network for Low Carbon Societies*. Wuppertal Spezial no. 53, 1-91 pp.

Lefale, P., P. Faiva, and A. C, 2017: *Living with change: An Integrated national strategy for enhancing the resilience of Tokelau to climate change and related hazards 2017-2030*. Government of Tokelau, Apia, Soamoa.

Leichenko, R. and J.A. Silva, 2014: Climate change and poverty: vulnerability, impacts, and alleviation strategies. *Wiley Interdisciplinary Reviews: Climate Change*, **5(4)**, 539-556, doi:10.1002/wcc.287.

Lemoine, D. and S. Kapnick, 2016: A top-down approach to projecting market impacts of climate change. *Nature Climate Change*, **6(1)**, 51-55, doi:10.1038/nclimate2759.

Lemos, C.M., Y. Lo, D.R. Nelson, H. Eakin, and A.M. Bedran-Martins, 2016: Linking development to climate adaptation: Leveraging generic and specific capacities to reduce vulnerability to drought in NE Brazil. *Global Environmental Change*, **39**, 170-179, doi:10.1016/J.GLOENVCHA.2016.05.001.

Ley, D., 2017: Sustainable Development, Climate Change, and Renewable Energy in Rural Central America. In: *Evaluating Climate Change Action for Sustainable Development* [Uitto, J.I., J. Puri, and R.D. van den Berg (eds.)]. Springer International Publishing, Cham, Switzerland, pp. 187-212.

Li, T. et al., 2016: Aging will amplify the heat-related mortality risk under a changing climate: projection for the elderly in Beijing, China. *Scientific Reports*, **6(1)**, 28161, doi:10.1038/srep28161.

Liddell, C. and C. Guiney, 2015: Living in a cold and damp home: Frameworks for understanding impacts on mental well-being. *Public Health*, **129(3)**, 191-199, doi:10.1016/j.puhe.2014.11.007.

Lilliestam, J. and A. Patt, 2015: Barriers, risks and policies for renewables in the Gulf states. *Energies*, **8(8)**, 8263-8285, doi:10.3390/en8088263.

Lin, B.B. et al., 2017: Adaptation Pathways in Coastal Case Studies: Lessons Learned and Future Directions. *Coastal Management*, **45(5)**, 384-405, doi:10.1080/08920753.2017.1349564.

Lin, J., Y. Hu, S. Cui, J. Kang, and A. Ramaswami, 2015: Tracking urban carbon footprints from production and consumption perspectives. *Environmental Research Letters*, **10(5)**, 054001, doi:10.1088/1748-9326/10/5/054001.

Lipper, L. et al., 2014: Climate-smart agriculture for food security. *Nature Climate Change*, **4(12)**, 1068-1072, doi:10.1038/nclimate2437.

Lorek, S. and J.H. Spangenberg, 2014: Sustainable consumption within a sustainable economy - Beyond green growth and green economies. *Journal of Cleaner Production*, **63**, 33-44, doi:10.1016/j.jclepro.2013.08.045.

Lotze-Campen, H. et al., 2014: Impacts of increased bioenergy demand on global food markets: an AgMIP economic model intercomparison. *Agricultural Economics*, **45(1)**, 103-116, doi:10.1111/agec.12092.

Lucas, K. and K. Pangbourne, 2014: Assessing the equity of carbon mitigation policies for transport in Scotland. *Case Studies on Transport Policy*, **2(2)**, 70-80, doi:10.1016/j.cstp.2014.05.003.

Lucon, O. et al., 2014: Buildings. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, S. I. Baum, P. Brunner, B. Eickemeier, J. Kriemann, S. Savolainen, C. Schlömer, V. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 671-738.

Luomi, M., 2014: Mainstreaming climate policy in the Gulf Cooperation Council States. , 1-73.

Lwasa, S., K. Buyana, P. Kasaija, and J. Mutyaba, 2018: Scenarios for adaptation and mitigation in urban Africa under 1.5°C global warming. *Current Opinion in Environmental Sustainability*, **30**, 52-58, doi:10.1016/j.cosust.2018.02.012.

Lyon, C., 2018: Complexity ethics and UNFCCC practices for 1.5°C climate change. *Current Opinion in Environmental Sustainability*, **31**, 48-55, doi:https://doi.org/10.1016/j.cosust.2017.12.008.

Mace, M.J., 2016: Mitigation commitments under the Paris Agreement and the way forward. *Climate Law*, **6(1-2)**, 21-39, doi:10.1163/18786561-00601002.

Macintyre, T., H. Lotz-Sisitka, A. Wals, C. Vogel, and V. Tassone, 2018: Towards transformative social learning on the path to 1.5°C degrees. *Current Opinion in Environmental Sustainability*, **31**, 80-87, doi:10.1016/j.cosust.2017.12.003.

Maclellan, N., 2015: *Yumi stap redi long klaemet jenis: Lessons from the Vanuatu NGO Climate Change Adaptation Program*. 48 pp.

Maidment, C.D., C.R. Jones, T.L. Webb, E.A. Hathway, and J.M. Gilbertson, 2014: The impact of household energy efficiency measures on health: A meta-analysis. *Energy Policy*, **65**, 583-593, doi:10.1016/j.enpol.2013.10.054.

Maor, M., J. Tosun, and A. Jordan, 2017: Proportionate and disproportionate policy responses to climate change: core concepts and empirical applications. *Journal of Environmental Policy and Planning*, 1-13, doi:10.1080/1523908X.2017.1281730.

Mapfumo, P. et al., 2017: Pathways to transformational change in the face of climate impacts: an analytical framework. *Climate and Development*, **9(5)**, 439-451, doi:10.1080/17565529.2015.1040365.

Marjanac, S. and L. Patton, 2018: Extreme weather event attribution science and climate change litigation: an essential step in the causal chain? *Journal of Energy & Natural Resources Law*, 1-34, doi:10.1080/02646811.2018.1451020.

Markandya, A. et al., 2018: Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. *The Lancet Planetary Health*, **2(3)**, e126 - e133, doi:https://doi.org/10.1016/S2542-5196(18)30029-9.

Marsh, J., 2015: Mixed motivations and complex causality in the Mekong. *Forced Migration Review*, 68-69.

Martinez-Baron, D., G. Orjuela, G. Renzoni, A.M. Loboguerrero Rodríguez, and S.D. Prager, 2018: Small-scale farmers in a 1.5°C future: the importance of local social dynamics as an enabling factor for implementation and scaling of climate-smart agriculture. *Current Opinion in Environmental Sustainability*, **31(February)**, 112-119, doi:10.1016/j.cosust.2018.02.013.

Mathur, V.N., S. Afionis, J. Paavola, A.J. Dougill, and L.C. Stringer, 2014: Experiences of host communities with carbon market projects: towards multi-level climate justice. *Climate Policy*, **14(1)**, 42-62, doi:10.1080/14693062.2013.861728.

Maupin, A., 2017: The SDG13 to combat climate change: an opportunity for Africa to become a trailblazer? *African Geographical Review*, **36(2)**, 131-145, doi:10.1080/19376812.2016.1171156.

Mayer, B., 2016: The relevance of the no-harm principle to climate change law and politics. *Asia Pacific Journal of Environmental Law*, **19(1)**, 79-104, doi:http://dx.doi.org/10.4337/apjel.2016.01.04.

Mbow, C., C. Neely, and P. Dobie, 2015: How can an integrated landscape approach contribute to the implementation of the Sustainable Development Goals (SDGs) and advance climate-smart objectives? In: *Climate-Smart Landscapes: Multifunctionality in Practice* [Minang, P.A., M. van Noordwijk, C. Mbow, J. de Leeuw, and D. Catacutan (eds.)]. World Agroforestry Centre (ICRAF), Nairobi, Kenya, pp. 103-117.

MCCA, 2016: *Corporate Plan 2016-2018*. Ministry of Climate Chanage and Adaptation, Government of Vanuatu.

McCollum, D. et al., 2017: Connecting the Sustainable Development Goals by their energy inter-linkages. .

McCollum, D.L. et al., 2018: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, doi:10.1038/s41560-018-0179-z.

McCubbin, S., B. Smit, and T. Pearce, 2015: Where does climate fit? Vulnerability to climate change in the context of multiple stressors in Funafuti, Tuvalu. *Global Environmental Change*, **30**, 43-55, doi:10.1016/j.gloenvcha.2014.10.007.

McGlade, C. and P. Ekins, 2015: The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature*, **517(7533)**, 187-190, doi:10.1038/nature14016.

McGranahan, G., D. Schensul, and G. Singh, 2016: Inclusive urbanization: can the 2030 Agenda be delivered without it? *Environment and Urbanization*, **28(1)**, 13-34, doi:10.1177/0956247815627522.

McKay, B., S. Sauer, B. Richardson, and R. Herre, 2016: The political economy of sugarcane flexing: initial insights from Brazil, Southern Africa and Cambodia. *The Journal of Peasant Studies*, **43(1)**, 195-223, doi:10.1080/03066150.2014.992016.

McNamara, E., 2015: Cross-border migration with dignity in Kiribati. *Forced Migration Review*, **49(May)**, 2015.

McNamara, K.E. and S.S. Prasad, 2014: Coping with extreme weather: Communities in Fiji and Vanuatu share their experiences and knowledge. *Climatic Change*, **123(2)**, 121-132, doi:10.1007/s10584-013-1047-2.

Mechler, R. and T. Schinko, 2016: Identifying the policy space for climate loss and damage. *Science*, **354(6310)**, 290-292, doi:10.1126/science.aag2514.

, 2018: *Loss and Damage from climate change: concepts, methods and policy options*. Springer International Publishing.

Meerow, S. and J.P. Newell, 2016: Urban resilience for whom, what, when, where, and why? *Urban Geography*, 1-21, doi:10.1080/02723638.2016.1206395.

Mehmood, A., 2016: Of resilient places: planning for urban resilience. *European Planning Studies*, **24(2)**, 407-419.

Meinshausen, M. et al., 2015: National post-2020 greenhouse gas targets and diversity-aware leadership. *Nature Climate Change*, **5(12)**, 1098-1106, doi:10.1038/nclimate2826.

Melica, G. et al., 2018: Multilevel governance of sustainable energy policies: The role of regions and provinces to support the participation of small local authorities in the Covenant of Mayors. *Sustainable Cities and Society*, **39(January)**, 729-739, doi:10.1016/j.scs.2018.01.013.

Michaelowa, A., M. Allen, and F. Sha, 2018: Policy instruments for limiting global temperature rise to 1.5°C - can humanity rise to the challenge? *Climate Policy*, **18(3)**, 275-286, doi:10.1080/14693062.2018.1426977.

Millar, R.J. et al., 2017: Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nature Geoscience*, 1-8, doi:10.1038/ngeo3031.

Millard-Ball, A., 2013: The limits to planning: causal impacts of city climate action plans. *Journal of Planning Education and Research*, **33(1)**, 5-19, doi:10.1177/0739456X12449742.

Mishra, V., S. Mukherjee, R. Kumar, and D. Stone, 2017: Heat wave exposure in India in current, 1.5ºC, and 2.0 ºC worlds. *Environmental Research Letters*, **12**, 124012, doi:10.1088/1748-9326/aa9388.

Mitchell, D. et al., 2016: Attributing human mortality during extreme heat waves to anthropogenic climate change.

Environmental Research Letters, **11(7)**, 74006, doi:10.1088/1748-9326/11/7/074006.

Moellendorf, D., 2015: Climate change justice. *Philosophy Compass*, **10**, 173-186, doi:10.3197/096327111X12997574391887.

Morita, K. and K. Matsumoto, 2015: Enhancing Biodiversity Co-benefits of Adaptation to Climate Change. In: *Handbook of Climate Change Adaptation* [Filho, W.L. (ed.)]. Springer-Verlag Berlin Heidelberg, pp. 953-972.

Mouratiadou, I. et al., 2018: Water demand for electricity in deep decarbonisation scenarios: a multi-model assessment. *Climatic Change*, **147(1)**, 91-106, doi:10.1007/s10584-017-2117-7.

MRFCJ, 2015a: *Women's participation: an enabler of climate justice*.

MRFCJ, 2015b: *Zero carbon, zero poverty the climate justice way*. Mary Robinson Foundation Climate Justice (MRFCJ), Dublin, Ireland, 69 pp.

Muratori, M., K. Calvin, M. Wise, P. Kyle, and J. Edmonds, 2016: Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters*, **11(9)**, 1-9, doi:10.1088/1748-9326/11/9/095004.

Murphy, D.J., L. Yung, C. Wyborn, and D.R. Williams, 2017: Rethinking climate change adaptation and place through a situated pathways framework: a case study from the Big Hole Valley, USA. *Landscape and Urban Planning*, **167(March 2016)**, 441-450, doi:10.1016/j.landurbplan.2017.07.016.

Murphy, K., G.A. Kirkman, S. Seres, and E. Haites, 2015: Technology transfer in the CDM: an updated analysis. *Climate Policy*, **15(1)**, 127-145, doi:10.1080/14693062.2013.812719.

Murtinho, F., 2016: What facilitates adaptation? An analysis of community-based adaptation to environmental change in the Andes. *International Journal of the Commons*, **10(1)**, 119-141, doi:10.18352/ijc.585.

Muttarak, R. and W. Lutz, 2014: Is education a key to reducing vulnerability to natural disasters and hence unavoidable climate change? *Ecology and Society*, **19(1)**, doi:10.5751/ES-06476-190142.

Myers, S.S. et al., 2017: Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. *Annual Review of Public Health*, 1-19, doi:10.1146/annurev-publhealth-031816-044356.

Naess, L.O. et al., 2015: Climate policy meets national development contexts: insights from Kenya and Mozambique. *Global Environmental Change*, **35**, 534-544, doi:10.1016/j.gloenvcha.2015.08.015.

Nagoda, S., 2015: New discourses but same old development approaches? Climate change adaptation policies, chronic food insecurity and development interventions in northwestern Nepal. *Global Environmental Change*, **35**, 570-579, doi:10.1016/j.gloenvcha.2015.08.014.

Nalau, J., J. Handmer, and M. Dalesa, 2017: The role and capacity of government in a climate crisis: Cyclone Pam in Vanuatu. In: *Climate Change Adaptation in Pacific Countries: Fostering Resilience and Improving the Quality of Life* [Leal Filho, W. (ed.)]. Springer International Publishing, Cham, pp. 151-161.

Nalau, J. et al., 2016: The practice of integrating adaptation and disaster risk reduction in the south-west Pacific. *Climate and Development*, **8(4)**, 365-375, doi:10.1080/17565529.2015.1064809.

NASEM, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. National Academies of Sciences, Engineering, and Medicine (NASEM). The National Academies Press, Washington DC, USA.

Nelson, D.R., M.C. Lemos, H. Eakin, and Y.–J. Lo, 2016: The limits of poverty reduction in support of climate change adaptation. *Environmental Research Letters*, **11(9)**, 094011, doi:10.1088/1748-9326/11/9/094011.

Newell, P. et al., 2014: The Political Economy of Low Carbon Energy in Kenya. IDS Working Papers Vol 2014 No 445, 38 pp.

Newman, P., T. Beatley, and H. Boyer, 2017: Resilient Cities: Overcoming Fossil Fuel Dependence. .

Nguyen, M.T., S. Vink, M. Ziemski, and D.J. Barrett, 2014: Water and energy synergy and trade-off potentials in mine water management. *Journal of Cleaner Production*, **84(1)**, 629-638, doi:10.1016/j.jclepro.2014.01.063.

Nhamo, G., 2016: New Global Sustainable Development Agenda: A Focus on Africa. *Sustainable Development*, **25**, 227-241, doi:10.1002/sd.1648.

Niang, I. et al., 2014: Africa. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1199-1265.

Nicholls, R.J. et al., 2018: Stabilisation of global temperature at 1.5°C and 2.0°C: implications for coastal areas. *Philosophical Transactions A*, **376(2119)**, 20160448, doi:10.1098/rsta.2016.0448.

Nicolosi, E. and G. Feola, 2016: Transition in place: Dynamics, possibilities, and constraints. *Geoforum*, **76**, 153-163, doi:10.1016/j.geoforum.2016.09.017.

Nilsson, M., D. Griggs, and M. Visback, 2016: Map the interactions between Sustainable Development Goals. *Nature*, **534(7607)**, 320-322, doi:10.1038/534320a.

Nkomwa, E.C., M.K. Joshua, C. Ngongondo, M. Monjerezi, and F. Chipungu, 2014: Assessing indigenous knowledge systems and climate change adaptation strategies in agriculture: a case study of Chagaka Village, Chikhwawa, Southern Malawi. *Physics and Chemistry of the Earth, Parts A/B/C*, **67-69**, 164-172, doi:10.1016/j.pce.2013.10.002.

Noble, I. et al., 2014: Adaptation needs and options. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-708.

Normann, H.E., 2015: The role of politics in sustainable transitions: The rise and decline of offshore wind in Norway. *Environmental Innovation and Societal Transitions*, **15(2015)**, 180-193, doi:10.1016/j.eist.2014.11.002.

North, P. and N. Longhurst, 2013: Grassroots localisation? The scalar potential of and limits of the 'transition' approach to climate change and resource constraint. *Urban Studies*, **50(7)**, 1423-1438, doi:10.1177/0042098013480966.

Nunan, F. (ed.), 2017: *Making climate compatible development happen*. Routledge, Abingdon, UK and New York, NY, USA, 262 pp.

Nunn, P.D., W. Aalbersberg, S. Lata, and M. Gwilliam, 2014: Beyond the core: Community governance for climate-change adaptation in peripheral parts of Pacific Island Countries. *Regional Environmental Change*, **14(1)**, 221-235, doi:10.1007/s10113-013-0486-7.

Nyantakyi-Frimpong, H. and R. Bezner-Kerr, 2015: The relative importance of climate change in the context of multiple stressors in semi-arid Ghana. *Global Environmental Change*, **32**, 40-56, doi:10.1016/j.gloenvcha.2015.03.003.

Ober, K. and P. Sakdapolrak, 2017: How do social practices shape policy? Analysing the field of 'migration as adaptation' with Bourdieu's 'Theory of Practice'. *The Geographical Journal*, **183(4)**, 359-369, doi:10.1111/geoj.12225.

Obersteiner, M. et al., 2016: Assessing the land resource-food price nexus of the Sustainable Development Goals. *Science Advances*, **2(9)**, e1501499-e1501499, doi:10.1126/sciadv.1501499.

O'Brien, K., 2016: Climate change adaptation and social transformation. In: *International Encyclopedia of Geography: People, the Earth, Environment and Technology* [Richardson, D., N. Castree, M.F. Goodchild, A. Kobayashi, W. Liu, and R.A. Marston (eds.)]. John Wiley & Sons Ltd.

O'Brien, K., 2018: Is the 1.5°C target possible? Exploring the three spheres of transformation. *Current Opinion in Environmental Sustainability*, **31**, 153-160, doi:10.1016/j.cosust.2018.04.010.

O'Brien, K., S. Eriksen, T.H. Inderberg, and L. Sygna, 2015: Climate change and development: adaptation through transformation. In: *Climate Change Adaptation and Development: Transforming Paradigms and Practices* [Inderberg, T.H., S. Eriksen, K. O'Brien, and L. Sygna (eds.)]. Routledge, Abingdon, UK and New York, USA.

O'Brien, K.L., 2016: Climate change and social transformations: is it time for a quantum leap? *Wiley Interdisciplinary Reviews: Climate Change*, **7(5)**, 618-626, doi:10.1002/wcc.413.

OECD, 2017: *Investing in green growth*. OECD, Paris, France.

Oei, P. and R. Mendelevitch, 2016: European scenarios of CO2 infrastructure investment until 2050. *The Energy Journal*, **37**, doi:10.5547/01956574.37.SI3.poei.

Ojea, E., 2015: Challenges for mainstreaming Ecosystem-based Adaptation into the international climate agenda. *Current Opinion in Environmental Sustainability*, **14**, 41-48, doi:10.1016/j.cosust.2015.03.006.

Okereke, C. and P. Coventry, 2016: Climate justice and the international regime: before, during, and after Paris. *Wiley Interdisciplinary Reviews: Climate Change*, **7(6)**, 834-851, doi:10.1002/wcc.419.

Olawuyi, D.S., 2017: From technology transfer to technology absorption: addressing climate technology gaps in Africa. Fixing Climate Governance Series.

Olsson, L. et al., 2014: Livelihoods and Poverty. In: *Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 793-832.

O'Neill, B.C. et al., 2017a: The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, **42**, 169-180, doi:10.1016/j.gloenvcha.2015.01.004.

O'Neill, B.C. et al., 2017b: IPCC reasons for concern regarding climate change risks. *Nature Climate Change*, **7(1)**, 28-37, doi:10.1038/nclimate3179.

O'Neill, D.W., A.L. Fanning, W.F. Lamb, and J.K. Steinberger, 2018: A good life for all within planetary boundaries. *Nature Sustainability*, **1(2)**, 88-95, doi:10.1038/s41893-018-0021-4.

Oosterhuis, F.H. and P. Ten Brink, 2014: *Paying the polluter: environmentally harmful subsidies and their reform*. Edward Elgar Publishing, Cheltenham, UK ; Northampton, MA, USA.

Oppenheimer, M., M. Campos, and R. Warren, 2014: Emergent risks and key vulnerabilities. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J.* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-708.

Orindi, V., Y. Elhadi, and C. Hesse, 2017: Democratising climate finance at local levels. *Building a climate resilient economy and society: challenges and opportunities*, 250-264.

Otto, F., R. Skeie, J.S. Fuglestvedt, T. Berntsen, and M.R. Allen, 2017: Assigning historical responsibilities for extreme weather events. *Nature Clim. Change*, **7**, 757-759, doi:doi:10.1038/nclimate3419.

Page, E.A. and C. Heyward, 2017: Compensating for climate change Loss and Damage. *Political Studies*, **65(2)**, 356-372, doi:10.1177/0032321716647401.

Pal, J.S. and E.A.B. Eltahir, 2016: Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nature Climate Change*, **18203(October)**, 1-4, doi:10.1038/nclimate2833.

Palazzo, A. et al., 2017: Linking regional stakeholder scenarios and shared socioeconomic pathways: Quantified West African food and climate futures in a global context. *Global Environmental Change*, **45**, 227-242, doi:10.1016/j.gloenvcha.2016.12.002.

Pan, X., M. Elzen, N. Höhne, F. Teng, and L. Wang, 2017: Exploring fair and ambitious mitigation contributions under the Paris Agreement goals. *Environmental Science and Policy*, **74(March)**, 49-56, doi:10.1016/j.envsci.2017.04.020.

Pandey, U.C. and C. Kumar, 2018: Emerging Paradigms of Capacity Building in the Context of Climate Change. In: *Climate Literacy and Innovations in Climate Change Education: Distance Learning for Sustainable Development* [Azeiteiro, U.M., W. Leal Filho, and L. Aires (eds.)]. Springer International Publishing, Cham, pp. 193-214.

Parikh, K.S., J.K. Parikh, and P.P. Ghosh, 2018: Can India grow and live within a 1.5 degree CO2 emissions budget? *Energy Policy*, **120(May)**, 24-37, doi:10.1016/j.enpol.2018.05.014.

Park, J., S. Hallegatte, M. Bangalore, and E. Sandhoefner, 2015: Households and heat stress estimating the distributional consequences of climate change. Policy Research Working Paper no. WPS 7479, 58 pp.

Parkinson, S.C. et al., 2016: Impacts of Groundwater Constraints on Saudi Arabia's Low-Carbon Electricity Supply Strategy. *Environmental Science & Technology*, **50(4)**, 1653-1662, doi:10.1021/acs.est.5b05852.

Parnell, S., 2017: Africa's urban risk and resilience. *International Journal of Disaster Risk Reduction*, **26**, 1-6, doi:10.1016/J.IJDRR.2017.09.050.

Patterson, J. et al., 2016: Exploring the governance and politics of transformations towards sustainability. *Environmental Innovation and Societal Transitions*, 1-16, doi:10.1016/j.eist.2016.09.001.

Patterson, J.J. et al., 2018: Political feasibility of 1.5°C societal transformations: the role of social justice. *Current Opinion in Environmental Sustainability*, **31**, 1-9, doi:https://doi.org/10.1016/j.cosust.2017.11.002.

Pearce, T., J. Ford, A.C. Willox, and B. Smit, 2015: Inuit Traditional Ecological Knowledge (TEK), subsistence hunting and adaptation to climate change in the Canadian Arctic. *Arctic*, **68(2)**, 233-245, doi:10.2307/43871322.

Pelling, M., T. Abeling, and M. Garschagen, 2016: Emergence and Transition in London's Climate Change Adaptation Pathways. *Journal of Extreme Events*, **3(3)**, 1650012, doi:10.1142/S2345737616500123.

Pelling, M. et al., 2018: Africa's urban adaptation transition under a 1.5° climate. *Current Opinion in Environmental Sustainability*, **31**, 10-15, doi:https://doi.org/10.1016/j.cosust.2017.11.005.

Petkova, E.P. et al., 2017: Towards more comprehensive projections of urban heat-related mortality: estimates for New York city under multiple population, adaptation, and climate scenarios. *Environmental Health Perspectives*, **125(1)**, 47-55, doi:10.1289/EHP166.

Pfeiffer, A., R. Millar, C. Hepburn, and E. Beinhocker, 2016: The '2°C carbon stock' for electricity generation: cumulative committed carbon emissions from the electricity generation sector and the transition to a green economy. *Applied Energy*, **179**, 1395-1408, doi:10.1016/j.apenergy.2016.02.093.

Phillips, J., P. Newell, and A. Pueyo, 2017: Triple wins? Propsects for pro-poor, low carbon, climate resilient energy services in Kenya. In: *Making climate compatible development happen* [Nunan, F. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 114-129.

Popescu, G.H. and F.C. Ciurlau, 2016: Can environmental sustainability be attained by incorporating nature within the capitalist economy? *Economics, Management, and Financial Markets*, **11(4)**, 75-81.

Popp, A. et al., 2014: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, **123(3-4)**, 495-509, doi:10.1007/s10584-013-0926-x.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, **42**, 331-

345, doi:10.1016/j.gloenvcha.2016.10.002.

Potouroglou, M. et al., 2017: Measuring the role of seagrasses in regulating sediment surface elevation. *Scientific Reports*, **7(1)**, 1-11, doi:10.1038/s41598-017-12354-y.

Pradhan, A., C. Chan, P.K. Roul, J. Halbrendt, and B. Sipes, 2018: Potential of conservation agriculture (CA) for climate change adaptation and food security under rainfed uplands of India: a transdisciplinary approach. *Agricultural Systems*, **163**, 27-35, doi:10.1016/j.agsy.2017.01.002.

Preston, F. and J. Lehne, 2017: *A wider circle? The circular economy in developing countries*. Chatham House: The Royal Institute of International Affairs, London.

Pretis, F., M. Schwarz, K. Tang, K. Haustein, and M.R. Allen, 2018: Uncertain impacts on economic growth when stabilizing global temperatures at 1.5°C or 2°C warming. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **376(2119)**, 20160460, doi:10.1098/rsta.2016.0460.

Purdon, M., 2015: Opening the black box of carbon finance "additionality": the political economy of carbon finance effectiveness across Tanzania, Uganda, and Moldova. *World Development*, **74**, 462-478, doi:10.1016/j.worlddev.2015.05.024.

Quan, J., L.O. Naess, A. Newsham, A. Sitoe, and M.C. Fernandez, 2017: The political economy of REDD+ in Mozambique: implications for climate compatible development. In: *Making climate compatible development happen* [Nunan, F. (ed.)]. pp. 151-181.

Rai, N. and S. Fisher, 2017: *The political economy of low carbon resilient development: planning and implementation*. Routledge, Abingdon, UK and New York, NY, USA.

Rao, N.D., 2014: International and intranational equity in sharing climate change mitigation burdens. *International Environmental Agreements: Politics, Law and Economics*, **14(2)**, 129-146, doi:10.1007/s10784-013-9212-7.

Rao, N.D. and J. Min, 2018: Less global inequality can improve climate outcomes. *Wiley Interdisciplinary Reviews: Climate Change*, **9**, e513, doi:10.1002/wcc.513.

Rao, N.D., B.J. van Ruijven, V. Bosetti, and K. Riahi, 2017: Improving poverty and inequality modeling in climate research. *Nature Climate Change*, **7**, 857-862, doi:10.1038/s41558-017-0004-x.

Rao, S. et al., 2016: Future Air Pollution in the Shared Socio-Economic Pathways. *Global Environmental Change*, **42**, 346-358, doi:10.1016/j.gloenvcha.2016.05.012.

Rasch, R., 2017: Income Inequality and Urban Vulnerability to Flood Hazard in Brazil. *Social Science Quarterly*, **98(1)**, 299-325, doi:10.1111/ssqu.12274.

Rasul, G. and B. Sharma, 2016: The nexus approach to water-energy-food security: an option for adaptation to climate change. *Climate Policy*, **16(6)**, 682-702, doi:10.1080/14693062.2015.1029865.

Raworth, K., 2017: A Doughnut for the Anthropocene: humanity's compass in the 21st century. *The Lancet Planetary Health*, **1(2)**, e48-e49, doi:10.1016/S2542-5196(17)30028-1.

Redclift, M. and D. Springett (eds.), 2015: *Routledge International Handbook of Sustainable Development*. Routledge, Abingdon, UK and New York, NY, USA, 448 pp.

Regmi, B.R. and C. Star, 2015: Exploring the policy environment for mainstreaming community-based adaptation (CBA) in Nepal. *International Journal of Climate Change Strategies and Management*, **7(4)**, 423-441, doi:10.1108/IJCCSM-04-2014-0050.

Reid, H., 2016: Ecosystem- and community-based adaptation: learning from community-based natural resource management. *Climate and Development*, **8(1)**, 4-9, doi:10.1080/17565529.2015.1034233.

Reid, H. and S. Huq, 2014: Mainstreaming community-based adaptation into national and local planning. *Climate and Development*, **6(4)**, 291-292, doi:10.1080/17565529.2014.973720.

Reij, C. and R. Winterbottom, 2015: *Scaling up Regreening: Six Steps to Success. A Practical Approach to Forest Landscape Restoration*. 72 pp.

Republic of Vanuatu, 2016: *Vanuatu 2030: The People's Plan*. 28 pp.

Republic of Vanuatu, 2017: *Vanuatu 2030: The People's Plan. National Sustainable Development Plan 2016-2030. Monitoring and Evaluation Framework*. 48 pp.

Revi, A. et al., 2014: Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 535-612.

Rey, T., L. Le De, F. Leone, and D. Gilbert, 2017: An integrative approach to understand vulnerability and resilience post-disaster: the 2015 cyclone Pam in urban Vanuatu as case study. *Disaster Prevention and Management*, **26(3)**, 259-275, doi:10.1108/DPM-07-2016-0137.

Reyer, C.P.O. et al., 2017a: Climate change impacts in Latin America and the Caribbean and their implications for development. *Regional Environmental Change*, **17(6)**, 1601-1621, doi:10.1007/s10113-015-0854-6.

Reyer, C.P.O. et al., 2017b: Turn down the heat: regional climate change impacts on development. *Regional*

*Environmental Change***, 17(6)**, 1563-1568, doi:10.1007/s10113-017-1187-4.

Riahi, K. et al., 2015: Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change***, 90**, 8-23, doi:10.1016/j.techfore.2013.09.016.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environmental Change***, 42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009.

Robertson, M., 2014: *Sustainability Principles and Practice*. Routledge.

Robinson, M. and T. Shine, 2018: Achieving a climate justice pathway to 1.5°C. *Nature Cliimate Change* (in press).

Robinson, S. and M. Dornan, 2017: International financing for climate change adaptation in small island developing states. *Regional Environmental Change,***, 17(4)**, 1103-1115.

Robiou du Pont, Y. et al., 2017: Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change***, 7(1)**, 38-43, doi:10.1038/NCLIMATE3186.

Rockström, J. et al., 2017: Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio***, 46(1)**, 4-17, doi:10.1007/s13280-016-0793-6.

Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, 1-8, doi:10.1038/s41558-018-0091-3.

Roger, C., T. Hale, and L. Andonova, 2017: The comparative politics of transnational climate governance. *International Interactions***, 43(1)**, 1-25, doi:10.1080/03050629.2017.1252248.

Rose, S.K. et al., 2014: Bioenergy in energy transformation and climate management. *Climatic Change***, 123(3-4)**, 477-493, doi:10.1007/s10584-013-0965-3.

Rosenbloom, D., 2017: Pathways: An emerging concept for the theory and governance of low-carbon transitions. *Global Environmental Change***, 43**, 37-50, doi:10.1016/j.gloenvcha.2016.12.011.

Rosenzweig, C. et al., 2018: *Climate change and cities: Second assessment port of the Urban Climate Change Research Network*. Cambridge University Press, London, UK and New York, NY, USA.

Roser, D. and C. Seidel, 2017: *Climate justice*. Routledge, Abingdon, Oxon.

Roser, D., C. Huggel, M. Ohndorf, and I. Wallimann-Helmer, 2015: Advancing the interdisciplinary dialogue on climate justice. *Climatic Change***, 133(3)**, 349-359, doi:10.1007/s10584-015-1556-2.

Rozenberg, J. and S. Hallegatte, 2016: Modeling the Impacts of Climate Change on Future Vietnamese Households: A Micro-Simulation Approach. World Bank Policy Research Working Paper.

Runhaar, H., B. Wilk, Persson, C. Uittenbroek, and C. Wamsler, 2018: Mainstreaming climate adaptation: taking stock about "what works" from empirical research worldwide. *Regional Environmental Change***, 18(4)**, 1201-1210, doi:10.1007/s10113-017-1259-5.

Rutledge, D. et al., 2017: Climate Change Impacts and Implications for New Zealand to 2100. In: *Identifying Feedbacks, Understanding Cumulative Impacts and Recognising Limits: A National Integrated Assessment. Synthesis Report.*. pp. 84.

Sachs, J., G. Schmidt-Traub, C. Kroll, D. Durand-Delacre, and K. Teksoz, 2017: *An SDG Index and Dashboards - Global Report*. 427 pp.

Salleh, A., 2016: Climate, Water, and Livelihood Skills: A Post-Development Reading of the SDGs. *Globalizations***, 13(6)**, 952-959, doi:10.1080/14747731.2016.1173375.

Sánchez, A. and M. Izzo, 2017: Micro hydropower: an alternative for climate change mitigation, adaptation, and development of marginalized local communities in Hispaniola Island. *Climatic Change***, 140(1)**, 79-87, doi:10.1007/s10584-016-1865-0.

Santarius, T., H.J. Walnum, and C. Aall (eds.), 2016: *Rethinking climate and energy policies: new perspectives on the rebound phenomenon*. Springer.

Santos, P., P. Bacelar-Nicolau, M.A. Pardal, L. Bacelar-Nicolau, and U.M. Azeiteiro, 2016: Assessing Student Perceptions and Comprehension of Climate Change in Portuguese Higher Education Institutions. In: *Implementing Climate Change Adaptation in Cities and Communities Integrating Strategies and Educational Approaches* [Filho, W.L., K. Adamson, R.M. Dunk, U.M. Azeiteiro, S. Illingworth, and F. Alves (eds.)]. pp. 221-236.

Satterthwaite, D., 2016: Missing the Millennium Development Goal targets for water and sanitation in urban areas. *Environment and Urbanization***, 28(1)**, 99-118, doi:10.1177/0956247816628435.

Satterthwaite, D. et al., 2018: Responding to climate change in cities and in their informal settlements and economies. In: *International Scientific Conference on Cities and Climate Change*. International Institute for Environment and Development, Edmonton, Canada.

Savo, V. et al., 2016: Observations of climate change among subsistence-oriented communities around the world. *Nature Climate Change***, 6(5)**, 462-473, doi:10.1038/nclimate2958.

Schade, J. and W. Obergassel, 2014: Human rights and the Clean Development Mechanism. *Cambridge Review of International Affairs***, 27(4)**, 717-735, doi:10.1080/09557571.2014.961407.

Schaeffer, M. et al., 2015: *Feasibility of limiting warming to 1.5 and 2°C*. Climate Analytics, Berlin, Germany, 20 pp.

Schaller, N. et al., 2016: Human influence on climate in the 2014 southern England winter floods and their impacts. *Nature Climate Change*, **6(6)**, 627-634, doi:10.1038/nclimate2927.

Schirmer, J. and L. Bull, 2014: Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects. *Global Environmental Change*, **24**, 306-320, doi:10.1016/J.GLOENVCHA.2013.11.009.

Schleussner, C.–F. et al., 2016: Differential climate impacts for policy-relevant limits to global warming: the case of 1.5°C and 2°C. *Earth System Dynamics*, **7(2)**, 327-351, doi:10.5194/esd-7-327-2016.

Schlosberg, D., L.B. Collins, and S. Niemeyer, 2017: Adaptation policy and community discourse: risk, vulnerability, and just transformation. *Environmental Politics*, **26(3)**, 1-25, doi:10.1080/09644016.2017.1287628.

Schwan, S. and X. Yu, 2017: Social protection as a strategy to address climate-induced migration. *International Journal of Climate Change Strategies and Management*, IJCCSM-01-2017-0019, doi:10.1108/IJCCSM-01-2017-0019.

Scoones, I. et al., 2017: *Pathways to Sustainable Agriculture*. Routledge, 132 pp.

Scott, F.L., C.R. Jones, and T.L. Webb, 2014: What do people living in deprived communities in the UK think about household energy efficiency interventions? *Energy Policy*, **66(September 2011)**, 335-349, doi:10.1016/j.enpol.2013.10.084.

Sealey-Huggins, L., 2017: 1.5°C to stay alive': climate change, imperialism and justice for the Caribbean. *Third World Quarterly*, **6597(October)**, 1-20, doi:10.1080/01436597.2017.1368013.

Serdeczny, O.M., S. Bauer, and S. Huq, 2017: Non-economic losses from climate change: opportunities for policy-oriented research. *Climate and Development*, 1-5, doi:10.1080/17565529.2017.1372268.

Seto, K.C. et al., 2016: Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources*, **41(1)**, 425-452, doi:10.1146/annurev-environ-110615-085934.

Sgouridis, S. et al., 2016: RE-mapping the UAE's energy transition: an economy-wide assessment of renewable energy options and their policy implications. *Renewable and Sustainable Energy Reviews*, **55**, 1166-1180, doi:10.1016/j.rser.2015.05.039.

Shackleton, S., G. Ziervogel, S. Sallu, T. Gill, and P. Tschakert, 2015: Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases. *Wiley Interdisciplinary Reviews: Climate Change*, **6(3)**, 321-344, doi:10.1002/wcc.335.

Shaffrey, L.C. et al., 2009: U.K. HiGEM: the new U.K. high-resolution global environment model - model description and basic evaluation. *Journal of Climate*, **22(8)**, 1861-1896, doi:10.1175/2008JCLI2508.1.

Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of leapfrogging to superefficiency and low global warming potential refrigerants in room air conditioning*. Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA, USA, 58 pp.

Sharpe, R.A., C.R. Thornton, V. Nikolaou, and N.J. Osborne, 2015: Higher energy efficient homes are associated with increased risk of doctor diagnosed asthma in a UK subpopulation. *Environment International*, **75**, 234-244, doi:10.1016/j.envint.2014.11.017.

Shaw, C., S. Hales, P. Howden-Chapman, and R. Edwards, 2014: Health co-benefits of climate change mitigation policies in the transport sector. *Nature Clim. Change*, **4(6)**, 427-433, doi:10.1038/nclimate2247.

Shi, L. et al., 2016: Roadmap towards justice in urban climate adaptation research. *Nature Climate Change*, **6(2)**, 131-137, doi:10.1038/nclimate2841.

Shi, Y., J. Liu, H. Shi, H. Li, and Q. Li, 2017: The ecosystem service value as a new eco-efficiency indicator for industrial parks. *Journal of Cleaner Production*, **164**, 597-605, doi:10.1016/j.jclepro.2017.06.187.

Shindell, D.T., G. Faluvegi, K. Seltzer, and C. Shindell, 2018: Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, **8(4)**, 291-295, doi:10.1038/s41558-018-0108-y.

Shindell, D.T. et al., 2017: A climate policy pathway for near- and long-term benefits. *Science*, **356(6337)**, 493-494, doi:10.1126/science.aak9521.

Shine, T., 2017: *Integrating climate action into national development planning - coherent implementation of the Paris Agreement and Agenda 2030*. Swedish International Development Cooperation Agency, Stockholm, Sweden.

Shine, T. and G. Campillo, 2016: The role of development finance in climate action post-2015. OECD Development Co-operation Working Papers.

Shue, H., 2014: *Climate Justice: Vulnerability and Protection*. Oxford University Press, Oxford UK.

Shue, H., 2017: Responsible for what? Carbon producer CO2 contributions and the energy transition. *Climatic Change*, 1-6, doi:10.1007/s10584-017-2042-9.

Shue, H., 2018: Mitigation gambles: uncertainty, urgency and the last gamble possible. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, **376(2119)**, 20170105, doi:10.1098/rsta.2017.0105.

Shultz, J.M., M.A. Cohen, S. Hermosilla, Z. Espinel, and Andrew McLean, 2016: Disaster risk reduction and sustainable development for small island developing states. *Disaster Health*, **3(1)**, 32-44, doi:10.1080/21665044.2016.1173443.

Sinclair, F.L., 2016: Systems science at the scale of impact: reconciling bottom-up participation with the production of widely applicable research outputs.. *Sustainable Intensification in Smallholder Agriculture: An Integrated Systems Research Approach*, 43-57.

Singh, C., 2018: Is participatory watershed development building local adaptive capacity? Findings from a case study in Rajasthan, India. *Environmental Development***, 25**, 43-58, doi:10.1016/j.envdev.2017.11.004.

Singh, C. et al., 2017: The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. *Climate and Development*, 1-17, doi:10.1080/17565529.2017.1318744.

Singh, R., K.K. Garg, S.P. Wani, R.K. Tewari, and S.K. Dhyani, 2014: Impact of water management interventions on hydrology and ecosystem services in Garhkundar-Dabar watershed of Bundelkhand region, Central India. *J. Hydrol***, 509**, 132-149, doi:10.1016/j.jhydrol.2013.11.030.

Skeie, R.B. et al., 2017: Perspective has a strong effect on the calculation of historical contributions to global warming. *Environmental Research Letters***, 12(2)**, doi:10.1088/1748-9326/aa5b0a.

SLoCaT, 2017: *Marrakech Partnership for Global Climate Action (MPGCA) Transport Initiatives: Stock-take on action toward implementation of the Paris Agreement and the 2030 Agenda on Sustainable Development. Second Progress Report*. Partnership on Sustainable Low Carbon Transport (SLoCaT), Bonn, Germany.

Smith, K.R. and A. Sagar, 2014: Making the clean available: escaping India's Chulha Trap. *Energy Policy***, 75**, 410-414, doi:10.1016/j.enpol.2014.09.024.

Smith, K.R. et al., 2014: Human health: impacts, adaptation, and co-benefits. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709-754.

Smith, P. et al., 2014: Agriculture, Forestry and Other Land Use (AFOLU). In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. Stechow, T. Zwickel, and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 811-922.

Smith, P. et al., 2016: Biophysical and economic limits to negative CO2 emissions. *Nature Clim. Change***, 6(1)**, 42-50, doi:10.1038/nclimate2870.

Smits, M. and C. Middleton, 2014: New arenas of engagement at the water governance-climate finance nexus? An analysis of the boom and bust of hydropower CDM projects in vietnam. *Water Alternatives***, 7(3)**, 561-583.

Smucker, T.A. et al., 2015: Differentiated livelihoods, local institutions, and the adaptation imperative: Assessing climate change adaptation policy in Tanzania. *Geoforum***, 59**, 39-50, doi:10.1016/j.geoforum.2014.11.018.

Solecki, W. et al., 2018: City transformations in a 1.5°C warmer world. *Nature Climate Change***, 8(3)**, 177-181, doi:10.1038/s41558-018-0101-5.

Sondak, C.F.A. et al., 2017: Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). *Journal of Applied Phycology***, 29(5)**, 2363-2373, doi:10.1007/s10811-016-1022-1.

Sonwa, D.J. et al., 2017: Drivers of climate risk in African agriculture. *Climate and Development***, 9(5)**, 383-398.

Sorrell, S., 2015: Reducing energy demand: A review of issues, challenges and approaches. *Renewable and Sustainable Energy Reviews***, 47**, 74-82, doi:10.1016/j.rser.2015.03.002.

Sovacool, B.K., B.–O. Linnér, and M.E. Goodsite, 2015: The political economy of climate adaptation. *Nature Climate Change***, 5(7)**, 616-618, doi:10.1038/nclimate2665.

Sovacool, B.K., B.O. Linner, and R.J.T. Klein, 2017: Climate change adaptation and the Least Developed Countries Fund (LDCF): qualitative insights from policy implementation in the Asia-Pacific. *Climatic Change***, 140(2)**, 209-226, doi:10.1007/s10584-016-1839-2.

SPC, 2015: *Vanuatu climate change and disaster risk reduction policy 2016-2030*. Secretariat of the Pacific Community (SPC), Suva, Fiji, 48 pp.

Spencer, T. et al., 2018: The 1.5°C target and coal sector transition: at the limits of societal feasibility. *Climate Policy***, 18(3)**, 335-331, doi:10.1080/14693062.2017.1386540.

Staggenborg, S. and C. Ogrodnik, 2015: New environmentalism and Transition Pittsburgh. *Environmental Politics***, 24(5)**, 723-741, doi:10.1080/09644016.2015.1027059.

Steering Committee on Partnerships for SIDS and UNDESA, 2016: *Partnerships for small island developing states, Samoa*. Partnerships for Small Island Developing States.

Sterrett, C.L., 2015: *Final evaluation of the Vanuatu NGO Climate Change Adaptation Program*. 96 pp.

Stevens, C., R. Winterbottom, J. Springer, and K. Reytar, 2014: *Securing rights, combating climate change: how strengthening community forests rights mitigates climate change*.

Stirling, A., 2014: *Emancipating Transformations: From controlling 'the transition' to culturing plural radical progress*. STEPS Centre (Social, Technological and Environmental Pathways to Sustainability), Brighton, UK, 48 pp.

Striessnig, E. and E. Loichinger, 2015: Future differential vulnerability to natural disasters by level of education. *Vienna Yearbook of Population Research*, **13**, 221-240.

Stringer, L.C., S.M. Sallu, A.J. Dougill, B.T. Wood, and L. Ficklin, 2017: Reconsidering climate compatible development as a new development landscape in southern Africa. In: *Making climate compatible development happen* [Nunan, F. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 22-43.

Stringer, L.C. et al., 2014: Advancing climate compatible development: Lessons from southern Africa. *Regional Environmental Change*, **14(2)**, 713-725, doi:10.1007/s10113-013-0533-4.

Suckall, N., E. Tompkins, and L. Stringer, 2014: Identifying trade-offs between adaptation, mitigation and development in community responses to climate and socio-economic stresses: Evidence from Zanzibar, Tanzania. *Applied Geography*, **46**, 111-121, doi:10.1016/j.apgeog.2013.11.005.

Suckall, N., L.C. Stringer, and E.L. Tompkins, 2015: Presenting Triple-Wins? Assessing Projects That Deliver Adaptation, Mitigation and Development Co-benefits in Rural Sub-Saharan Africa. *Ambio*, **44(1)**, 34-41, doi:10.1007/s13280-014-0520-0.

Suffolk, C. and W. Poortinga, 2016: Behavioural changes after energy efficiency improvements in residential properties. In: *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon* [Santarius, T., H.J. Walnum, and C. Aall (eds.)]. Springer International Publishing, Cham, pp. 121-142.

Surminski, S., L.M. Bouwer, and J. Linnerooth-Bayer, 2016: How insurance can support climate resilience. *Nature Climate Change*, **6(4)**, 333-334, doi:10.1038/nclimate2979.

Szabo, S. et al., 2015: Sustainable Development Goals Offer New Opportunities for Tropical Delta Regions. *Environment: Science and Policy for Sustainable Development*, **57(4)**, 16-23, doi:10.1080/00139157.2015.1048142.

Tàbara, J.D., A.L. St. Clair, and E.A.T. Hermansen, 2017: Transforming communication and knowledge production processes to address high-end climate change. *Environmental Science & Policy*, **70**, 31-37, doi:10.1016/j.envsci.2017.01.004.

Tàbara, J.D. et al., 2018: Positive tipping points in a rapidly warming world. *Current Opinion in Environmental Sustainability*, **31**, 120-129, doi:10.1016/j.cosust.2018.01.012.

Tait, L. and M. Euston-Brown, 2017: What role can African cities play in low-carbon development? A multilevel governance perspective of Ghana, Uganda and South Africa. *Journal of Energy in Southern Africa*, **28(3)**, 43, doi:10.17159/2413-3051/2017/v28i3a1959.

Tanner, T. et al., 2017: Political economy of climate compatible development: artisanal fisheries and climate change in Ghana. In: *Making climate compatible development happen* [Nunan, F. (ed.)]. Routledge, Abingdon, UK and New York, NY, USA, pp. 223-241.

Taylor, M., 2017: Climate-smart agriculture: what is it good for? *The Journal of Peasant Studies*, **45(1)**, 89-107, doi:10.1080/03066150.2017.1312355.

Taylor Aiken, G., 2015: (Local-) community for global challenges: carbon conversations, transition towns and governmental elisions. *Local Environment*, **20(7)**, 764-781, doi:10.1080/13549839.2013.870142.

Taylor Aiken, G., 2016: Prosaic state governance of community low carbon transitions. *Political Geography*, **55**, 20-29, doi:10.1016/j.polgeo.2016.04.002.

Taylor Aiken, G., L. Middlemiss, S. Sallu, and R. Hauxwell-Baldwin, 2017: Researching climate change and community in neoliberal contexts: an emerging critical approach. *Wiley Interdisciplinary Reviews: Climate Change*, **8(4)**, n/a-n/a, doi:10.1002/wcc.463.

Teferi, Z.A. and P. Newman, 2018: Slum upgrading: can the 1.5°C carbon reduction work with SDGs in these settlements? *Urban Planning*, **3(2)**, 52-63, doi:10.17645/up.v3i2.1239.

Thomas, A. and L. Benjamin, 2017: Management of loss and damage in small island developing states: implications for a 1.5 °C or warmer world. *Regional Environmental Change*, **17(81)**, 1-10, doi:10.1007/s10113-017-1184-7.

Thompson-Hall, M., E.R. Carr, and U. Pascual, 2016: Enhancing and expanding intersectional research for climate change adaptation in agrarian settings. *Ambio*, **45(s3)**, 373-382, doi:10.1007/s13280-016-0827-0.

Thornton, T.F. and C. Comberti, 2017: Synergies and trade-offs between adaptation, mitigation and development. *Climatic Change*, 1-14, doi:10.1007/s10584-013-0884-3.

Thorp, T.M., 2014: *Climate justice: a voice for the future*. Palgrave Macmillan, New York.

Tilman, D. and M. Clark, 2014: Global diets link environmental sustainability and human health. *Nature*, **515(7528)**, 518-522, doi:10.1038/nature13959.

Tokar, B., 2014: *Toward climate justice: perspectives on the climate crisis and social change*. New Compass Press, Porsgrunn, Norway.

Toole, S., N. Klocker, and L. Head, 2016: Re-thinking climate change adaptation and capacities at the household scale. *Climatic Change*, **135(2)**, 203-209, doi:10.1007/s10584-015-1577-x.

Tschakert, P. et al., 2016: Micropolitics in collective learning spaces for adaptive decision making. *Global Environmental Change*, **40**, 182-194, doi:10.1016/j.gloenvcha.2016.07.004.

Tschakert, P. et al., 2017: Climate change and loss, as if people mattered: Values, places, and experiences. *Wiley Interdisciplinary Reviews: Climate Change*, **8(5)**, e476, doi:10.1002/wcc.476.

Tung, R.L., 2016: Opportunities and Challenges Ahead of China's "New Normal". *Long Range Planning*, **49(5)**, 632-640, doi:10.1016/j.lrp.2016.05.001.

UN, 2014a: *Resolution adopted by the General Assembly on 14 November 2014: SIDS accelerated modalities of action (SAMOA) pathway*. A/RES/69/15.

UN, 2014b: *World urbanisation prospects, 2014 revisions*. Department of Economic and Social Affairs, New York, NY, USA.

UN, 2015a: *The Millennium Development Goals Report 2015*. United Nations (UN), New York, NY, USA, 75 pp.

UN, 2015b: *Transforming Our World: The 2030 Agenda for Sustainable Development (A/RES/70/1)*. A/RES/70/1, 35 pp.

UN Women, 2016: *Time to Act on Gender, Climate Change and Disaster Risk Reduction: An overview of progress in the Pacific region with evidence from The Republic of Marshall Islands, Vanuatu and Samoa*. 92 pp.

UN Women and MRFCJ, 2016: *The Full View: Ensuring a comprehensive approach to achieve the goal of gender balance in the UNFCCC process*.

UNDP, 2016: *Risk Governance: Building Blocks for Resilient Development in the Pacific*. Policy Brief: October 2016, United Nations Development Programme (UNDP) and Pacific Risk Resilience Programme (PRRP), Suva, Fiji, 20 pp.

UNEP, 2017: *The Emissions Gap Report 2017*. United Nations Environment Programme (UNEP), Nairobi, Kenya.

UNFCCC, 2010: *Decision 1/CP.16: Warsaw international mechanism for loss and damage associated with climate change impacts*.

UNFCCC, 2011: *Decision 7/CP.17: Work programme on loss and damage*.

UNFCCC, 2013: *Decision 2/CP.19: Warsaw international mechanism for loss and damage associated with climate change impact*.

UNFCCC, 2015: *Adoption of the Paris Agreement*. FCCC/CP/2015/L.9, 32 pp.

UNRISD, 2016: *Policy Innovations for Transformative Change: Implementing the 2030 Agenda for Sustainable Development*. 248 pp.

UNU-EHS, 2016: *World Risk Report 2016 - Logistics and infrastructure*. 74 pp.

Ürge-Vorsatz, D., S.T. Herrero, N.K. Dubash, and F. Lecocq, 2014: Measuring the co-benefits of climate change mitigation. *Annual Review of Environment and Resources*, **39(October)**, 549-582, doi:10.1146/annurev-environ-031312-125456.

Ürge-Vorsatz, D. et al., 2016: Measuring multiple impacts of low-carbon energy options in a green economy context. *Applied Energy*, **179**, 1409-1426, doi:10.1016/j.apenergy.2016.07.027.

Ustadi, I., T. Mezher, and M.R.M. Abu-Zahra, 2017: The effect of the carbon capture and storage (CCS) technology deployment on the natural gas market in the United Arab Emirates. *Energy Procedia*, **114**, 6366-6376, doi:https://doi.org/10.1016/j.egypro.2017.03.1773.

Vale, L.J., 2014: The politics of resilient cities: whose resilience and whose city? *Building Research and Information*, **42(2)**, 191-201, doi:10.1080/09613218.2014.850602.

Van Aelst, K. and N. Holvoet, 2016: Intersections of gender and marital status in accessing climate change adaptation: evidence from rural Tanzania. *World Development*, **79(July 2015)**, 40-50, doi:10.1016/j.worlddev.2015.11.003.

Van de Graaf, T. and A. Verbruggen, 2015: The oil endgame: strategies of oil exporters in a carbon-constrained world. *Environmental Science & Policy*, **54**, 456-462, doi:https://doi.org/10.1016/j.envsci.2015.08.004.

van der Geest, K. and K. Warner, 2015: Editorial: Loss and damage from climate change: emerging perspectives. *International Journal of Global Warming*, **8(2)**, 133-140.

Van der Heijden, J., 2018: The limits of voluntary programs for low-carbon buildings for staying under 1.5°C. *Current Opinion in Environmental Sustainability*, **30**, 59-66, doi:10.1016/j.cosust.2018.03.006.

van Noorloos, F. and M. Kloosterboer, 2017: Africa's new cities: The contested future of urbanisation. *Urban Studies*, 1-19, doi:0.1177/0042098017700574.

van Vuuren, D.P. et al., 2017a: The Shared Socio-economic Pathways: Trajectories for human development and global environmental change. *Global Environmental Change*, **42**, 148-152, doi:10.1016/j.gloenvcha.2016.10.009.

van Vuuren, D.P. et al., 2017b: Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. *Global Environmental Change*, **42**, 237-250, doi:10.1016/j.gloenvcha.2016.05.008.

van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(May)**, 1-7, doi:10.1038/s41558-018-0119-8.

Vanhala, L. and C. Hestbaek, 2016: Framing climate change Loss and Damage in UNFCCC negotiations. *Global Environmental Politics*, **16(4)**, 111-129, doi:10.1162/GLEP_a_00379.

Vardakoulias, O. and N. Nicholles, 2014: *Managing uncertainty: An economic evaluation of community-based adaptation in Dakoro, Niger*. 54 pp.

Veland, S. et al., 2018: Narrative matters for sustainability: the transformative role of storytelling in realizing 1.5°C futures. *Current Opinion in Environmental Sustainability*, **31**, 41-47, doi:https://doi.org/10.1016/j.cosust.2017.12.005.

Vermeulen, S. et al., 2016: *The Economic Advantage: Assessing the value of climate change actions in agriculture*. International Fund for Agricultural Development (IFAD), 77 pp.

Vierros, M., 2017: Communities and blue carbon: the role of traditional management systems in providing benefits for carbon storage, biodiversity conservation and livelihoods. *Climatic Change*, **140(1)**, 89-100, doi:10.1007/s10584-013-0920-3.

Vinyeta, K., K.P. Whyte, and K. Lynn, 2015: *Climate change through an intersectional lens: gendered vulnerability and resilience in indigenous communities in the United States*. United States Department of Agriculture, 80 pp.

Vogt-Schilb, A. and S. Hallegatte, 2017: Climate policies and NDCs: reconciling the needed ambition with the political economy. IDB Working Paper Series.

Volz, U. et al., 2015: *Financing green transformation: how to make green finance work in Indonesia*. Palgrave Macmillan, Basingstoke, Hampshire, UK.

von Stechow, C. et al., 2015: Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. *Annual Review of Environment and Resources*, **40(1)**, 363-394, doi:10.1146/annurev-environ-021113-095626.

von Stechow, C. et al., 2016: 2°C and SDGs: United they stand, divided they fall? *Environmental Research Letters*, **11(3)**, 34022, doi:10.1088/1748-9326/11/3/034022.

Voorn, T., J. Quist, and C. Pahl-Wostl, 2017: Envisioning robust climate change adaptation futures for coastal regions: a comparative evaluation of cases in three continents. *Mitigation and Adaptation*.

Wachsmuth, D., D. Cohen, and H. Angelo, 2016: Expand the frontiers of urban sustainability. *Nature*, **536**, 391-393.

Waisman, H.–D., C. Guivarch, and F. Lecocq, 2013: The transportation sector and low-carbon growth pathways: modelling urban, infrastructure, and spatial determinants of mobility. *Climate Policy*, **13(sup01)**, 106-129, doi:10.1080/14693062.2012.735916.

Wallimann-Helmer, I., 2015: Justice for climate loss and damage. *Climatic Change*, **133(3)**, 469-480, doi:10.1007/s10584-015-1483-2.

Walsh-Dilley, M. and W. Wolford, 2015: (Un)Defining resilience: subjective understandings of 'resilience' from the field. *Resilience*, **3(3)**, 173-182, doi:10.1080/21693293.2015.1072310.

Wamsler, C., C. Luederitz, E. Brink, C. Wamsler, and C. Luederitz, 2014: Local levers for change: mainstreaming ecosystem-based adaptation into municipal planning to foster sustainability transitions. *Global Environmental Change*, **29**, 189-201, doi:10.1016/j.gloenvcha.2014.09.008.

Wang, X., 2017: The role of attitudinal motivations and collective efficacy on Chinese consumers' intentions to engage in personal behaviors to mitigate climate change. *The Journal of Social Psychology*, 1-13, doi:10.1080/00224545.2017.1302401.

Wang, Y., Q. Song, J. He, and Y. Qi, 2015: Developing low-carbon cities through pilots. *Climate Policy*, **15(November)**, 81-103, doi:10.1080/14693062.2015.1050347.

Wanner, T., 2014: The new 'Passive Revolution' of the green economy and growth discourse: Maintaining the 'Sustainable Development' of Neoliberal capitalism. *New Political Economy*, **20(1)**, 1-21, doi:10.1080/13563467.2013.866081.

Warner, B.P. and C.P. Kuzdas, 2017: The role of political economy in framing and producing transformative adaptation. *Current Opinion in Environmental Sustainability*, **29**, 69-74, doi:10.1016/j.cosust.2017.12.012.

Warner, B.P., C. Kuzdas, M.G. Yglesias, and D.L. Childers, 2015: Limits to adaptation to interacting global change risks among smallholder rice farmers in Northwest Costa Rica. *Global Environmental Change*, **30**, 101-112, doi:10.1016/J.GLOENVCHA.2014.11.002.

Warner, K. and K. Geest, 2013: Loss and damage from climate change: local-level evidence from nine vulnerable countries. *International Journal of Global Warming*, **5(4)**, 367, doi:10.1504/IJGW.2013.057289.

Watts, N. et al., 2015: Health and climate change: policy responses to protect public health. *The Lancet*, **386(10006)**, 1861-1914.

Wegner, G.I., 2016: Payments for ecosystem services (PES): a flexible, participatory, and integrated approach for improved conservation and equity outcomes. *Environment, Development and Sustainability*, **18(3)**, 617-644, doi:10.1007/s10668-015-9673-7.

Weisser, F., M. Bollig, M. Doevenspeck, and D. Müller-Mahn, 2014: Translating the 'adaptation to climate change' paradigm: the politics of a travelling idea in Africa. *The Geographical Journal*, **180(2)**, 111-119, doi:10.1111/geoj.12037.

Wells, E.M. et al., 2015: Indoor air quality and occupant comfort in homes with deep versus conventional energy efficiency renovations. *Building and Environment*, **93(P2)**, 331-338, doi:10.1016/j.buildenv.2015.06.021.

Welsch, M. et al., 2014: Adding value with CLEWS - Modelling the energy system and its interdependencies for Mauritius. *Applied Energy*, **113**, 1434-1445, doi:10.1016/j.apenergy.2013.08.083.

Weng, X., Z. Dong, Q. Wu, and Y. Qin, 2015: *China's path to a green economy: decoding China's green economy concepts and policies, IIED Country Report*. 40 pp.

Werfel, S.H., 2017: Household behaviour crowds out support for climate change policy when sufficient progress is perceived. *Nature Climate Change*, **7(7)**, 512-515, doi:10.1038/nclimate3316.

Wesseling, J.H. et al., 2017: The transition of energy intensive processing industries towards deep decarbonization: characteristics and implications for future research. *Renewable and Sustainable Energy Reviews*, **79(May)**, 1303-1313, doi:10.1016/j.rser.2017.05.156.

Weston, P., R. Hong, C. Kaboré, and C.A. Kull, 2015: Farmer-managed natural regeneration enhances rural livelihoods in dryland West Africa. *Environmental Management*, **55(6)**, 1402-1417, doi:10.1007/s00267-015-0469-1.

Wewerinke-Singh, M., 2018a: Climate migrants' right to enjoy their culture. In: *Climate refugees: beyond the legal impasse?* [Behrman, S. and A. Kent (eds.)]. Earthscan/Routledge, Abingdon, UK and New York, NY, USA.

Wewerinke-Singh, M., 2018b: State responsibility for human rights violations associated with climate change. In: *Routledge Handbook of Human Rights and Climate Governance* [Jodoin, S., S. Duyck, and A. Johl (eds.)]. Routledge, Abingdon, UK and New York, NY, USA.

WHO, 2014: *Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s*. World Health Organization (WHO), Geneva, Switzerland, 128 pp.

Wiebe, K. et al., 2015: Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. *Environmental Research Letters*, **10(8)**, 085010, doi:10.1088/1748-9326/10/8/085010.

Wiktorowicz, J., T. Babaeff, J. Eggleston, and P. Newman, 2018: WGV: an Australian urban precinct case study to demonstrate the 1.5C agenda including multiple SDGs. *Urban Planning*, **3(2)**, 64-81, doi:10.17645/up.v3i2.1245.

Wilkinson, E., A. Kirbyshire, L. Mayhew, P. Batra, and A. Milan, 2016: *Climate-induced migration and displacement: closing the policy gap*.

Willand, N., I. Ridley, and C. Maller, 2015: Towards explaining the health impacts of residential energy efficiency interventions - A realist review. Part 1: Pathways. *Social Science and Medicine*, **133**, 191-201, doi:10.1016/j.socscimed.2015.02.005.

Winkler, H. and N.K. Dubash, 2016: Who determines transformational change in development and climate finance? *Climate Policy*, **16(6)**, 783-791, doi:10.1080/14693062.2015.1033674.

Winkler, H. et al., 2018: Countries start to explain how their climate contributions are fair: more rigour needed. *International Environmental Agreements: Politics, Law and Economics*, **18(1)**, 99-115, doi:10.1007/s10784-017-9381-x.

Winsemius, H.C. et al., 2018: Disaster risk, climate change, and poverty: assessing the global exposure of poor people to floods and droughts. *Environment and Development Economics*, **17**, 1-21, doi:10.1017/S1355770X17000444.

Wise, R.M. et al., 2014: Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, **28**, 325-336, doi:10.1016/j.gloenvcha.2013.12.002.

Wood, B.T., 2017: Socially just triple-wins? An evaluation of projects that pursue climate compatible development goals in Malawi., University of Leeds, Leeds, UK, 278 pp.

Wood, B.T., S.M. Sallu, and J. Paavola, 2016a: Can CDM finance energy access in Least Developed Countries? Evidence from Tanzania. *Climate Policy*, **16(4)**, 456-473, doi:10.1080/14693062.2015.1027166.

Wood, B.T., A.J. Dougill, C.H. Quinn, and L.C. Stringer, 2016b: Exploring Power and Procedural Justice Within Climate Compatible Development Project Design: Whose Priorities Are Being Considered? *The Journal of Environment & Development*, **25(4)**, 363-395, doi:10.1177/1070496516664179.

Work, C., 2015: Intersections of climate change mitigation policies, land grabbing and conflict in a fragile state: insights from Cambodia.

Wright, H., S. Huq, and J. Reeves, 2015: Impact of climate change on least developed countries: are the SDGs possible? IIED Briefing May 2015, 4 pp.

WWF, 2017: *Responsible sourcing of forest products: the business case for retailers*. World Wide Fund for Nature (WWF), Gland, Switzerland.

Wyborn, C., L. Yung, D. Murphy, and D.R. Williams, 2015: Situating adaptation: how governance challenges and perceptions of uncertainty influence adaptation in the Rocky Mountains. *Regional Environmental Change*, **15(4)**, 669-682, doi:10.1007/s10113-014-0663-3.

Yang, S., B. Chen, and S. Ulgiati, 2016: Co-benefits of CO2 and PM2.5 Emission Reduction. *Energy Procedia*, **104**, 92-97, doi:10.1016/j.egypro.2016.12.017.

Yaro, J.A., J. Teye, and S. Bawakyillenuo, 2015: Local institutions and adaptive capacity to climate change/variability in the northern savannah of Ghana. *Climate and Development*, **7(3)**, 235-245, doi:10.1080/17565529.2014.951018.

Zeng, H., X. Chen, X. Xiao, and Z. Zhou, 2017: Institutional pressures, sustainable supply chain management, and circular economy capability: Empirical evidence from Chinese eco-industrial park firms. *Journal of Cleaner*

Production, **155**, 54-65, doi:10.1016/j.jclepro.2016.10.093.

Zhang, H. and W. Chen, 2015: The role of biofuels in China's transport sector in carbon mitigation scenarios. *Energy Procedia*, **75**, 2700-2705, doi:10.1016/j.egypro.2015.07.682.

Zhang, S., E. Worrell, and W. Crijns-Graus, 2015: Cutting air pollution by improving energy efficiency of China's cement industry. *Energy Procedia*, **83**, 10-20, doi:10.1016/j.egypro.2015.12.191.

Zhang, Y. et al., 2017: Processes of coastal ecosystem carbon sequestration and approaches for increasing carbon sink. *Science China Earth Sciences*, **60(5)**, 809-820, doi:10.1007/s11430-016-9010-9.

Zhao, D., A.P. McCoy, J. Du, P. Agee, and Y. Lu, 2017: Interaction effects of building technology and resident behavior on energy consumption in residential buildings. *Energy and Buildings*, **134**, 223-233, doi:10.1016/j.enbuild.2016.10.049.

Ziervogel, G., A. Cowen, and J. Ziniades, 2016: Moving from adaptive to transformative capacity: Building foundations for inclusive, thriving, and regenerative urban settlements. *Sustainability*, **8(9)**, doi:10.3390/su8090955.

Ziervogel, G. et al., 2017: Inserting rights and justice into urban resilience: a focus on everyday risk. *Environment and Urbanization*, **29(1)**, 123-138, doi:10.1177/0956247816686905.

Zimm, C., F. Sperling, and S. Busch, 2018: Identifying sustainability and knowledge gaps in socio-economic pathways vis-à-vis the Sustainable Development Goals. *Economies*, **6(2)**, 20, doi:10.3390/economies6020020.

Chapter 5 – Table 5.3

<table>
<tr><th></th><th></th><th>INTERACTION</th><th>SCORE</th><th>EVIDENCE</th><th>AGREEMENT</th><th>CONFIDENCE</th><th>INTERACTION</th><th>SCORE</th><th>EVIDENCE</th><th>AGREEMENT</th><th>CONFIDENCE</th><th>INTERACTION</th><th>SCORE</th><th>EVIDENCE</th><th>AGREEMENT</th><th>CONFIDENCE</th><th>INTERACTION</th><th>SCORE</th><th>EVIDENCE</th><th>AGREEMENT</th><th>CONFIDENCE</th></tr>
<tr><td rowspan="12">**Industry**</td><td rowspan="4">**Accelerating energy efficiency improvement**</td><td colspan="5">**Reduces poverty**</td><td colspan="5"></td><td colspan="5">**Air, water pollution reduction and better health (3.9)**</td><td colspan="5">**Technical education, vocational training, education for sustainability (4.3, 4.4,4.5,4.7)**</td></tr>
<tr><td>↑</td><td>**[+2]**</td><td>🕮</td><td>☺</td><td>★</td><td></td><td>**[0]**</td><td></td><td></td><td></td><td>↑</td><td>**[+2]**</td><td>🕮🕮</td><td>☺☺</td><td>★★</td><td>↑</td><td>**[+1]**</td><td>🕮🕮</td><td>☺☺</td><td>★★</td></tr>
<tr><td colspan="5">% of people living below poverty line declines from 49% to 18% in South African context.</td><td colspan="5">No direct interaction</td><td colspan="5">People living in the deprived communities feel positive and predict considerable financial savings. Efficiency changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment. In extractive industries there is trade off unless strategically managed. Behavioral changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment.</td><td colspan="5">Awareness, knowledge and technical and managerial capability are closely linked, energy audit , information for trade unions, product /appliance labeling help in sustianbility education</td></tr>
<tr><td colspan="5">Altieri et al (2016)</td><td colspan="5"></td><td colspan="5">Xi et al. (2013), Zhang et al. (2015), Vassolo and Doell (2005); Fricko et al. (2016); Holland et al. (2016); Nguyen et al. (2014)</td><td colspan="5">Fernando et al. (2016), Apeaning and Thollandar (2013), Roy et al. (2018)</td></tr>
<tr><td rowspan="4">**Low-carbon fuel switch**</td><td colspan="5"></td><td colspan="5"></td><td colspan="5">**water and air pollution reduction and better health (3.9)**</td><td colspan="5">**Technical education, vocational training,education for sustainability (4.b,4.7)**</td></tr>
<tr><td></td><td>**[0]**</td><td></td><td></td><td></td><td></td><td>**[0]**</td><td></td><td></td><td></td><td>↑</td><td>**[+2]**</td><td>🕮🕮</td><td>☺☺</td><td>★★</td><td>↑</td><td>**[+1]**</td><td>🕮🕮</td><td>☺☺</td><td>★★</td></tr>
<tr><td colspan="5">No direct interaction</td><td colspan="5">No direct interaction</td><td colspan="5">Industries are becoming supplier of energy, waste heat , water, roof tops for solar energy generation and hence helping in improving air and water quality.</td><td colspan="5">New technplogy deployment creates demand for awareness, knowledge with technical and managerial capability otherwise acts as barrier for rapid expansion.</td></tr>
<tr><td colspan="5"></td><td colspan="5"></td><td colspan="5">Vassolo and Doell (2005); Fricko et al. (2016); Holland et al. (2016); Nguyen et al (2014), Karner et al (2015)</td><td colspan="5">Fernando et al. (2016), Apeaning and Thollandar (2013), Roy et al. (2018)</td></tr>
<tr><td rowspan="4">**Decarbonisation/ CCS/CCU**</td><td colspan="5"></td><td colspan="5"></td><td colspan="5">**Disease and Mortality (3.1/3.2/3.3/3.4)**</td><td colspan="5"></td></tr>
<tr><td></td><td>**[0]**</td><td></td><td></td><td></td><td></td><td>**[0]**</td><td></td><td></td><td></td><td>↓</td><td>**[-1]**</td><td>🕮🕮</td><td>☺☺☺</td><td>★★★</td><td></td><td>**[0]**</td><td></td><td></td><td></td></tr>
<tr><td colspan="5">No direct interaction</td><td colspan="5">No direct interaction</td><td colspan="5">There is a risk of CO2 leakage both from geological formations as well as from the transportation infrastructure from source to sequestration locations.</td><td colspan="5">No direct interaction</td></tr>
<tr><td colspan="5"></td><td colspan="5"></td><td colspan="5">IPCC AR5 WG3 (2014); Atchley et al. (2013); Apps et al. (2010); Siirila et al. (2012); Wang and Jaffe (2004); Koorneef et al. (2011); Singh et al. (2011); Hertwich et al. (2008); Veltman et al. (2010); Corsten et al.(2013)</td><td colspan="5"></td></tr>
<tr><td rowspan="12">**Buildings**</td><td rowspan="4">**Behaviorial response**</td><td colspan="5">**Poverty reduction via financial savings (1.1)**</td><td colspan="5"></td><td colspan="5">**Improved warmth and comforts**</td><td colspan="5"></td></tr>
<tr><td>↑</td><td>**[+2]**</td><td>🕮</td><td>☺</td><td>★</td><td></td><td>**[0]**</td><td></td><td></td><td></td><td>↑</td><td>**[+2]**</td><td>🕮🕮🕮</td><td>☺☺☺</td><td>★★★</td><td></td><td>**[0]**</td><td></td><td></td><td></td></tr>
<tr><td colspan="5">People living in the deprived communities feel positive and predict considerable financial savings.</td><td colspan="5">No direct interaction</td><td colspan="5">Home occupants reported warmth as the most important aspect of comfort which were largely temperature-related and low in energy costs. Residents living in the deprived areas expect improved warmth in their properties after energy efficiency measures are employed.</td><td colspan="5">No direct interaction</td></tr>
<tr><td colspan="5">Scott, Jones, and Webb (2014)</td><td colspan="5"></td><td colspan="5">Scott, Jones, and Webb (2014); Huebner, Cooper, and Jones (2013); Yue, Long, and Chen (2013); Zhao et al. 2017</td><td colspan="5"></td></tr>
<tr><td rowspan="4">**Accelerating energy efficiency improvement**</td><td colspan="5">**Poverty and Development (1.1/1.2/1.3/1.4)**</td><td colspan="5">**Food Security (2.1)**</td><td colspan="5">**Healthy lives and well-being for all at all ages(3.2, 3.9)**</td><td colspan="5">**Equal Access to Educational Institutions (4.1/4.2/4.3/4.5)**</td></tr>
<tr><td>↑ / ↓</td><td>**[+2,-1]**</td><td>🕮🕮🕮</td><td>☺☺☺</td><td>★★★</td><td>↑</td><td>**[+2]**</td><td>🕮</td><td>☺</td><td>★</td><td>↑</td><td>**[+2]**</td><td>🕮🕮🕮🕮</td><td>☺☺☺☺</td><td>★★★★</td><td>↑</td><td>**[+2]**</td><td>🕮</td><td>☺</td><td>★</td></tr>
<tr><td colspan="5">Energy efficiency interventions lead to cost savings which are realized due to reduced energy bills that further lead to poverty reduction. Participants with low incomes experience greater benefits. 'Energy efficiency and biomass strategies benefitied poor more than wind and solar whose benefits are captured by industry. carbon mitigation can increase or decrease inequalitites. The distributional costs of new energy policies (e.g., supporting renewables and energy efficiency) are dependent on instrument design. If costs fall disproportionately on the poor, then this could impair progress toward universal energy access and, by extension, counteract the fight to eliminate poverty. (Quote from McCollum et al., 2018), Smart Home Technology</td><td colspan="5">Using the improved stoves supports local food security and has significantly impacted on food security. By making fuel lasting longer, the improved stoves also help improve food security and provide a better buffer against fuel shortages induced by climate change-related events such as droughts, floods or hurricanes (Berrueta et al. 2017).</td><td colspan="5">Efficient cookstove improves health especially for indigenous and poor rural communities. Household energy efficiency has positive health impacts on children’s respiratory health, weight, and susceptibility to illness, and the mental health of adults. Household energy efficiency improves winter warmth, lowers relative humidity with benefits for cardiovascular and respiratory health. Further improved Indoor Air Quality by thermal regulation and occupant comfort are realised. However in one instance negative health impacts (asthma) of increased household energy efficiency were also noted when housing upgrades take place without changes in occupant behaviours. Home occupants reported warmth as the most important aspect of comfort which were largely temperature-related and low in energy costs. Residents living in the deprived areas expect improved warmth in their properties after energy efficiency measures are employed.</td><td colspan="5">Household energy efficiency measures reduce school absences for children with asthma due to indoor pollution</td></tr>
<tr><td colspan="5">Maidment et al. (2014); Scott, Jones, and Webb (2014); Berrueta et al. (2017); McCollum et al. (2018); Cameron et al. (2016); Casillas and Kammen (2012); Fay et al. (2015); Hallegate et al. (2016); Hirth and Ueckerdt (2013); Jakob and Steckel (2014); Casillas et al (2012)</td><td colspan="5">Berrueta et al. (2017)</td><td colspan="5">Berrueta et al. (2017); Maidment et al. (2014); Willand, Ridley, and Maller (2015); Wells et al. (2015); Cameron, Taylor, and Emmett (2015); Liddell and Guiney (2015); Sharpe et al. (2015); Derbez (2014); Djamila, Chu, and Kumaresan (2013); Scott, Jones, and Webb (2014); Huebner, Cooper, and Jones (2013); Yue, Long, and Chen (2013); Zhao et al.</td><td colspan="5">Maidment et al. (2014)</td></tr>
<tr><td rowspan="4">**Improved access & fuel switch to modern low-carbon energy**</td><td colspan="5">**Poverty and Development (1.1/1.2/1.3/1.4)**</td><td colspan="5">**Food Security and Agricultural Productivity (2.1/2.4)**</td><td colspan="5">**Disease and Mortality (3.1/3.2/3.3/3.4)**</td><td colspan="5">**Equal Access to Educational Institutions (4.1/4.2/4.3/4.5)**</td></tr>
<tr><td>↑</td><td>**[+2]**</td><td>🕮🕮🕮</td><td>☺☺☺</td><td>★★★★</td><td>~ / ↓</td><td>**[0,-1]**</td><td>🕮🕮</td><td>☺☺☺</td><td>★★</td><td>↑</td><td>**[+2]**</td><td>🕮🕮🕮</td><td>☺☺☺</td><td>★★★★</td><td>↑</td><td>**[+1]**</td><td>🕮</td><td>☺☺☺</td><td>★★</td></tr>
<tr><td colspan="5">Access to modern energy forms (electricity, clean cook-stoves, high-quality lighting) is fundamental to human development since the energy services made possible by them help alleviate chronic and persistent poverty. Strength of the impact varies in the literature. (Quote from McCollum et al., 2018)</td><td colspan="5">Modern energy access is critical to enhance agricultural yields/productivity, decrease post-harvest losses, and mechanize agri-processing - all of which can aid food security. However, large-scale bioenergy and food production may compete for scarce land and other inputs (e.g., water, fertilizers), depending on how and where biomass supplies are grown and the indirect land use change impacts that result. If not implemented thoughtfully, this could lead to higher food prices globally, and thus reduced access to affordable food for the poor. Enhanced agricultural productivities can ameliorate the situation by allowing as much bioenergy to be produced on as little land as possible.</td><td colspan="5">Access to modern energy services can contribute to fewer injuries and diseases related to traditional solid fuel collection and burning, as well as utilization of kerosene lanterns. Access to modern energy services can facilitate improved health care provision, medicine and vaccine storage, utilization of powered medical equipment, and dissemination of health-related information and education. Such services can also enable thermal comfort in homes and contribute to food preservation and safety. (Quote from McCollum et al., 2018)</td><td colspan="5">Access to modern energy is necessary for schools to have quality lighting and thermal comfort, as well as modern information and communication technologies. Access to modern lighting and energy allows for studying after sundown and frees constraints on time management that allow for higher school enrollment rates and better literacy outcomes. (Quote from McCollum et al., 2018)</td></tr>
<tr><td colspan="5">McCollum et al. (2018); Bonan et al. (2014); Burlig and Preonas (2016); Casillas and Kammen (2010); Cook (2011); Kirubi et al. (2009); Pachauri et al. (2012); Pueyo et al. (2013); Rao et al. (2014); Zulu and Richardson, 2013; Pode, 2013</td><td colspan="5">McCollum et al. (2018); Asaduzzaman et al. (2010); Cabraal et al. (2005); Finco and Doppler (2010); Hasegawa et al. (2015); Lotze-Campen et al. (2014); Msangi et al. (2010); Smith et al. (2013); Smith, P. et al. (2014); Sola et al. (2016); Tilman et al. (2009); van Vuuren et al. (2009)</td><td colspan="5">McCollum et al. (2018); Aranda et al. (2014); Lam et al. (2012); Lim et al. (2012); Smith et al (2013)</td><td colspan="5">McCollum et al. (2018); Lipscomb et al. (2013); van de Walle et al. (2013)</td></tr>
</table>

Transport	**Behavioural response**	**Equal right to economic resources acces basic services (1.1,1.4,1.a, 1.b)** ↑ / ↓ **[+2,-1]** 🕮🕮🕮 ☺☺☺ ★★★ The costs of daily mobility can have important economic stress impacts not only impacting carless family with low-mobility, but in countries with high levels of car dependence, the costs of motoring can be burdensome, raising questions of affordability for households with limited economic resources.During economic crisis public transport authorities may react by reducing levels of service and increasing fares, likely exacerbating the situation for low-income households. Dodson et al. (2004); Cascajo et al. (2017)	**Ensure Access to Safe Nutritious Food (2.1; 2.2)** ↑ **[+2]** 🕮 ☺ ★★★ Low-income community residents (non-white) who lack local access to affordable, quality sources of nutrition have to travel outside their immediate neighborhood to find better sources of food to feed themselves and their families. Lack of locally available healthy food often exacerbates the rates of obesity in many of these communities since it is often difficult or expensive to travel long distances on a regular basis to shop for food . Lowery et al. (2016); Hillier et al. (2011); Krukowski et al. (2013); LeDoux and Vojnovic (2013); Zenk et al. (2014); Ghosh-Dastidar et al. (2014); Clifton (2004)	**Road Traffic Accidents (3.4/3.6)** ↑ / ↓ **[+2,-1]** 🕮🕮🕮 ☺☺☺ ★★ Active travel modes' (such as walking and cycling) represent strategies not only for boosting energy efficiency but also, potentially, for improving health and well-being (e.g., lowering rates of diabetes, obesity, heart disease, dementia, and some cancers). However, a risk associated with these measures is that they could increase rates of road traffic accidents, if the provided infrastructure is unsatisfactory. Overall health effects will depend on the severity of the injuries sustained from these potential accidents relative to the health benefits accruing from increased exercise (McCollum et al., 2018). McCollum et al. (2018); Creutzig et al. (2012); Haines and Dora (2012); Saunders et al. (2013); Shaw et al. (2014); Woodcock et al. (2009); Shaw et al (2017); Chakrabarti and Shin (2017); Hunag et al. (2017)	**Equal Safe Access to Educational Institutions (4.1/4.2/4.3/4.5)** ↑ **[+1]** 🕮 ☺☺☺ ★★ Differences in road ways affects school travel safety, collaborative efforts need to address safety issues from a dual perspective, first by working to change the existing infrastructure and use of roads to better address the traffic problems that children currently face walking to school, and then to better site schools and better control the roadways and land uses around them in the future Chia-Yuan Yu (2015)
	Accelerating energy efficiency improvement	**End Poverty in all its forms everywhere (1.1,1.4,1.a, 1.b)** ↑ / ↓ **[+2,-1]** 🕮🕮🕮 ☺☺☺ ★★★ Decarbonisation of public bus in Sweden is receiving attention more than efficiency improvement. With more electrification electricity price goes up and affordibility can worsen for poor unless redistributive policies are in place. Xylia et al (2017)	**[0]** No direct interaction	**Reduce illnesses from hazardous air, water and soil pollution (3.9)** ↑ **[+2]** 🕮🕮🕮 ☺☺☺ ★★★ Locally relevant policies targetting traffic reductions and ambitious diffusion of electric vehicles results in measured changes in non-climatic population exposure included ambient air pollution, physical activity, and noise. The transition to low-carbon equitable and sustainable transport can be fostered by numerous short- and medium-term strategies that would benefit energy security, health, productivity, and sustainability. Evidence-based approach that takes into account greenhouse gas emissions, ambient air pollutants, economic factors (affordability, cost optimisation), social factors (poverty alleviations, public health benefits), and political acceptability is needed tackle these challenges. Schucht et al. (2015); Figueroa et al. (2014); Peng et al. (2017); Klausbruckner et al. (2016)	**[0]** No direct interaction
	Improved access & fuel switch to modern low-carbon energy	**End Poverty in all its forms everywhere (1.1,1.4,1.a, 1.b)** ↑ / ↓ **[+2,-1]** 🕮🕮🕮 ☺☺☺ ★★★ Increasingly volatile global oil prices have raised concerns for the vulnerability of households to fuel price increases. Pricing measures as a key component of sustainable transport policy need to consider equity. Pro-poor mitigation policies are needed to reduce climate impact reduce threat; for example investing more and better in infrastructure by leveraging private resources and using designs that account for future climate change and the related uncertainty. Communities in poor areas cope with and adapt to multiple-stressors including climate change. Coping strategies provide short-term relief but in the long-term may negatively affect development goals. And responses generate a trade-off between adaptation, mitigation and development . African cities with slums and due to high commuting costs many walk to work places which limit access. In Latin america tripple informality leading to low productivity and living standards. Dodson and Sipe (2007); Hallegate et al. (2015); Suckall, Tompkins, and Stringer (2014); Lall, Henderson, and Venables (2017); Corporacion Andina de Fomento (2017); Klausbruckner et al. (2016)	**Ensure Access to Food Security (2.1, 2.3, 2.a, 2.b,2.c)** ~ **[0]** 🕮 ☺ ★ 21 projects aiming at resilient transport infrastructure development to improve access (e.g. C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) do not substantially contribute to realizing the (indirect) transport targets with mostly a rural focus: Agricultural Productivity (SDG 2) and Access to Safe Drinking Water (SDG 6) Partnership on Sustainable Low Carbon Transport (2017)	**Reduce illnesses from hazardous air pollution (3.9)** ↑ **[+2]** 🕮 ☺ ★ Projects aiming at resilient transport infrastructure development (e.g. C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are targetting at reducing airpollution, Electric vehicles using electricity from renewables or low carbon sources combined with e-mobility options such as trolleybuses, metros, trams and electro buses, as well as promote walking and biking, especially for short distances need consieration Partnership on Sustainable Low Carbon Transport (2017); Ajanovic (2015)	**[0]** No direct interaction

		1 NO POVERTY					2 ZERO HUNGER					3 GOOD HEALTH AND WELL-BEING					4 QUALITY EDUCATION				
		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE	INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE	INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE	INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Replacing coal	**Non-biomass renewables**											**Air Pollution (3.9)**									
	solar, wind, hydro	↑	**[+2]**	🕮🕮🕮	☺☺☺	★★★		**[0]**				↑	**[+2]**	🕮🕮🕮	☺☺☺	★★★★	↑	**[+1]**	🕮	☺	★
		Deployment of renewable energy and improvements in energy efficiency globally will aid climate change mitigation efforts, and this, in turn, can help to reduce the exposure of the world's poor to climate-related extreme events, negative health impacts, and other environmental shocks (McCollum et al., 2018).					No direct interaction					Promoting most types of renewables and boosting efficiency greatly aid the achievement of targets to reduce local air pollution and improve air quality; however, the order of magnitude of the effects, both in terms of avoided emissions and monetary valuation, varies significantly between different parts of the world. Benefits would especially accrue to those living in the dense urban centers of rapidly developing countries. Utilization of biomass and biofuels might not lead to any air pollution benefits, however, depending on the control measures applied. In addition, household air quality can be significantly improved through lowered particulate emissions from access to modern energy services (McCollum et al., 2018).					Decentralized renewable energy systems (e.g., home- or village-scale solar power) can support education and vocational training.				
		McCollum et al. (2018); Hallegatte et al. (2016); IPCC (2014); Riahi et al. (2012)										McCollum et al. (2018); Anenberg et al. (2013); Chaturvedi and Shukla (2014); Haines et al. (2007); IEA (2016); Kaygusuz (2011); Nemet et al. (2010); Rafaj et al. (2013); Rao et al (2013); Rao et al (2016); Riahi et al. (2012); Rose et al. (2014); Smith and Sagar (2014); van Vliet et al. (2012); West et al. (2013)					Anderson A., Loomba P., Orajaka I., Numfor J., Saha S., Janko S., Johnson N., Podmore R., Larsen R. (2017)				
	Increased use of biomass						**Farm Employment and Incomes (2.3)**					**Disease and Mortality (3.1/3.2/3.3/3.4), Air Pollution (3.9)**									
		↑ / ↓	**[+2,-2]**	🕮🕮	☺☺	★	↑ / ↓	**[+2,-2]**	🕮🕮🕮	☺☺☺	★★★	↑	**[+2]**	🕮🕮🕮	☺☺☺	★★★		**[0]**			
		Large-scale bioenergy production could lead to the creation of agricultural jobs, as well higher farm wages and more diversified income streams for farmers. Modern energy access can make marginal lands more cultivable, thus potentially generating on-farm jobs and incomes; on the other hand, greater farm mechanization can also displace labor. On the other hand, large-scale bioenergy production could alter the structure of global agricultural markets in a way that is, potentially, unfavorable to small-scale food producers. see SDG2 (McCollum et al., 2018).					Large-scale bioenergy production could lead to the creation of agricultural jobs, as well higher farm wages and more diversified income streams for farmers. Modern energy access can make marginal lands more cultivable, thus potentially generating on-farm jobs and incomes; on the other hand, greater farm mechanization can also displace labor. On the other hand, large-scale bioenergy production could alter the structure of global agricultural markets in a way that is, potentially, unfavorable to small-scale food producers. The distributional effects of bioenergy production are underexplored in the literature (McCollum et al., 2018).					Replacing coal by biomass can reduce adverse impacts of upstream supply-chain activities, in particular local air and water pollution, and prevent coal mining accidents. Improvements to local air pollution in power generation compared to coal-fired power plants depend on the technology and fuel of biomass powerplants, but could be significant when switching from outdated coal combustion technologies to state-of-the-art biogas power generation.					No direct interaction				
		McCollum et al. (2018); Balishter et al. (1991); Creutzig et al. (2013); de Moraes et al. (2010); Gohin (2008); Rud (2012); Satolo and Bacchi (2013); van der Horst and Vermeylen (2011); Corbera and Pascual (2012); Creutzig et al. (2013); Davis et al. (2013); van der Horst and Vermeylen (2011); Muys et al. (2014); Ertem, Kappler, and Neubauer (2017)					McCollum et al. (2018); Balishter et al. (1991); Creutzig et al. (2013); de Moraes et al. (2010); Gohin (2008); Rud (2012); Satolo and Bacchi (2013); van der Horst and Vermeylen (2011); Corbera and Pascual (2012); Creutzig et al. (2013); Davis et al. (2013); van der Horst and Vermeylen (2011); Muys et al. (2014); Ertem, Kappler, and Neubauer (2017)					IPCC AR5 WG3 (2014); Koorneef et al. (2011); Singh et al. (2011); Hertwich et al. (2008); Veltman et al. (2010); Corsten et al.(2013); Ashworth et al. (2012); Einsiedel et al. (2013); IPCC (2005); Miller et al. (2007); de Best-Waldhober et al. (2009); Shackley et al. (2009); Wong-Parodi and Ray (2009); Waööquist et al. (2009, 2010); Reiner and Nuttall (2011); Epstein et al. (2010); Burgherr et al. (2012); Chen et al. (2012); Chan and Griffiths (2010); Asfaw et al. (2013)									
	Nuclear/Advanced Nuclear											**Disease and Mortality (3.1/3.2/3.3/3.4)**									
			[0]					**[0]**				↓	**[-1]**	🕮🕮🕮	☺☺☺	★★★		**[0]**			
		No direct interaction					No direct interaction					In spite of the industry's overall safety track record, a non-negligible risk for accidents in nuclear power plants and waste treatment facilities remains. The long-term storage of nuclear waste is a politically fraught subject, with no large-scale long-term storage operational worldwide. Negative impacts from upsteam uranium mining and milling are comparable to those of coal, hence replacing fossil fuel combustion by nuclear power would be neutral in that aspect. Increased occurrence of childhood leukaemia in popoulations living within 5 km of nuclear power plants was identified by some studies, even though a direct causal relation to ionizing radiation could not be established and other studies could not confirm any correlation (low evidence/agreement in this issue).					No direct interaction				
												IPCC AR5 WG3 (2014); Cardis et al. (2006); Balonov et al. (2011); Moomaw et al. (2011a); WHO (2013); Abdelouas (2006); Al-Zoughool and Kewski (2009) cited in Sathaye et al. (2011a); Smith et al. (2013); Schnelzer et al. (2010); Tirmarche (2012); Brugge and Buchner (2011); Møller et al. (2012); Hiyama et al. (2013); Mousseau and Møller (2013); Møller and Mousseau (2011); Møller et al. (2011); von Stechow et al. (2016); Heinävaara et al. (2010), Kaatsch et al. (2008); Sermage-Faure et al. (2012); Hoeve and Jacobson (2012)									
	CCS: Bio energy						**Farm Employment and Incomes (2.3)**					**Disease and Mortality (3.1/3.2/3.3/3.4)**									
		↑ / ↓	**[+2,-2]**	🕮🕮	☺☺	★	↑ / ↓	**[+1,-2]**	🕮🕮🕮	☺☺☺	★★★	↑ / ↓	**[+2,-1]**	🕮🕮	☺☺☺	★★★		**[0]**			
		See effects of increased bioenergy use.					See increased use of biomass efects. In addition, the concern that more bioenergy (for BECCS) necessarily leads to unacceptably high food prices is not founded on large agreement in the literature. AR5, for example, finds a significantly lower effect of large-scale bioenergy deployment on food prices by mid-century than the effect of climate change on crop yields. Also, Muratori et al. (2016) show that BECCS reduces the upward pressure on food crop prices by lowering carbon prices and lowering the total biomass demand in climate change mitigation scenarios. Competition for land-use. Use of agricultural residue for bioenergy can reduce soil carbon thereby threathing agricultural productivity.					See positive impacts of increased biomass use. On the other hand, there is a non-negligible risk of CO2 leakage both from geological formations as well as from the transportation infrastructure from source to sequestration locations.					No direct interaction				
							See literature on increased biomass use and Muratori et al. (2016), IPCC AR5 (2014), Dooley,K. & Kartha,S. (2018)					IPCC AR5 WG3 (2014); Atchley et al. (2013); Apps et al. (2010); Siirila et al. (2012); Wang and Jaffe (2004); Koorneef et al. (2011); Singh et al. (2011); Hertwich et al. (2008); Veltman et al. (2010); Corsten et al.(2013)									
Advanced coal	**CCS: Fossil**											**Disease and Mortality (3.1/3.2/3.3/3.4)**									
			[0]					**[0]**				↓	**[-1]**	🕮🕮	☺☺☺	★★★		**[0]**			
		No direct interaction					No direct interaction					The use of fossil CCS imply continued adverse impacts of upstream supply-chain activities in the coal sector, and because of lower efficiency of CCS coal power plants, upstream impacts and local air pollution are likely to be exacerbated. Furthermore, there is a non-					No direct interaction				
												IPCC AR5 WG3 (2014); Atchley et al. (2013); Apps et al. (2010); Siirila et al. (2012); Wang and Jaffe (2004); Koorneef et al. (2011); Singh et al. (2011); Hertwich et al. (2008); Veltman et al. (2010); Corsten et al.(2013)									

1 NO POVERTY

		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Agriculture & Livestock	**Behavioural response: Sustainable healthy diets and reduced food waste**	**Poverty and Development (1.1/1.2/1.3/1.4)**				
		~ / ↓	**[0,-1]**	🕮🕮	☺☺☺	★★
		Cutting livestock consumption can increase food security for some if land grows food not feed, but can also undermine livelihoods and culture where livestock has long been the best use of land such as in parts of SSA.				
		IPCC WGIII, 2014				
	Land based greenhouse gas reduction and soil carbon sequestration	**Poverty and Development (1.1/1.2/1.3/1.4)**				
		↑	**[+2]**	🕮🕮🕮🕮	☺☺☺☺	★★★★
		Many climate smart agriculture interventions aim to improve rural livelihoods, thereby contributing to poverty alleviation. Agroforestry or integrated crop–livestock–biogas systems can substitute costly, external inputs, saving on household expenditures – or even lead to the selling of some of the products, providing the farmer with extra income, leading to increased adaptive capacity (Bogdanski, 2012).				
		Lipper et al. (2014), Bogdanski (2012), Branca et al. (2011), Campbell et al. (2014), Hammond et al. (2016), Mbow et al. (2013), Scherr et al. (2012), Steenwerth et al. (2014), Vermeulen et al. (2012)				
	Greenhouse gas reduction from improved livestock production and manure management systems	**Poverty reduction and minimize exposure to risk (1.5)**				
		↑	**[+2]**	🕮	☺	★
		Mixed-farming systems, can not only farmers mitigate risks by producing a multitude of commodities, but they can also increase the productivity of both crops and animals in a more profitable and sustainable way, (Quoted from Sansoucy, R. (1995))				
		Sansoucy (1995)				

2 ZERO HUNGER

		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Agriculture & Livestock	**Behavioural response: Sustainable healthy diets and reduced food waste**	**Food Security and promotion of Sustainable Agriculture(2.1/2.4/2a)**				
		↑	**[+2]**	🕮🕮🕮🕮	☺☺☺☺	★★★★
		Curbing consumer waste of major food crops (i.e., wheat, rice, and vegetables) and meats (i.e., beef, pork, and poultry) in China , USA and India alone could feed ~413 million people per year (West et al., 2014). One billion extra people could be fed if food crop losses could be halved (Kummu et al., 2012). Reducing waste, especially from meat and dairy could play a role in delivering food security and reduce the need for sustainable intensification (Smith, 2013). Dietary change toward global healthy diets could improve nutritional health, food security and reduce emissions.				
		West et al.(2014), Kummu et al. (2012), Smith, P. (2013), Beddington et al. (2012), Lamb et al. (2016), Garnett, T., 2011; Bajželj et al., 2014; Tilman & Clark, 2014)				
	Land based greenhouse gas reduction and soil carbon sequestration	**Food Security, sustainable agriculture and Improved nutrition**				
		↑	**[+2]**	🕮🕮🕮🕮	☺☺☺☺	★★★★
		Safe application of biotechnology, both conventional and mordern methods can help to improve agricultural productivity,improving crops adaptability thereby catering to food security. Reducing tillage,eliminating fallow and keeping the soil covered with residue, cover crops or perennial vegetation help prevent soil erosion and has the potential to increase Soil Organic Matter (SOC). Efficient land management techniques can help in increasing crop yield and hence food security issues can be addressed. Yield projections are actually higher for developing countries than for developed countries, reflecting the fact that they have more ‘‘catch-up’’ potential (Evenson, 1999). Action is needed throughout the food system, on moderating demand, reducing waste, improving governance and producing more food. (Godfray & Garnett, 2014). Improving cropland management is the key to increase crop productivity without further degrading soil and water resources (Branca et al., 2011). Climatee Smart Agriculture practices increases productivity and priotizes food security.				
		Mtui (2011); Harvey et al. (2014); Campbell et al. (2014); West and Post (2002); Johnson et al. (2007); Harvey et al. (2014); Evenson (1999); Godfray and Garnett (2014); Branca et al. (2011); McCarthy, Lipper, and Branca (2011); Behnassi, Boussaid, and Gopichandran (2014); Lipper et al. (2014); Steenwerth (2014)				
	Greenhouse gas reduction from improved livestock production and manure management systems	**Food Security and promotion of Sustainable Agriculture(2.1/2.4/2a)**				
		↑	**[+2]**	🕮🕮🕮🕮	☺☺☺☺	★★★★
		Fostering transitions toward more productive livestock production systems targeting land-use change appears to be the most efficient lever to deliver food availability outcomes. (Quoted from Havlík, P., et al. (2014)) Genomic selection should be able to at least double the rate of genetic gain in the dairy industry. Given the prevalence of mixed crop–livestock systems in many parts of the world, closer integration of crops and livestock in such systems can give rise to increased productivity and increased soil fertility (Thornton, 2010). Managing the indirect effects of livestock systems intensification is critical for the sustainability of the global food system: like improving productivity and their close link to land sparing (Herrero and Thornton, 2013). In East Africa pastoralists have shifted from cows to camels, which are better-adapted to survive periods of water scarcity and able to consistently provide more milk (Steenwerth et al., 2014). Scenarios where zero human-edible concentrate feed is use for livestocks soil erosion potential reduces by 12%.				
		Havlík et al. (2014); Steenwerth (2014), Thornton (2010); Herrero and Thornton (2013); Steenwerth et al. (2014); Schader et al. (2015)				

3 GOOD HEALTH AND WELL-BEING

		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Agriculture & Livestock	**Behavioural response: Sustainable healthy diets and reduced food waste**	**Tobacco Control (3.a/ 3.a.1)**				
		↑	**[+1]**	🕮	☺	★
		Consume fewer foods with low nutritional value e.g. alcohol, (Garnett, 2011). Demand-side measures aimed at reducing the proportion of livestock products in human diets, where the consumption of animal products is higher than recommended, are associated with multiple health benefits, especially in industrialized countries (Bustamante et al., 2014).				
		Garnett, T. (2011), Bustamante, M., et al. (2014)				
	Land based greenhouse gas reduction and soil carbon sequestration	**Ensure healthy lives (3.c)**				
		↑ / ↓	**[+2,-2]**	🕮🕮	☺☺	★★
		Growing crops such as cassava, sorghums and millets even in harsh conditions are important to the diets of very poor people. The policy scenarios show that reduced research support, delayed industrialization, delayed biotechnology, and climate change will delay progress in reducing malnutrition of children. The ‘‘global’’ effects are small, but local effects for some countries, e.g., Bangladesh and Nigeria, are significant (Evenson, 1999).				
		Godfray & Garnett (2014); Evenson (1999)				
	Greenhouse gas reduction from improved livestock production and manure management systems	**Ensure healthy lives (3.c)**				
		↑ / ↓	**[+2,-2]**	🕮🕮	☺☺	★★
		Bio-digestion which has positive public-health aspects, particularly where toilets are coupled with the bio-digester, and the anaerobic conditions kill pathogenic organisms as well as digest toxins. Separation processes can improve or worsen health risks related to food crops or to livestock.				
		Sansoucy (1995); Burton (2007)				

4 QUALITY EDUCATION

		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Agriculture & Livestock	**Behavioural response: Sustainable healthy diets and reduced food waste**		**[0]**			
		No direct interaction				
	Land based greenhouse gas reduction and soil carbon sequestration	**Ensure inclusive and quality education(4.4/4.7)**				
		↑ / ↓	**[+2,-2]**	🕮🕮	☺	★
		Science-based actions within CSA is required to integrate data sets and sound metrics for testing hypotheses about feedback regarding climate, weather data products and agricultural productivity, such as the nonlinearity of temperature effects on crop yield and the assessment of trade-offs and synergies that arise from different agricultural intensification strategies (Steenwerth, 2014). Low commodity prices have led to declining investment in research and development, farmer education, etc. (Lamb et al., 2016).				
		Steenwerth, K. L., (2014); Lamb, A., et al. (2016)				
	Greenhouse gas reduction from improved livestock production and manure management systems		**[0]**			
		No direct interaction				

Forest	**Reduced deforestation, REDD+**	**Poverty reduction (1.5)** ↑ [+2] 📖 ☺ ★ Partnerships between local forest managers, community enterprises and private sector companies can support local economies and livelihoods, and boost regional and national economic growth. Katila et al. (2017)	**Food Security and promotion of Sustainable Agriculture(2.1/2.4/2a)** ↑ / ↓ [+1,-2] 📖📖 ☺ ★ Food security, may lead to the conversation of productive land under forest, including community forests, into agricultural production. In a similar fashion, the production of biomass for energy purposes(SDG 7) may reduce land available for food production and/or for community forest activities Katila et al., 2017). Efforts by the Government of Zambia to reduce emissions by REDD+ have contributed erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Katila et al. (2017); Turpie, Warr, & Ingram (2015); Epstein and Theuer (2017); Dooley and Kartha (2018)	**[0]** No direct interaction	**Ensure inclusive and quality education(4.4/4.7)** ↑ [+1] 📖 ☺ ★ Local forest users learn to understand laws, regulations and policies which facilitate their participation in the society. Education and capacity building provide technical skill and knowledge (Katila et al., 2017). Katila et al. (2017)
	Afforestation and reforestation	**Poverty and Development (1.1/1.2/1.3/1.4)** ↑ / ↓ [+2,-2] 📖📖 ☺☺ ★★★ CDM-AR can have different implications on local community livelihoods. Willingness to adopt afforestation is influenced in particular by Australian landholder's perceptions of its potential to provide a diversified income stream, and its impacts on flexibility of land management (Schirmer and Bull, 2014). Land sparing would have far reaching implications for the UK countryside and would affect landowners, rural communities (Lamb et al., 2016). Livelihoods threatened if subsistence agriculture targeted (Dooley and Kartha, 2018). Zomer et al. (2008); Schirmer and Bull (2014); Lamb et al. (2016); Dooley and Kartha (2018)	**Food Security (2.1)** ↑ / ↓ [+1,-1] 📖 ☺ ★ CDM-AR can have different implications on local to regional food security and local community livelihoods. Zomer et al. (2008); Dooley and Kartha (2018)	**Ensure healthy lives (3.c)** ↑ [+1] 📖 ☺ ★ Urban trees are increasingly seen as a way to reduce harmful air pollutants and hence improve cardio-respiratory health. Jones et al. (2018)	**Promote knowledge and skill to promote SD (4.7)** ↓ [-1] 📖 ☺ ★ Most landholders reported having low levels of knowledge about tree planting for carbon sequestration–particularly available programmes, prices and markets, and government rules and regulations Schirmer and Bull, 2014). Schirmer and Bull (2014)
	Behaviourial response (responsible sourcing)	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction
Oceans	**Ocean iron fertilization**	**[0]** No direct interaction	**Food Security (2.2/2.3)** ↑ / ↓ [+1,-1] 📖📖 ☺ ★ OIF can have different implications on fish stocks and aquaculture, it might actually increase food availability for fish stocks (inceasing yields) but potentially at the cost of reducing the yields of fisheries outside the enhancement region by depleting other nutrients. Smetacek and Naqvi (2008); Lampitt et al. (2008); Williamson et al. (2012)	**[0]** No direct interaction	**[0]** No direct interaction
	Blue carbon	**Poverty and Development (1.1/1.2/1.5)** ↑ [+3] 📖📖📖 ☺☺☺ ★★★ Avoiding loss of mangroves and maintaining the 2000 stock could save a value of ecosystem services from mangroves in Southeast Asia of approximately US$2.16 billion until 2050 (2007prices), with a 95% prediction interval of US$1.58–2.76 billion (case study area South East Asia); Seaweed aquaculture will enhance carbon uptake and provide employment; traditional management systems provide benefits for blue carbon and support livelihoods for local communities; Greening of aquaculture can significantly enhance carbon storage; PES schemes could help capture the benefits derived from multiple ecosystem services beyond carbon sequestration. Zomer et al. (2008); Schirmer and Bull (2014); Lamb et al. (2016)	**Food Production (2.3/2.4)** ↑ [+3] 📖📖📖 ☺☺☺ ★★★ avoiding loss of mangroves and maintaining the 2000 stock could save a value of ecosystem services from mangroves in Southeast Asia including fisheries; Seaweed aquaculture will provide employment; traditional management systems provide livelihoods for local communities; Greening of aquaculture can increase income and well-being; Mariculture is a promising approach for China. Brander et al. (2012); Sondak et al. (2017); Vierros (2017); Ahmed et al. (2017a); Ahmed	**[0]** No direct interaction	**[0]** No direct interaction
	Enhanced Weathering	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction

		5 GENDER EQUALITY INTERACTION · SCORE · EVIDENCE · AGREEMENT · CONFIDENCE	10 REDUCED INEQUALITIES INTERACTION · SCORE · EVIDENCE · AGREEMENT · CONFIDENCE	16 PEACE, JUSTICE AND STRONG INSTITUTIONS INTERACTION · SCORE · EVIDENCE · AGREEMENT · CONFIDENCE	17 PARTNERSHIPS FOR THE GOALS INTERACTION · SCORE · EVIDENCE · AGREEMENT · CONFIDENCE
Industry	**Accelerating energy efficiency improvement**	**[0]** No direct interaction	**Knowledge and skill needed to promote sustainable development (4.7)** ↑ **[+1]** 📖 ☺☺☺ ★★★ There is need for skill in manging in house energy efficiency. Sometimes ESCOs also help. Energy audit but many a times absence of skill acts as barrier for energy efficiency improvement. In many countries especially in developing countries these act as barrier Johansson and Thollander (2018); Apeaning and Thollander (2013)	**[0]** No direct interaction	**Global Partnership (17.6, 17.7)** ↑ **[+2]** 📖📖 ☺☺☺ ★★★ Driving force for Energy efficiency is collaboration among companies, networks, experience sharing, Management tools . Sharing among countries can help accelerating managerial action. Absence of Information, budgetary funding, lack of access to capital etc. play important barrier to advance action. Cooperation at various levels e.g. value chain collaboration can open up with need for accelerating action. Johansson and Thollander (2018); Apeaning and Thollander (2013); Lawrence et al (2018); Griffin et al. (2017)
	Low-carbon fuel switch	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**Global Partnership (17.6, 17.7)** ↑ **[+2]** 📖 ☺☺ ★★ Ultra low carbon steel making and breakthrough technologies are under trial across many countries and helping in enhancing the learning. Quader et al (2016)
	Decarbonisation/ CCS/CCU	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**Global Partnership (17.6, 17.7)** ↑ **[+2]** 📖 ☺☺☺ ★★★ EPI plants are capital intensive and are mostly operated by multinational with long investment cycles. In developed countries new innovation investments are happening in brown fields . Such large innovation investmets need strong collaboration among partners/competitors which can be facilitated by public fund. They happen at national ,supra national scale, across sectors, needs fresh revisit at IPR issues. Global production of biobased polymers increase need public support, incentive to push forward. Wesseling et al. (2017); Griffin et al. (2017)
Buildings	**Behaviorial response**	**[0]** No direct interaction	**[0]** No direct interaction	**Environmental justice (16.7)** ↑ **[+2]** 📖 ☺ ★ Hult et al. found that consumption perspective strengthens the environmental justice discourse (as it claims to be a more just way of calculating global and local environmental effects) while possibly also increasing the participatory environmental discourse. Hult and Larsson (2016)	**[0]** No direct interaction
	Accelerating energy efficiency improvement	**Gender equality and Women empowerment (5.1, 5.4)** ↑ **[+1]** 📖 ☺☺ ★★ Efficient cookstoves lead to empowerment of rural and indigenous women. Berrueta et al. (2017); Bhojvaid Vasundhara et al. (2014)	**Empowerment and Inclusion (10.1/10.2/10.3/10.4)** ↑ / ↓ **[1,-1]** 📖📖📖 ☺☺☺ ★★★ Energy efficiency measures and the provision of energy access can free up resources that can then be put towards other productive uses (e.g., educational and employment opportunities), especially for women and children in poor, rural areas. The distributional costs of new energy policies are dependent on instrument design. If costs fall disproportionately on the poor, then this could work against the promotion of social, economic and political equality for all. The impacts of energy efficiency measures and policies on inequality can be both positive, if they reduce energy costs, or negative, if mandatory standards increase the need for purchasing more expensive equipment and appliances. McCollum et al. (2018); Cameron et al. (2016); Casillas and Kammen (2012); Fay et al. (2015); Hallegate et al. (2016); Hirth and Ueckerdt (2013); Jakob and Steckel (2014); Cayla and Osso (2013); Dinkelman (2011); Pachauri et al. (2012); Pueyo et al. (2013)	**Institutional Capacity and Accountability (16.1/16.3/16.5/16.6/16.7/16.8)** ↑ **[+2]** 📖📖📖 ☺☺☺ ★★★★ Institutions that are effective, accountable, and transparent are needed at all levels of government (local to national to international) for providing energy access, promoting modern renewables, and boosting efficiency. Strengthening the participation of developing countries in international institutions (e.g., international energy agencies, United Nations organizations, World Trade Organization, regional development banks and beyond) will be important for issues related to energy trade, foreign direct investment, labor migration, and knowledge and technology transfer. Reducing corruption, where it exists, will help these bodies and related domestic institutions maximize their societal impacts. Limiting armed conflict and violence will aid most efforts related to sustainable development, including progress in the energy dimension. McCollum et al. (2018); Acemoglu (2009); Acemoglu et al. (2014); ICSU, ISSC (2015); Tabellini (2010)	**Enhance Policy Coherence for Sustainable Development (17.4)** ↑ **[+2]** 📖 ☺ ★ Implementing refrigerant transition and energy efficiency improvement policies in parallel for room ACs, roughly doubles the benefit of either policy implemented in isolation Shah et al (2015)
	Improved access & fuel switch to modern low-carbon energy	**Women's Safety & Worth (5.1/5.2/5.4) / Opportunities for Women (5.1/5.5)** ↑ **[+1]** 📖📖 ☺☺ ★★ Improved access to electric lighting can improve women's safety and girls' school enrollment. Cleaner cooking fuel and lighting access can reduce health risks and drudgery, which are disproportionately faced by women. Access to modern energy services has the potential to empower women by improving their income-earning and entrepreneurial opportunities and reducing drudgery. Participating in energy supply chains can increase women's opportunities and agency and improve business outcomes (McCollum et al., 2018). McCollum et al. (2018); Anenberg et al. (2013); Chowdhury (2010); Haves (2012); Matinga (2012); Pachauri and Rao (2013); Chowdhury (2010); Clancy et al (2011); Dinkelman (2011); Haves (2012); Kaygusuz (2011); Kohlin et al. (2011); Pachauri and Rao (2013); Burney J., Alaofè H., Naylor R., Taren D. (2017)	**[0]** No direct interaction	**Institutional Capacity and Accountability (16.1/16.3/16.5/16.6/16.7/16.8)** ↑ **[+2]** 📖📖📖 ☺☺☺ ★★★★ Institutions that are effective, accountable, and transparent are needed at all levels of government (local to national to international) for providing energy access, promoting modern renewables, and boosting efficiency. Strengthening the participation of developing countries in international institutions (e.g., international energy agencies, United Nations organizations, World Trade Organization, regional development banks and beyond) will be important for issues related to energy trade, foreign direct investment, labor migration, and knowledge and technology transfer. Reducing corruption, where it exists, will help these bodies and related domestic institutions maximize their societal impacts. Limiting armed conflict and violence will aid most efforts related to sustainable development, including progress in the energy dimension. McCollum et al. (2018); Acemoglu (2009); Acemoglu et al. (2014); ICSU, ISSC (2015); Tabellini (2010)	**Promote transfer and diffusion of technology (17.6,17.7)** ↑ **[+2]** 📖 ☺ ★ Green building technology in Kazakhstan was based on transfer of knowledge among various parties. Kim et al (2017)

Transport	**Behavioural response**	**Recognize Women's unpaid Work (5.1/5.4) / Opportunities for Women (5.1/5.5)** ↑ **[+1]** 🕮🕮 ☺☺ ★★ The average woman's trip to work differs markedly from the average man's. Working-poor mothers rely on extensive social networks creating communities of spatial necessity, bartering for basic needs to overcome transportation constraints.Women earn lower wages and so are less likely to justify longer commutes. Many women need to manage dual roles as workers and mothers. Women tend to perform multi-purpose commuting, combining both work and household needs . Rogalsky, 2010; Crane, 2007	**Reduce Inequality (10.2)** ↑ **[+2]** 🕮🕮 ☺☺ ★★ The equity impacts of climate change mitigation measures for transport, and indeed of transport policy intervention overall, are poorly understood by policymakers. This is in large part because standard assessment of these impacts is not a statutory requirement of current policy making. Managing transport energy demand growth will have to be advanced alongside efforts in passenger travel toward reducing the deep inequalities in access to transport services that currently affect the poor worldwide.Free provision of roads and parking spaces converts vast amounts of public land and capital into underpriced space for cars, in extreme cases like Los Angeles, CA, roads and streets free for parking and driving are 20% of land area, as governments give drivers free land people drive more than they would otherwise. High levels of car dependence, and the costs of motoring can be burdensome, and lead to increasing debt, raising questions of affordability for households with limited resources, particularly low-income houses located in suburban areas. Lucas and Pangbourne (2014); Figueroa et al. (2014); Manville (2017); Walks (2015); Belton et al. (2017)	**Accountable and transparent institutions at all levels (16.6, 16.8)** ↑ / ↓ **[+1, -1]** 🕮 ☺ ★ With behaviourial change towards walking for short distance pedestrian safety on the road might reduce unless public policy is appropriately formulated. Prevalence of high level of tripple forms of informality of jobs, housing and transportation are responsible for low productivity and low standards of living as major challenge for policies targeting urban growth in Latin America. Partnership on Sustainable Low Carbon Transport (2017); Corporacion Andina de Fomento (2017)	**Help promote global partnership(17.1, 17.3,17.5,17.6,17.7)** ↑ **[+2]** 🕮 ☺ ★ Projects aiming at resilient transport infrastructure development (e.g. C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are happening through multistakeholder coalition Partnership on Sustainable Low Carbon Transport (2017)
	Accelerating energy efficiency improvement	**[0]** No direct interaction	**[0]** No direct interaction	**Ensure responsive, inclusive, participatory decision making (16.7)** ↑ **[+2]** 🕮🕮 ☺☺ ★★ In transport mitigation is necessartb to conduct need assessment and stakeholder consultation to determine plausible challenges, prior to introducing a desired planning reforms. Further, the involved personnel should actively engage transport-based stakeholders during policy identification and its effective implementation to achieve desired results. User behaviour and stakeholder integration is key for successful transport policy implementation Aggarwal, 2017, AlSabbagh, Siu, Guehnemann, & Barrett (2017)	**Help promote global partnership(17.1, 17.3,17.5,17.6,17.7)** ↑ **[+2]** 🕮 ☺ ★ Projects aiming at resilient transport infrastructure development and technology adoption (e.g. C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are happening through multistakeholder coalition Partnership on Sustainable Low Carbon Transport (2017)
	Improved access & fuel switch to modern low-carbon energy	**[0]** No direct interaction	**Reduce Inequality (10.2)** ↑ **[+2]** 🕮🕮 ☺☺ ★★ The equity impacts of climate change mitigation measures for transport, and indeed of transport policy intervention overall, are poorly understood by policymakers. This is in large part because standard assessment of these impacts is not a statutory requirement of current policy making. Managing transport energy demand growth will have to be advanced alongside efforts in passenger travel toward reducing the deep inequalities in access to transport services that currently affect the poor worldwide. Lucas & Pangbourne, 2014; Figueroa et al. (2014)	**Ensure responsive, inclusive, participatory decision making (16.7)** ↑ / ↓ **[+1, -1]** 🕮 ☺ ★ Formal transport infrastrcuture improvement in many cities in developing countries lead to eviction from infromal settlements which need appropriate redistributive policies and cooperation and partnership with all. Colenrander et al 2017)	**Help promote global partnership(17.1, 17.3,17.5,17.6,17.7)** ↑ **[+2]** 🕮 ☺ ★ Projects aiming at resilient transport infrastructure development (e.g. C40 Cities Clean Bus Declaration, UITP Declaration on Climate Leadership, Cycling Delivers on the Global Goals, Global Sidewalk Challenge) are happening through multistakeholder coalition Partnership on Sustainable Low Carbon Transport (2017)

		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Replacing coal	**Non-biomass renewables**					
	solar, wind, hydro	↑	**[+1]**	🕮	☺	★
		Decentralized renewable energy systems (e.g., home- or village-scale solar power) can reduce the burden on girls and women of procuring traditional biomass.				
		Schwerhoff G., Sy M. (2017)				
	Increased use of biomass		**[0]**	No direct interaction		
	Nuclear/Advanced Nuclear		**[0]**	No direct interaction		
	CCS: Bio energy		**[0]**	No direct interaction		
Advanced coal	**CCS: Fossil**		**[0]**	No direct interaction		

		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Replacing coal	**Non-biomass renewables**	**Empowerment and Inclusion (10.1/10.2/10.3/10.4)**				
	solar, wind, hydro	↑	**[+1]**	🕮🕮	☺☺	★★
		Decentralized renewable energy systems (e.g., home- or village-scale solar power) can enable a more participatory, democratic process for managing energy-related decisions within communities. (Quote from McCollum et al., 2018)				
		McCollum et al. (2018); Cass et al. (2010); Cumbers (2012); Kunze and Becker (2015); Walker and Devine-Wright (2008)				
	Increased use of biomass		**[0]**	No direct interaction		
	Nuclear/Advanced Nuclear		**[0]**	No direct interaction		
	CCS: Bio energy		**[0]**	No direct interaction		
Advanced coal	**CCS: Fossil**		**[0]**	No direct interaction		

		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Replacing coal	**Non-biomass renewables**	**Energy justice**				
	solar, wind, hydro	↑	**[+2]**	🕮	☺	★
		The energy justice framework serves as an important decision-making tool in order to understand how different principles of justice can inform energy systems and policies. Islar et al. (2017) states that off-grid and micro-scale energy development offers an alternative path to fossil-fuel use and top-down resource management as they democratize the grid and increase marginalized communities' access to renewable energy, education and health care.				
		Islar et al. (2017)				
	Increased use of biomass		**[0]**	No direct interaction		
	Nuclear/Advanced Nuclear	**Reduce illicit arms trade (16.4)**				
		↓	**[-1]**	🕮🕮	☺☺	★★
		Continued use of nuclear power poses a constant risk of proliferation.				
		IPCC AR5 WG3 (2014); von Hippel et al. (2011, 2012); Sagan (2011); Yim and Li (2013); Adamantiades and Kessides (2009); Rogner (2010).				
	CCS: Bio energy		**[0]**	No direct interaction		
Advanced coal	**CCS: Fossil**		**[0]**	No direct interaction		

		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Replacing coal	**Non-biomass renewables**	**International Cooperation (all goals)**				
	solar, wind, hydro	↑ / ~	**[+2,0]**	🕮🕮	☺☺	★★
		International cooperation (in policy) and collaboration (in science) is required for the protection of shared resources. Fragmented approaches have been shown to be more costly. Specific to SDG7, to achieve the targets for energy access, renewables, and efficiency, it will be critical that all countries: (i) are able to mobilize the necessary financial resources (e.g., via taxes on fossil energy, sustainable financing, foreign direct investment, financial transfers from industrialized to developing countries); (ii) are willing to disseminate knowledge and share innovative technologies between each other; (iii) follow recognized international trade rules while at the same time ensuring that the least developed countries are able to take part in that trade; (iv) respect each other’s policy space and decisions; (v) forge new partnerships between their public and private entities and within civil society; and (vi) support the collection of high-quality, timely, and reliable data relevant to the furthering their missions. There is some disagreement in the literature on the effect of some of the above strategies, such as free trade. Regarding international agreements, ""no-regrets options"", where all sides gain through cooperation, are seen as particularly beneficial (e.g., nuclear test ban treaties) (McCollum et al., 2018).				
		McCollum et al. (2018); Clarke et al. (2009); Eis et al. (2016); Montreal Protocol (1989); New Climate Economy (2015); O'Neill et al. (2017); Ramaker et al. (2003); Riahi et al. (2015); Riahi et al. (2017)				
	Increased use of biomass		**[0]**	No direct interaction		
	Nuclear/Advanced Nuclear		**[0]**	No direct interaction		
	CCS: Bio energy		**[0]**	No direct interaction		
Advanced coal	**CCS: Fossil**		**[0]**	No direct interaction		

		5 GENDER EQUALITY					10 REDUCED INEQUALITIES				
		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE	INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Agriculture & Livestock	**Behaviourial response: Sustainable healthy diets and reduced food waste**		**[0]**	No direct interaction				**[0]**	No direct interaction		
	Land based greenhouse gas reduction and soil carbon sequestration	**Equal access, empowerment of women (5.5)**					**Empower economic and political inclusion of all, irrespective of sex (10.2)**				
		↑ / ~	**[+2,0]**	🕮🕮	☺☺	★★★	↑ / ~	**[+1,0]**	🕮🕮	☺☺	★★
		Many programmes for climate smart agriculture have been used to empower women and to improve gender equality. Women often have an especially important role to play in adaptation, because of their gendered indigenous knowledge on matters such as agriculture (Terry, 2009). Without access to land, credit and agricultural technologies, women farmers face major constraints in their capacity to diversify into alternative livelihoods (Demetriades and Esplen, 2008).					In many rural societies women are sidelined from decisions regarding agriculture even when male household heads are absent, and they often lack access to important inputs such as irrigation water, credit, tools, and fertiliser. To be effective, agricultural mitigation strategies need to take these and other aspects of local gender relations into account (Terry, 2009). Women's key role in maintaining biodiversity, through conserving and domesticating wild edible plant seed, and in food crop breeding, is not sufficiently recognised in agricultural and economic policy-making; nor is the importance of biodiversity to sustainable rural livelihoods in the face of predicted climate changes (Nelson et al., 2002).				
		Bernier et al (2013); Demetriades and Esplen (2008); Terry (2009); Nelson et al. (2002); Denton (2002); Jost et al. (2015); Morton (2007)					Terry (2009); Nelson et al (2002); Demetriades and Esplen (2008)				
	Greenhouse gas reduction from improved livestock production and manure management systems	**Equal access to economic resources, promote empowerment of women (5.5/5.a/5.b)**					**Empower economic and political inclusion of all, irrespective of sex (10.2)**				
		↑ / ~	**[+2,0]**	🕮	☺	★	↑ / ~	**[+1,0]**	🕮	☺	★
		Most of the animal farming activities such as fodder collection, feeding, are performed by women. Besides, considerable involvement and contribution of women, considerable gender inequalities also exist in Indian villages in terms of accessing natural resources, extension services, marketing opportunities and financial services as well as in exercising their decision-making powers. Therefore, there is a need to correct gender bias in livestock sector. Efforts are needed to increase the capacity of women to negotiate with confidence and meet their strategic needs.Access, control and management of small ruminants, grazing areas and feed resources empower women and lead to an overall positive impact on the welfare of the household.					Livestock ownership is increasing women's decision-making and economic power within both the household and the community. Access, control and management of small ruminants, grazing areas and feed resources empower women and lead to an overall positive impact on the welfare of the household.				
		Patel et al (2016)					Patel et al (2016)				

		16 PEACE, JUSTICE AND STRONG INSTITUTIONS					17 PARTNERSHIPS FOR THE GOALS				
		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE	INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Agriculture & Livestock	**Behaviourial response: Sustainable healthy diets and reduced food waste**	**Strong and effective institutions and responsive decision making (16.6/ 16.7 / 16.a)**					**Resource mobilization and Strenghten Partnership (17.1/17.14)**				
		↑ / ↓	**[+1,-1]**	🕮🕮🕮	☺☺	★★	↑ / ↓	**[+1,-1]**	🕮	☺	★
		Appropriate incentives to reduce food waste may require some policy innovation and experimentation, but a strong commitment for devising and monitoring them seems essential. (Quoted from Bajželj et al.(2014)) A financial incentive to minimise waste could be created through effective taxation (e.g. by taxing foods with the highest wastage rates, or by increasing taxes on waste disposal). Decision makers should try to integrate agricultural, environmental and nutritional objectives through appropriate policy measures to achieve sustainable healthy diets coupled with reduction in food waste. It is surprising that politicians and policy makers demonstrate little regarding the need of having strategies to reduce meat consumption and to encourage more sustainable eating practices in Netherlands.					Decision makers should try to integrate agricultural,environmental and nutritional objectives through appropriate policy measures to achieve sustainable healthy diets coupled with reduction in food waste. It is surprising that politicians and policy makers demonstrate little regarding the need of having strategies to reduce meat consumption and to encourage more sustainable eating practices in Netherlands.				
		Bajželj et al.(2014); Lamb et al. (2016); Garnett (2011); Dagevos and Voordouw (2013)					Garnett (2011); Dagevos and Voordouw (2013)				
	Land based greenhouse gas reduction and soil carbon sequestration	**Build effective, accountable and inclusive institutions (16.6/ 16.7/16.8)**					**Resource mobilization and Strenghten multi-stakeholder Partnership**				
		~ / ↓	**[0,-1]**	🕮🕮🕮	☺☺	★★	↑	**[+2]**	🕮🕮🕮	☺☺☺	★★★
		Action is needed throughout the food system for improving governance and producing more food (Godfray and Garnett, 2014). CSA requires policy intervention for careful adjustment of agricultural practices to natural conditions, a knowledge-intensive approach, huge financial investment etc, so having strong institutional framework is very important. The main source of climate finance for CSA in developing countries is the public sector. Lack of institutional capacity (as a means for securing creation of equal institutions amongsocial groups and individuals) can reduce feasibility of AFOLU mitigation measures in the near future, especially in areas where small-scale farmers or forest users are the mainstakeholders (Bustamante, 2014).					Climate Smart Agriculture requires more careful adjustment of agricultural practices to natural conditions, a knowledge-intensive approach, huge financial investment, and policy and institutional innovation, etc. Besides private investment quality of public investment is also important. (Behnass et al., 2014). Sources of climate finance for CSA in developing countries, including bilateral donors, multilateral financial institutions besides public sector finance. CSA is committed to new ways of engaging in participatory research and partnerships with producers (Steenwerth, 2014).				
		Godfray and Garnett (2014); Behnassi, Boussaid and Gopichandran (2014); Steenwerth (2014); Lipper et al. (2014); Bustamante (2014)					Behnassi, Boussaid and Gopichandran (2014); Lipper et al. (2014); Steenwerth (2014)				
	Greenhouse gas reduction from improved livestock production and manure management systems	**Responsible decision making (16.7)**					**Improve domestic capacity for tax collection (17.1)**				
		↑	**[+1]**	🕮	☺	★	↑	**[+2]**	🕮🕮	☺☺	★★
		To minimize the economic and social cost, policies should target emissions at their source—on the supply side—rather than on the demand side as supply-side policies have lower calorie cost than demand-side policies.The role of livestock system transitions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies.					The role of livestock system transitions in emission reductions depends on the level of the carbon price and which emissions sector is targeted by the policies (Havlík et al., 2014). Mechanisms for effecting behavioral change in livestock systems need to be better understood by implementing combinations of incentives and taxes simultaneously in different parts of the world (Herrero and Thornton, 2013).				
		Havlík, P., et al. (2014)					Havlík,et al. (2014); Herrero and Thornton (2013)				

Forest	**Reduced deforestation, REDD+**	**Opportunities for Women (5.1/5.5)** ↑ / ↓ **[+1,-1]** 📖 ☺ ★ Women have been less involved in REDD+ initiative (pilot project) design decisions and processes than men. Girls and women have an important role in forestry activities, related to fuel-wood, forest-food and medicine. Their empowerment contributes to sustainable forestry as well as reducing inequality (Katila et al., 2017). Brown (2011); Larson et al. (2015); Katila et al. (2017)	**Reduced inequality, empowerment and inclusion (10.1/10.2/10.3/10.4)** ↑ **[+2]** 📖 ☺ ★ Urges developed country to support, through multilateral and bilateral channels, the development of REDD+ national strategies or action plans and implementation (Lima et al., (2017).Girls and women have an important role in forestry activities, related to fuel-wood, forest-food and medicine. Their empowerment contributes to sustainable forestry as well as reducing inequality (Katila et al., 2017). Lima et al. (2017); Katila et al. (2017)	**Build effective, accountable and inclusive institutions, Responsible decision making (16.6/ 16.7/16.8)** ↑ **[+2]** 📖📖 ☺☺☺ ★★★ Institutional building (National Forest Monitoring Systems, Safeguard Information Systems, etc.), with full and effective participation of all relevant countries (Lima et al., 2017). REDD+ actions also deliver non-carbon benefits (e.g. local socioeconomic benefits, governance improvements, Lima et al., 2015). Forest governance is another central aspect in recent studies, including debate on decentralization of forest management, logging concessions in public owned commercially valuable forests, and timber certification, primarily in temperate forests (Bustamante et al., 2014). Lima et al. (2017); Lima et al. (2015); Bustamante et al. (2014)	**Resource mobilization and Strenghten multi-stakeholder Partnership (17.1/ 17.3/17.5/17.17)** ↑ / ↓ **[+1,-1]** 📖 ☺ ★ To provide finance and technology to developing countries to support emissions reductions. Be supported by adequate and predictable financial and technology support, including support for capacity-building (Lima et al., 2017). Partnerships in the form of significant aid money from, e.g., Norway, other bilateral donors, and the World Bank's Forest Carbon Partnership Facility (FCPF) are forthcoming (Andrew, 2017). Estimates of opportunity cost for REDD are very low. Lower costs and/or higher carbon prices could combine to protect more forests, including those with lower carbon content. Conversely, where the cost of action is high, a large amount of additional funding would be required for the forest to be protected (Miles and Kapos, 2008). Forest governance is another central aspect in recent studies, including debate on decentralization of forest management, logging concessions in public owned commercially valuable forests, and timber certification, primarily in temperate forests (Bustamante et al., 2014). Partnerships betewen local forest managers, community enterprises and private sector companies can support local economies and livelihoods, and boost regional and national economic growth (Katila et al., 2017). Lima et al. (2017); Andrew (2017); Miles and Kapos (2008); Bustamante et al. (2014); Katila et al. (2017)
	Afforestation and reforestation	**Opportunities for Women (5.1/5.5)** ↑ **[+1]** 📖 ☺ ★ Many women in developing countries are already prominently engaged in economic sectors related to climate adaptation and mitigation efforts such as agriculture, renewable energy, forest management and are important drivers and leaders in climate responses that are innovative and effective, benefitting not only their families but their larger communities as well. Women's participation in the decision-making process of forest management, for example, has been shown to increase rates of reforestation while decreasing the illegal extraction of forest products UNDESA, 2016	**Empower economic and political inclusion of all, irrespective of sex (10.2)** ↑ **[+1]** 📖 ☺ ★ Women's participation in the decision-making process of forest management, for example, has been shown to increase rates of reforestation while decreasing the illegal extraction of forest products. UNDESA, 2016	**Responsible decision making (16.7)** ↑ **[+1]** 📖 ☺ ★ Land-related mitigation, such as biofuel production, as well as conservation and reforestation action can increase competition for land and natural resources so these measures should be accompanied by complementary policies.(Quoted from Epstein, A. H., & Theuer, S. L. H. (2017)) Epstein and Theuer (2017)	**Resource mobilization and Strenghten Partnership (17.1/17.14)** ↑ **[+2]** 📖📖 ☺☺ ★★ Financing at the national and international level is required to grow more seedlings/sapling, restore land, create awareness education factsheets, providing training of local communities regarding the benefits of af-forestation and reforestation. Article 12 of the Kyoto Protocol further sets a Clean Development Mechanism through which countries in Annex I earn 'certified emissions reductions' through projects implemented in developing countries (Montanarella and Alva, 2015). Afforestation and reforestation in India are being carried out under various programmes, namely social forestry initiated in the early 1980s, Joint Forest Management Programme initiated in 1990, afforestation under National Afforestation and Eco-development Board (NAEB) programmes since 1992, and private farmer and industry initiated plantation forestry. If the current rate of afforestation and reforestation is assumed to continue, the carbon stock could increase of 11% by 2030 (Ravindranath, Chaturvedi, and Murthy, 2008). Kibria, G. (2015); Montanarella and Alva (2015); Ravindranath, Chaturvedi, and Murthy (2008)
	Behaviourial response (responsible sourcing)	**[0]** No direct interaction	**[0]** No direct interaction	**Responsible decision making (16.7)** ↑ **[+1]** 📖📖 ☺☺ ★★ Indonesian factories may seek advantages through non-price competition—perhaps by highlighting decent working conditions or the existence of a union—or to see trade associations or government agencies promoting the country as a responsible sourcing location (Bartley, 2010). In the absence of domestic legal instruments providing incentives to improve sustainability of sourcing, it appears that initiatives to engage the major importing enterprises in developing responsible sourcing practices and policies is a practical approach. Unless initiatives involve all the major importers, they are unlikely to be successful since the high costs associated with accreditation would increase production costs for these firms relative to their competitors (Huang, Wilkes, Sun and Terheggen, 2013). Bartley (2010); Huang, Wilkes, Sun and Terheggen (2013)	**Finance and trade (17.1/17.10)** ↑ **[+1]** 📖📖 ☺☺ ★★ Private certification initiatives for wood product and biomass sourcing may extend their schemes with criteria for "leakage" (external GHG effects).Also Recycling of waste wood in pellets is not yet practiced, due to unclear rules in the EU Waste Directive about overseas shipping (Sikkema et al., 2014). Engagement of Chinese government and private sector stakeholders in supply country sustainability initiatives may be the best way to support this gradual process of improvement. Although carrying out due diligence in timber sourcing can require considerable internal resources, it may be substantially less of a financial burden than the potential fines and reputational damage resulting from sourcing unknown or controversial timber (Huang, Wilkes, Sun and Terheggen, 2013). Sikkema et al. (2014); Huang, Wilkes, Sun, and Terheggen (2013)
Oceans	**Ocean iron fertilization**	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction
	Blue carbon	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction
	Enhanced Weathering	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction

		6 CLEAN WATER AND SANITATION					12 RESPONSIBLE CONSUMPTION AND PRODUCTION					14 LIFE BELOW WATER					15 LIFE ON LAND				
		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE	INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE	INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE	INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Industry	**Accelerating energy efficiency improvement**	**Water efficiency and pollution prevention (6.3/6.4/6.6)**					**Sustainable and Efficient resource (12.2,12.5, 12.6, 12.7 , 12 a)**														
		↑ / ↓	[+2,-1]	🕮🕮	☺☺	★★	↑	[+1]	🕮🕮🕮	☺☺☺	★★★		[0]					[0]			
		Efficiency and behavioural changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment. Likewise, reducing material inputs for industrial processes through efficiency and behavioural changes will reduce water inputs in the material supply chains. In extractive industries there can be a trade off with production unless strategically managed.and wastewater, resulting in more clean water for other sectors and the environment. In extractive industries there is trade off unless strategically managed. Behavioral changes in the industrial sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in industrial demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment.					Once started leads to chain of actions within the sector and policy space to sustain the effort. Help in expansion of sustianable industrial production (Ghana)					No direct interaction					No direct interaction				
		Vassolo and Doell (2005); Fricko et al. (2016); Holland et al. (2016); Nguyen et al (2014)					Apeaning and Thollandar (2013); Fernando et al. (2017)														
	Low-carbon fuel switch	**Water efficiency and pollution prevention (6.3/6.4/6.6)**					**Sustainable production (12.2.,12.3, 12.a)**										**Sustainable production (15.1,15.5,15.9,15.10)**				
		↑ / ↓	[+2,-2]	🕮🕮	☺☺	★★★	↑	[+2]	🕮🕮🕮🕮	☺☺☺☺	★★★★		[0]				↑	[+1,-1]	🕮	☺	★
		A switch to low-carbon fuels can lead to a reduction in water demand and wastewater if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as e.g., biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock.					Circular economy instead of liner global economy can achieve climate goal and can help in economic growth through industrialisation which saves on resources, enviornment and supports small, edium and even large industries, can lead to employment generation. so new regulations, incentives, tax regime can help in achieving the goal especially in newly emerging developing cpuntries although applicable for large indsutrialised countries also.					No direct interaction					Circular economy instead of linear global economy can achieve climate goal and can help in economic growth through industrialisation which saves on resources, enviornment and supports small, medium and even large industries, can lead to employment generation. so new regulations, incentives, tax regime can help in achieving the goal especially in newly emerging developing countries although applicable for large indsutrialised countries also.				
		Hejazi et al. (2015); Song et al. (2016); Fricko et al. (2016)					Supino et al. (2015); Fan et al. (2017); Leider et al. (2015); Zheng et al. (2016); Shi et al.										Shi et al. (2017)				
	Decarbonisation/ CCS/CCU	**Water efficiency and pollution prevention (6.3/6.4/6.6)**					**Sustainable production and consumption (12.1,12.6 12.a)**					**Conserve and Sustainably use ocean (14.1, 14.5)**									
		↑ / ↓	[+1,-1]	🕮🕮🕮	☺	★★	↑	[+2]	🕮	☺☺☺☺	★★★★	~	[-1]	🕮	☺	★		[0]			
		CCU/S requires access to water for cooling and processing which could contribute to localized water stress. CCS/U process can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration.					EPI plants are capital intensive and are mostly operated by multinational with long investment cycles. In developed countries new investments are happening in brown fields , while in developing countries these are in green fields. Collaboration among partners and user demand change, policy change are essential for encouraging these large risky investments.					CCU/S in chemical industry faces challenge for transport cost and storage. In UK cluster region have been identified fro storage under sea.					No direct interaction				
		Meldrum et al. (2013); Fricko et al. (2016); Byers et al. (2016); Brandl et al. (2017)					Wesseling et al. (2017)					Griffin et al (2017)									
Buildings	**Behaviorial response**	**Water efficiency and pollution prevention (6.3/6.4/6.6)**					**Responsible and sustainable consumption**														
		↑	[+2]	🕮🕮	☺☺☺	★★★	↑	[+2]	🕮🕮🕮	☺☺☺	★★★		[0]					[0]			
		Behavioral changes in the residential sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in residential demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment.					Technological improvements alone are not sufficient to increase energy savings. Zhao et al. (2017) findings indicate that building technology and occupant behaviors interact with each other and finally affect energy consumption from home. They found that occupant habits could not take advantage of more than 50 percent of energy efficiency potential allowed by an efficient building. In the electronic segment product obsolescence represents a key challenge for sustainability. Echegaray (2015) discusses the dissonance between consumers' product durability experience, orientations to replace devices before terminal technical failure, and perceptions of industry responsibility and performance. The results from their urban sample survey indicate that technical failure is far surpassed by subjective obsolescence as a cause for fast product replacement. At the same time Liu, Oosterveer, and Spaargaren (2017) suggest that we need to go beyond individualist and structuralist perspectives to analyse sustainable consumption (i.e. combines both human agency paradigm and social structural perspective).					No direct interaction					No direct interaction				
		Bartos and Chester (2014); Fricko et al. (2016) Holland et al. (2016)					Zhao et al. (2017); Somerfeld, Buys, and Vine (2017); Isenhour and Feng (2016); He, Xiong,														
	Accelerating energy efficiency improvement	**Water efficiency and pollution prevention (6.3/6.4/6.6)**					**Sustainable Practices and Lifestyles (12.6/12.7/12.8)**										**Reduced deforestation (15.2)**				
		↑	[+2]	🕮🕮🕮	☺☺☺	★★★	↑	[+1]	🕮🕮🕮	☺☺☺	★★★		[0]				↑	[+2]	🕮🕮	☺☺☺	★★★
		Efficiency changes in the residential sector that lead to reduced energy demand can lead to reduced requirements on energy supply. As water is used to convert energy into useful forms, the reduction in residential demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment. A switch to low-carbon fuels in the residential sector can lead to a reduction in water demand and wastewater if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as e.g., biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. 'As water is used to convert energy into useful forms, energy efficiency is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment. Subsidies for renewables are anticipated to lead to the benefits and tradeoffs outlined when deploying renewables. Subsidies for renewables could lead to improved water acccess and treatment if subsidies support projects that provide both water and energy services (e.g., solar desalination).					Sustainable practices adopted by public and private bodies in their operations (e.g., for goods procurement, supply chain management, and accounting) create an enabling environment in which renewable energy and energy efficiency measures may gain greater traction (McCollum et al., 2018).					No direct interaction					Improved cook stove help halting deforestation in rural India				
		Hendrickson et al. (2014); Bartos and Chester (2014); Fricko et al. (2016); Holland et al. (2016); Bartos and Chester (2014); Bilton et al. (2011); Scott et al. (2011); Kumar et al. (2012); Kern et al. (2014); Meldrum et al. (2014); Kim et al (2017)					McCollum et al. (2018); CDP (2015); European Climate Foundation (2014); Khan et al. (2015); New Climate Economy (2015); Stefan and Paul (2008)										Bhojvaid Vasundhara et al. (2014)				
	Improved access & fuel switch to modern low-carbon energy	**Access to improved water and sanitation (6.1/6.2), Water efficiency and pollution**					**Sustainable use and management of natural resource (12.2)**										**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)**				
		↑ / ↓	[+2,-1]	🕮🕮	☺☺	★★★	↑ / ↓	[+2,-1]	🕮🕮	☺☺	★★★		[0]				↑	[+2]	🕮🕮	☺☺☺	★★★
		A switch to low-carbon fuels in the residential sector can lead to a reduction in water demand and wastewater if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as e.g., biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. Improved access to energy can support clean water and sanitation technologies. If energy access is supported with water-inensive energy sources, there could be tradeoffs with water efficiency targets.					A switch to low-carbon fuels in the residential sector can lead to a reduction in water demand and wastewater if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as e.g., biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. Improved access to energy can support clean water and sanitation technologies. If energy access is supported with water-inensive energy sources, there could be tradeoffs with water efficiency targets.					No direct interaction					Ensuring that the world's poor have access to modern energy services would reinforce the objective of halting deforestation, since firewood taken from forests is a commonly used energy resource among the poor (McCollum et al., 2018).				
		Hejazi et al. (2015); Song et al. (2016); Fricko et al. (2016); Rao and Pachauri (2017); Cibin et al. (2016)					Hejazi et al. (2015); Song et al. (2016); Fricko et al. (2016); Rao and Pachauri (2017); Cibin et al. (2016)										McCollum et al. (2018); Bailis et al. (2015); Bazilian et al (2011); Karekezi et al. (2012); Winter et al. (2015)				

Transport	**Behavioural response**	**Water efficiency and pollution prevention (6.3/6.4/6.6)** ↑ **[+2]** 📖📖 ☺☺ ★★ Behavioral changes in the transport sector that lead to reduced transport demand can lead to reduced transport energy supply. As water is used to produce a number of important transport fuels, the reduction in transport demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment. Vidic et al. (2013); Tiedemann et al. (2016); Fricko et al. (2016); Holland et al. (2016)	**Ensure Sustainable Consumption& Production patterns (12.3)** ↑ **[+2]** 📖📖 ☺☺ ★★ Urban carbon mitigation must consider the supply chain management of imported goods, the production efficiency within the city, the consumption patterns of urban consumers, and the responsibility of the ultimate consumers outside the city. Important for climate policy of monitoring the CO2 clusters that dominate CO2 emissions in global supply chains because they offer insights on where climate policy can be effectively directed. Lin et al. (2015); Kagawa et al. (2015); Felix et al (2016)	**[0]** No direct interaction	**[0]** No direct interaction
	Accelerating energy efficiency improvement	**Water efficiency and pollution prevention (6.3/6.4/6.6)** ↑ **[+2]** 📖📖📖 ☺☺☺ ★★★ Similar to behavioral changes, efficiency measures in the transport sector that lead to reduced transport demand can lead to reduced transport energy supply. As water is used to produce a number of important transport fuels, the reduction in transport demand is anticipated to reduce water consumption and wastewater, resulting in more clean water for other sectors and the environment. Vidic et al. (2013); Tiedemann et al. (2016); Fricko et al. (2016); Holland et al. (2016)	**Sustainable Consumption (12.2/12.8)** ↑ **[+2]** 📖📖📖 ☺☺☺ ★★★ Relational complex transport behavior resulting in significant growth in energy-inefficient car choices, as well as differences in mobility patterns (distances driven, driving styles) and actual fuel consumption between different car segments all affect the non-progress on transport decarbonisation. Consumption choices, and individual lifestyles are situated tied to the form of the surrounding urbanization. Major behavioral changes and emissions reductions requires understanding of this relational complexity, consideration of potential interactions with other policies and the local context and implementation of both command-and-control as well as market-based measures. Stanley, Hensher and Loader (2011); Heinonen et al. (2013); Gallego, Montero and Salas (2013); Aamaas and Peters (2017); Gössling and Metzler (2017); Azevedo and Leal (2017)	**[0]** No direct interaction	**[0]** No direct interaction
	Improved access & fuel switch to modern low-carbon energy	**Water efficiency and pollution prevention (6.3/6.4/6.6)** ↑ / ↓ **[+2,-1]** 📖📖 ☺☺ ★★★ A switch to low-carbon fuels in the transport sector can lead to a reduction in water demand and wastewater if the existing higher-carbon fuel is associated with a higher water intensity than the lower-carbon fuel. However, in some situations the switch to a low-carbon fuel such as e.g., biofuel could increase water use compared to existing conditions if the biofuel comes from a water-intensive feedstock. Transport electricfication could lead to tradeoffs with water use if the electicity is provided with water intensive power generation. Hejazi et al. (2015); Song et al. (2016); Fricko et al. (2016)	**Ensure Sustainable Consumption& Production patterns (12.3)** ↑ **[+2]** 📖📖📖 ☺☺☺ ★★★ Due to persistent reliance on fossil fuels, it is posited that transport is more difficult to decarbonize than other sectors. This study partially confirms that transport is less reactive to a given carbon tax than the non-transport sectors: in the first half of the century, transport mitigation is delayed by 10–30 years compared to non-transport mitigation. The extent to which earlier mitigation is possible strongly depends on implemented technologies and model structure. Pietzcker et al. (2013); Figueroa et al. (2014); IPCC AR5 WG3 (2014); Creutzig et al., (2015)	**[0]** No direct interaction	**[0]** No direct interaction

		INTERACTION SCORE EVIDENCE AGREEMENT CONFIDENCE	INTERACTION SCORE EVIDENCE AGREEMENT CONFIDENCE	INTERACTION SCORE EVIDENCE AGREEMENT CONFIDENCE	INTERACTION SCORE EVIDENCE AGREEMENT CONFIDENCE
Replacing coal	**Non-biomass renewables** solar, wind, hydro	**Water efficiency and pollution prevention (6.3/6.4/6.6) / Access to improved water** ↑ / ↓ **[+2,-2]** 🕮🕮🕮🕮 ☺☺☺☺ ★★★★ Wind/solar renewable energy technologies are associated with very low water requirements compared to existing thermal power plant technologies. Widespread deployment is therefore anticipated to lead to improved water efficiency and avoided thermal pollution. However, managing wind and solar variability can increase water use at thermal power plants and can cause poor water quality downstream from hydropower plants. Access to distributed renewables can provide power to improve water access, but could also lead to increased groundwater pumping and stress if mismanaged. Developing dams to support reliable hydropower production can fragment rivers and alter natural flows reducing water and ecosystem quality. Developing dams to support reliable hydropower production can result in disputes for water in basins with up- and down-stream users. Storing water in reservoirs increases evaporation, which could offset water conservation targets and reduce availability of water downstream. However, hydropower plays an important role in energy access for water supply in developing regions, can support water security, and has the potential to reduce water demands if used without reservoir storage to displace other water intensive energy processes. Bilton et al. (2011); Scott et al. (2011); Kumar et al. (2012); Kern et al. (2014); Meldrum et al. (2014); Fricko et al. (2016); Ziv et al. (2012); Grill et al. (2015); Grubert et al. (2016); Fricko et al. (2016); De Stefano et al. (2017)	**Natural Resource Protection (12.2/12.3/12.4/12.5)** ↑ **[+2]** 🕮🕮🕮 ☺☺☺ ★★★★ Renewable energy and energy efficiency slow the depletion of several types of natural resources, namely coal, oil, natural gas, and uranium. In addition, the phasing-out of fossil fuel subsidies encourages less wasteful energy consumption; but if that is done, then the policies implemented must take care to minimize any counteracting adverse side-effects on the poor (e.g., fuel price rises). (Quote from McCollum et al., 2018) McCollum et al. (2018); Banerjee et al. (2012); Bhattacharyya et al. (2016); Cameron et al. (2016); Riahi et al. (2012); Schwanitz et al. (2014)	**Marine Economies (14.7) / Marine Protection (14.1/14.2/14.4/14.5)** ↑ / ↓ **[2,-1]** 🕮🕮 ☺☺☺ ★★★ Ocean-based energy from renewable sources (e.g., offshore wind farms, wave and tidal power) are potentially significant energy resource bases for island countries and countries situated along coastlines. Multi-use platforms combining renewable energy generation, aqua-culture, transport services and leisure activities can lay the groundwork for more diversified marine economies. Depending on the local context and prevailing regulations, ocean-based energy installations could either induce spatial competition with other marine activities, such as tourism, shipping, resources exploitation, and marine and coastal habitats and protected areas, or provide further grounds for protecting those exact habitats, therefore enabling marine protection. (Quote from McCollum et al., 2018). Hydropower disrupts the integrity and connectivity of aquatic habitats and impact the productivity of inland waters and their fisheries McCollum et al. (2018); Buck and Krause (2012); Michler-Cieluch et al. (2009); WBGU (2013); Inger et al. (2009); Matthews N., Mccartney M. (2017); Cooke S.J., Allison E.H., Beard T.D., Jr., Arlinghaus R., Arthington A.H., Bartley D.M., Cowx I.G., Fuentevilla C., Leonard N.J., Lorenzen K., Lynch A.J., Nguyen V.M., Youn S.-J., Taylor W.W., Welcomme R.L. (2016)	**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)** ↓ **[-1]** 🕮🕮🕮 ☺☺☺ ★★★ Landscape and wildlife impact for wind, habitat impact for hydropower. Wiser et al. (2011); Lovich and Ennen (2013); Garvin et al. (2011); Grodsky et al. (2011); Dahl et al. (2012); de Lucas et al. (2012); Dahl et al. (Dahl et al., 2012); Jain et al. (2011); Kumar et al. (2011); Alho (2011); Kunz et al. (2011); Smith et al. (2013); Ziv et al. (2012); Matthews N., Mccartney M. (2017)
	Increased use of biomass	**Water efficiency and pollution prevention (6.3/6.4/6.6)** ↑ / ↓ **[+1,-2]** 🕮🕮🕮🕮 ☺☺ ★★★★ Biomass expansion could lead to increased water stress when irrigated feedstocks and water-intensive processing steps are used. Bioenergy crops can alter flow over land and through soils as well as require fertilizer and this can reduce water availability and quality. Planting bioenergy crops on marginal lands or in some situations to replace existing crops can lead to reductions in soil erosion and fertilzer inputs, improving water quality. Hejazi et al. (2015); Bonsch et al. (2016); Cibin et al. (2016); Song et al. (2016); Gao et al. (2017); Taniwaki (2017); Woodbury et al. (2017); Griffiths et al. (2017); Ha et al. (2017)	**Natural Resource Protection (12.2/12.3/12.4/12.5)** ↑ **[+2]** 🕮🕮🕮 ☺☺☺ ★★★★ Switching to renewable energy reduce the depletion of finite natural resources. McCollum et al. (2018); Banerjee et al. (2012); Bhattacharyya et al. (2016); Cameron et al. (2016); Riahi et al. (2012); Schwanitz et al. (2014)	**[0]** No direct interaction	**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)** ↑ / ↓ **[+1,-2]** 🕮 ☺☺☺ ★★ Protecting terrestrial ecosystems, sustainably managing forests, halting deforestation, preventing biodiversity loss and controlling invasive alien species could potentially clash with renewable energy expansion, if that would mean constraining large-scale utilization of bioenergy or hydropower. Good governance, cross-jurisdictional coordination, and sound implementation practices are critical for minimizing trade-offs (McCollum et al., 2018). McCollum et al. (2018); Smith et al. (2010); Smith et al. (2014); Acheampong M., Ertem F.C., Kappler B., Neubauer P. (2017)
	Nuclear/Advanced Nuclear	**Water efficiency and pollution prevention (6.3/6.4/6.6)** ↑ / ↓ **[+2,-1]** 🕮🕮🕮 ☺☺☺ ★★★ Nuclear power generation requires water for cooling which can lead to localized water stress and the resulting cooling effluents can cause thermal pollution in rivers and oceans. Webster et al. (2013); Fricko et al. (2016); Raptis et al. (2016); Holland et al. (2016)	**[0]** No direct interaction	**[0]** No direct interaction	**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)** ↓ **[-1]** 🕮🕮 ☺☺ ★★ Safety and waste concerns, uranium mining and milling IPCC AR5 WG3 (2014); Visschers and Siegrist (2012); Greenberg (2013a); Kim et al. (2013); Visschers and Siegrist (2012); Bickerstaff et al. (2008); Sjoberg and Drottz-Sjoberg (2009); Corner et al. (2011); Ahearne (2011)
	CCS: Bio energy	**Water efficiency and pollution prevention (6.3/6.4/6.6)** ↑ / ↓ **[+1,-2]** 🕮🕮 ☺ ★★ CCU/S requires access to water for cooling and processing which could contribute to localized water stress. However, CCS/U process can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration. The bioenergy component adds the additional tradeoffs associated with bioenergy use. Large-scale bioenergy increases input demand, resulting in environmental degradation and water stress Meldrum et al. (2013); Fricko et al. (2016); Byers et al. (2016); Brandl et al. (2017), Dooley,K. & Kartha,S. (2018)	**Natural Resource Protection (12.2/12.3/12.4/12.5)** ↑ **[+1]** 🕮🕮 ☺☺ ★★ Switching to renewable energy reduce the depletion of finite natural resources. On the other hand, the available of underground storage is limated and therefore reduces the benefits of switching from finite resources to bioenergy. McCollum et al. (2018); Banerjee et al. (2012); Bhattacharyya et al. (2016); Cameron et al. (2016); Riahi et al. (2012); Schwanitz et al. (2014)	**[0]** No direct interaction	**Healthy Terrestrial Ecosystems (15.1/15.2/15.4/15.5/15.8)** ↑ / ↓ **[+1,-2]** 🕮 ☺☺☺ ★★ Protecting terrestrial ecosystems, sustainably managing forests, halting deforestation, preventing biodiversity loss and controlling invasive alien species could potentially clash with renewable energy expansion, if that would mean constraining large-scale utilization of bioenergy or hydropower. Good governance, cross-jurisdictional coordination, and sound implementation practices are critical for minimizing trade-offs (McCollum et al., 2018). Large-scale bioenergy increases input demand, resulting in environmental degradation and water stress. McCollum et al. (2018); Smith et al. (2010); Smith et al. (2014); Acheampong er al. (2017); Dooley and Kartha (2018)
Advanced coal	**CCS: Fossil**	**Water efficiency and pollution prevention (6.3/6.4/6.6)** ↑ / ↓ **[+1,-2]** 🕮🕮🕮 ☺ ★★ CCU/S requires access to water for cooling and processing which could contribute to localized water stress. However, CCS/U process can potentially be configured for increased water efficiency compared to a system without carbon capture via process integration. Coal mining to support clean coal CCS will negatively impact water resources due to the associated water demands, wastewater and land-use requirements. Meldrum et al. (2013); Fricko et al. (2016); Byers et al. (2016); Brandl et al. (2017)	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction

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		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE		
Agriculture & Livestock	**Behaviourial response: Sustainable healthy diets and reduced food waste**	↑ / ↓	[+2,-1]	🕮🕮🕮🕮	☺☺☺☺	★★★★	**Water efficiency and pollution prevention (6.3/6.4/6.6)** Reduced food waste avoids direct water demand and wastewater for crops and food processing, and avoids water used for energy supply by reducing agricultural, food processing and waste management energy inputs. Healthy diets will support water efficiency targets if the shift towards healthy foods results in food supply chains that are less water intensive than the supply chains supporting the historical dietary pattern.	Khan et al. (2009); Bajzelj et al. (2014); Ran et al. (2016); Villarroel Walker et al. (2014);
	Land based greenhouse gas reduction and soil carbon sequestration	↑ / ↓	[+1,-1]	🕮🕮🕮	☺☺	★★★	**Water efficiency and pollution prevention (6.3/6.4/6.6)** Soil carbon sequestration can alter the capacity of soils to store water, which impacts the hydrological cycle and could be positive or negative from a water perspective, dependent on existing conditions. Climate Smart Agriculture enrich linkages across sectors including management water resources. Minimum tillage systems have been reported to reduce water erosion and thus sedimentation of water courses (Bustamante, 2014).	Smith (2016); Behnassi, Boussaid and Gopichandran (2014); Bustamante (2014)
	Greenhouse gas reduction from improved livestock production and manure management systems	↑ / ↓	[+2,-1]	🕮🕮🕮	☺☺☺	★★★	**Water use efficiency and pollution prevention (6.3/6.4/6.6)** Livestock efficiency measures are expected to reduce water required for livestock systems as well as associated livestock wastewater flows. However, efficiency measures that include agricultural intensification could increase water demands locally, leading to increased water stress if the intensification is mismananged. Scenarios where zero human-edible concentrate feed is use for livestocks freshwater use reduces by 21%.	Mekonnen et al. (2013); Kong et al. (2016); Ran et al. (2016); Schader et al. (2015)

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		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE		
Agriculture & Livestock	**Behaviourial response: Sustainable healthy diets and reduced food waste**	↑	[+2]	🕮🕮🕮🕮	☺☺☺☺	★★★★	**Ensure Sustainable Consumption& Production patterns, Sustainable** Reduce loss and waste in food systems, processing, distribution and by changing household habits. To reduce environmental impact of livestock both production and consumption trends of this sector should be traced. Livestock production needs to be intensified in a responsible way (i.e., be made more efficient in the way that it uses natural resources). Wasted food represents a waste of all the emissions generated during the course of producing and distributing that food. Mitigation measures include: Eat no more than needed to maintain a healthy body weight, Eat seasonal, robust, field grown vegetables rather than protected, fragile foods prone to spoilage and requiring heating and lighting in their cultivation, refrigeration stage, Consume fewer foods with low nutritional value e.g. Alcohol, tea, coffee, chocolate, bottled water (These foods are not needed in our diet and need not be produced), Shop on foot or over the internet (Reduced energy use).Reduction in food waste will not only pave the path for sustainable production but will also help in achieving sustainable consumption (Garnett, 2011). Reduce meat consumption to encourage more sustainable eating practices.	Beddington et al. (2012), Steinfeld, H., & Gerber, P. (2010),Bajželj et al.(2014),Ingram, J.
	Land based greenhouse gas reduction and soil carbon sequestration	↑	[+1]	🕮	☺	★	**Ensure Sustainable Production patterns(12.3)** Yield of millet or sorghum can double as compared with unimproved land more than 1 tonne per hectare due to sustainable intensification. An integrated approach to safe applications of both conventional and modern agricultural biotechnologies will contribute to increased yield (Lakshmi et al., 2015).	Campbell et al. (2014), Lakshmi et. al (2015)
	Greenhouse gas reduction from improved livestock production and manure management systems	↑	[+1]	🕮🕮	☺☺	★★	**Ensure Sustainable Production patterns and restructing taxation(12.3/12c)** In the future, many developed countries will see a continuing trend in which livestock breeding focuses on other attributes in addition to production and productivity, such as product quality, increasing animal welfare, disease resistance (Thornton, 2010). Diet composition and quality are key determinants of the productivity and feed-use efficiency of farm animals (Herrero, et al., 2013). Mechanisms for effecting behavioral change in livestock systems need to be better understood by implementing combinations of incentives and taxes simultaneously in different parts of the world (Herrero and Thornton, 2013). Reducing the amount of human-edible crops that are fed to livestock represents a reversal of the current trend of steep increases in livestock production, and especially of monogastrics, so would require drastic changes in production and consumption (Schader et al., 2015).	Thornton (2010); Herrero et al. (2013); Herrero and Thornton (2013); Schader et al. (2015)

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		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE
Agriculture & Livestock	**Behaviourial response: Sustainable healthy diets and reduced food waste**		[0]	No direct interaction		
	Land based greenhouse gas reduction and soil carbon sequestration		[0]	No direct interaction		
	Greenhouse gas reduction from improved livestock production and manure management systems		[0]	No direct interaction		

		15						
		INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE		
Agriculture & Livestock	**Behaviourial response: Sustainable healthy diets and reduced food waste**	↑	[+1]	🕮	☺	★	**Conservation of Biodiversity and restoration of land (15.1/ 15.5/15.9)** Reducing food waste has secondary benefits like protecting soil from degradation, and decreasing pressure for land conversion into agriculture and thereby protecting biodiversity. The agricultural area that becomes redundant through the dietary transitions can be used for other agricultural purposes such as energy crop production, or will revert to natural vegetation.A global food transition to less meat, or even a complete switch to plant-based protein food have a dramatic effect on land use. Up to 2,700 Mha of pasture and 100 Mha of cropland could be abandoned (Quoted from Stehfest et al. (2009))	Kummu et al. (2012), Stehfest et al. (2009)
	Land based greenhouse gas reduction and soil carbon sequestration	↑ / ↓	[+1,-1]	🕮🕮🕮	☺☺☺	★★★	**Conservation of Biodiversity and restoration of land (15.1/ 15.5/15.9)** Agricultural intensification can promote conservation of biological diversity by reducing deforestation, and by rehabilitation and restoration of biodiverse communities on previously developed farm or pasture land. However, planting monocultures on biodiversity hot spots can have adverse side-effects, reducing biodiversity. Genetically modified crops reduces demand for cultivated land. Adoptation of integrated landscape approaches can provide various ecosystem services. CSA enrich linkages across sectors including management of land and bio-resources. Land sparing has the potential to be beneficial for biodiversity, including for many species of conservation concern, but benefits will depend strongly on the use of spared land. In addition, high yield farming involves trade-offs and is likely to be detrimental for wild species associated with farmland. (Lamb et al., 2016).	IPCC WGIII (2014); Lamb et al. (2016); Lybbert and Sumner (2010); Harvey et al. (2014); Behnassi, Boussaid and Gopichandran (2014); Lamb et al. (2016)
	Greenhouse gas reduction from improved livestock production and manure management systems	↑	[+1]	🕮	☺	★	**Restoration of land (15.1)** Grasslands Are Precious, but improved management is required as grass accounts for close to 50% of feed use in livestock systems (Herrero et al., 2013). The scenario with 100% reduction of Food-Competing-Feedstuffs resulted in a 335 Mha decrease in arable land area, which corresponds to a decrease of 22% in arable and 7% in the total agricultural area (Schader et al., 2015).	Herrero, M., et al. (2013), Schader, C., et al. (2015)

Forest	**Reduced deforestation, REDD+**	**Water efficiency and pollution prevention (6.3/6.4/6.6)** ↑ / ↓ [+1,-1] 🕮🕮 ☺☺ ★★ Forest management alters the hydrological cycle which could be positive or negative from a water perspective and is dependent on existing conditions. Conservation of ecosystem services—indirectly could help countries maintain watershed integrity. Forests provide sustainable and regulated provision and helps in water purification. Bonsch et al. (2016); Griffiths et al. (2016); Gao et al (2017); Zomer et al. (2008); Kibria (2015); Katila et al. (2017)	**Ensure Sustainable consumption(12.3)** ↑ [+1] 🕮 ☺ ★ Reduce the human pressure on forests, including actions to address drivers of deforestation. Lima et al. (2017)	**[0]** No direct interaction	**Conservation of Biodiversity, sustainability of terrestrial ecosystems** ↑ [+1] 🕮🕮🕮 ☺☺☺ ★★★ Policies and programs for reducing deforestation and forest degradation, for rehabilitation and restorationof degraded lands can promote conservation of biological diversity. Reduce the human pressure on forests, including actions to address drivers of deforestation. Efforts by the Government of Zambia to reduce emissions byREDD+, have contributed erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. IPCC WGIII (2014); Lima et al. (2015); Miles and Kapos (2008); Katila et al. (2017); Turpie, Warr and Ingram (2015); Epstein and Theuer (2017)
	Afforestation and reforestation	**Enhance water quality (6.3)** ↑ / ↓ [+2,-1] 🕮🕮🕮 ☺☺☺ ★★★ Similar to REDD+, forest management alters the hydrological cycle which could be positive or negative from a water perspective and is dependent on existing conditions. Forest landscape restoration can have a large impact water cycles. Strategic placement of tree belts in lands affected by dryland salinity can remediate the affected lands by modifying landscape water balances.Watershed scale reforestation can result in the restoration of water quality. Fast-growing species can increase nutrient input and water inputs that can cause ecological damage and alter local hydrological patterns.Reforestation of mixed native species and in carefully chosen sites could increase biodiversity and restore waterways, reducing run-off and erosion (Dooley and Kartha,2018). Kibria, G. (2015), Zomer et al. (2008); Lamb et al. (2016); Bustamante et al. (2014); Dooley and Kartha (2018)	**[0]** No direct interaction	**Marine Economies (14.7) / Marine Protection and income generation** ↑ [+2] 🕮 ☺ ★ Mangroves would help to enhance fisheries, tourism business. Kibria, G. (2015)	**Conservation of Biodiversity and restoration of land (15.1/ 15.5/15.9)** ↑ [+2] 🕮🕮🕮🕮 ☺☺☺☺ ★★★★ Identified large amounts of land (749 Mha) globally as biophysically suitable and meeting the CDM-AR eligibility criteria (Zomer et al., 2008). Forest landscape restoration can conserve biodiversity and reduce land degradation. Mangroves reduce impacts of disasters (cyclones/storms/floods) acting as live seawalls,enhance forest resources /biodiversity. Forest loss goal can conserve/ restore 3.9 – 8.8 m ha / year average, 77.2 – 176.9 m ha in total and 7.7 – 17.7 m ha / year in 2030 of forest area by 2030 (Wolosin, 2014). Forest and biodiversity conservation, protected area formation, and forestry-based afforestation are practices enhance resilience of forest ecosystems to climate change (IPCC, 2014). Strategic placement of tree belts in lands affected by dryland salinity can remediate the affected lands by modifying landscape water balances and protect livestock.It can restore biologically diverse communities on previously developed farmland (Bustamante et al., 2014). Large-scale restoration is likely to benefit ecosystem service provision, including recreation biodiversity conservationand flood mitigation. Reforestation of mixed native species and in carefully chosen sites could increase biodiversity , reducing run-off and erosion (Dooley and Kartha, 2018). Zomer et al. (2008); Kibria (2015); Dooley and Kartha (2018); Wolosin (2014); IPCC, 2014; Epstein and Theuer (2017); Bustamante et al. (2014); Lamb et al. 2016
	Behaviourial response (responsible sourcing)	**Water efficiency and pollution prevention (6.3/6.4/6.6)** ↑ / ↓ [+2,-1] 🕮 ☺☺ ★★ Responsible sourcing will have co-benefits for water efficiency and pollution prevention if the sourcing strategies incorporate water metrics. There is a risk that shifting supply sources could lead to increased water use in another part of the economy. At local levels, Forest certification programmes and practicing sustainable forest management (SFM) provides freshwater supplies. van Oel et al. (2012); Launiainen et al. (2014); Hontelez (2016)	**Ensure Sustainable Production patterns (12.3)** ↑ [+1] 🕮 ☺ ★ At local levels, Forest certification programmes and practicing sustainable forest management (SFM) provides the provision of raw materials for a 'low ecological footprint' economy. Hontelez J. (2016)	**[0]** No direct interaction	**Sustainability and Conservation (15.1/15.2/15.3)** ↑ / ↓ [+1,-1] 🕮 ☺ ★ At the macro level, forest certification has done little to stem the tide of forest degradation, conversion of forest land to agriculture, and illegal logging—all of which remain serious threats to Indonesian forests (Bartley, 2010). At local levels, forest certification programmes and practicing sustainable forest management (SFM) helps in biodiversity protection. Bartley, T. (2010); Hontelez J. (2016)
Oceans	**Ocean iron fertilization**	**[0]** No direct interaction	**[0]** No direct interaction	**Nutrient Pollution, Ocean Acidification, Fish Stocks, MPAs, SISD** ↑ / ↓ [+1,-2] 🕮🕮🕮 ☺☺ ★ OIF could exacerbate or reduce nutrient pollution, increase the likelihood of mid-water deoxygenation, increases ocean acidification, might contribute to the rebuilding of fish stocks in producing plankton, generating therefore benefits for SISD, but might be in conflict with designing MPAs. Gnanadesikan et al. (2003); Jin and Gruber (2003); Denman (2008); Smetacek and Naqvi (2008); Lampitt et al. (2008); Oschlies et al. (2010); Güssow et al. (2010); Trick et al. (2010); Williamson et al. (2012)	**[0]** No direct interaction
	Blue carbon	**Integrated water resources management (6.3/6.5)** ↑ [+2] 🕮 ☺ ★ Development of blue carbon resources (coastal and marine vegetated ecosystems) can lead to coordinated management of water in coastal areas. Vierros et al. (2013)	**[0]** No direct interaction	**Ocean Acidification, Nutrient Pollution (14.3, 14.1)** ↑ / ~ [+2,0] 🕮 ☺☺☺ ★★★ Mangroves could buffer acidification it their immediate vicinity; Seaweeds have not been able to mitigate the effect on ocean foraminifera Sippo et al. (2016); Pettit et al. (2015)	**conservation of Biodiversity and restoration of land (15.1, 15.2, 15.3, 15.4, 15.9)** ↑ [+3] 🕮 ☺☺☺☺ ★★★★ average difference of 31 mm per year in elevation rates between areas with seagrass and unvegetated areas (case study areas Scotland, Kenya, Tanzania and Saudi Arabia); Mangroves fostering sediment accretion of about 5mm a year) Potouroglou et al (2017); Alongi (2012)
	Enhanced Weathering	**[0]** No direct interaction	**[0]** No direct interaction	**Ocean Acidification, Nutrient Pollution (14.3, 14.1)** ↑ / ↓ [+2,-1] 🕮🕮🕮 ☺☺☺ ★★★ Enhanced weathering (either by spreading lime or quicklime (in combination with CCS) over the ocean or olivine at beaches or the catchment area of rivers) opposes ocean acidification. "End-of-century ocean acidification is reversed under RCP4.5 and reduced by about two-thirds under RCP8.5; additionally, surface ocean aragonite saturation state, a key control on coral calcification rates, is maintained above 3.5 throughout the low latitudes, thereby helping maintain the viability of tropical coral reef ecosystems (Tick et al. 2010)" However, also marine biology would be affected, in particular if spreading olivine is used which actually works rather like ocean (iron) fertilization. Köhler et al. (2010); Hartmann et al. (2013); Köhler et al. (2013); Paquay und Zeebe (2013); Taylor et al. (2015); Smith et al. (2015)	**Protect inland freshwater systems (14.1)** ↓ [-1] 🕮 ☺ ★ Olivine can contain toxic metals such as nickel which could accumulate in the environment or disrupt the local ecosystem by changing the pH of the water (in case of spreading in the catchment area of rivers). Hartmann et al. (2013)

		INTERACTION / SCORE / EVIDENCE / AGREEMENT / CONFIDENCE	INTERACTION / SCORE / EVIDENCE / AGREEMENT / CONFIDENCE	INTERACTION / SCORE / EVIDENCE / AGREEMENT / CONFIDENCE	INTERACTION / SCORE / EVIDENCE / AGREEMENT / CONFIDENCE
Industry	**Accelerating energy efficiency improvement**	**Energy savings (7.1, 7.3, 7a, 7b)** ↑ [+2] 🕮🕮🕮🕮 ☺☺☺ ★★★★ Energy Efficiency lead to reduced relatively less energy demand and hence energy supply and energy security, reduces import. Positive rebound effect can raise demand but to a very less extent due to low rebound effect in industry sector in many countries and by appropriate mix of industries (china) can maintain energy savings gain. supplying surplus energy to cities is also happening.proving mtenance culture, Switching off idle equipment help saving energy (e.g Ghana) Apeaning and Thollandar (2013); Zhang et al. (2015); IPCC WGIII (2014); Chakravarty et al. (2013); Karner et al. (2015); Fernando et al. (2017); Li et al. (2016); Wesseling et al. (2017)	**Reduces Unemployment (8.2,8.3,8.4,8.5, 8.6)** ↑ [+1] 🕮🕮 ☺☺☺ ★★★ Unemployment rate reduction from 25% to 12% in south africa. Enhances firm productivity and technical and managerial capapcity of the employees . New jobs for manginenergy efficiency opens up opportunoties in energy service delivery sector. Altieri et al (2016); Fernando et al. (2017); Johasson and Thollandar (2018)	**Infrastructure renewal (9.1/9.3/9.5,9a)** ↑ [+1] 🕮🕮 ☺☺ ★★ Transitioning to a more renewably-based energy system that is highly energy efficient is well alighed with the goal of upgrading energy infrastructure and making the energy industry more sustainable. In the reverse direction, infrastructure upgrades in other parts of the economy, such as modernized telecommunication networks, can create the conditions for a successful expansion of renewable energy and energy efficiency measures (e.g., smart-metering and demand-side management, McCollum et al., 2018). Apeaning and Thollandar (2013); McCollum et al. (2018); Bhattacharyya et al. (2016); Goldthau (2014); Meltzer (2016); Riahi et al. (2012)	**Sustainable cities (15.6,15.8,15.9)** ↑ [+2] 🕮 ☺ ★ Industries are becoming supplier of energy, waste heat , water, to neighbourial human settlements and hence reduced primary energy demand also and make towns and cities grow sustainably Karner et al (2015)
	Low-carbon fuel switch	**Sustainable and modern (7.2, 7.a)** ↑ [+2] 🕮 ☺ ★ Industries are becoming supplier of energy, waste heat , water, roof tops for solar energy generation and hence reduced primary energy demand. CHP in chemical industries can help providing surplus power in the grid. Karner et al (2015); Griffin et al (2017)	**Economic growth with decent employment (8.1,8.2,8.3,8.4)** ↑ [+2] 🕮🕮🕮🕮 ☺☺☺☺ ★★★★ Circular economy instead of liner global economy can achieve climate goal and can help in economic growth through industrialisation which saves on resources, enviornment and supports small, edium and even large industries, can lead to employment generation. so new regulations, incentives, tax regime can help in achieving the goal. Supino et al (2015); Fan et al (2017); Leider et al (2015); Zheng et al (2016); Shi et al (2017); Liu et al (2014); Stahel (2017)	**Innovation and new infrastrcutture (9.2,9.3,9.4,9.5.9.a)** ↑ [+2] 🕮🕮🕮🕮 ☺☺☺☺ ★★★★ Circular economy instead of liner global economy is helping new innovation and infrastrcuture can achieve climate goal and can help in economic growth through industrialisation which saves on resources, enviornment and supports small, edium and even large industries, can lead to employment generation. so new regulations, incentives, tax regime can help in achieving the goal. Supino et al (2015); Fan et al (2017); Leider et al (2015); Zeng et al (2016); Shi et al (2017); Liu et al (2014); Stahel (2017)	**Sustainable cities (15.6,15.8,15.9)** ↑ [+2] 🕮 ☺ ★ Industries are becoming supplier of energy, waste heat , water, roof tops for solar energy generation and supply to neighbourial human settlements and hence reduced primary energy demand also and make towns and cities grow sustainably Karner et al (2015)
	Decarbonisation/ CCS/CCU	**Affordable and sustainable energy sources** ↑ / ↓ [+2,-2] 🕮🕮 ☺☺ ★★ CCS for EPIs can be incremental but needs additional space and can need additional energy sometimes compensating for higher efficiency otherwise, Recirculating Blast R Furnace & CCS for iron steel means high energy demand, electric melting in glass can mean higher electricity prices, in paper industry new separation and drying technologies are key to reduce the energy intensity, allowing for carbon neutral operation in the future , bio refineries can reduce petrorefineries, DRI in iron and steel with H2 encourages innovation in hydrogen infrastructure, in chemicals industry also encourage renewable electricity and hydrogen, biobased polymers can increase biomass price. Wesseling et al. (2017); Griffin et al. (2017)	**Decouple growth from environ degradation (8.1, 8.2, 8.4)** ↑ [+2] 🕮🕮 ☺☺☺ ★★★ EPI s are important players for economic growth. Deep decarbonisation of EPI through radical innovation is consistent with well below 2C scenario Wesselinget al. (2017) , Åhman et al. (2016); Denis-Ryan et al. (2016)	**Innovation and new infrastrcutture (9.2,9.4,9.5)** ↑ [+2] 🕮 ☺☺☺☺ ★★★★ Deep decarbonisation through radical technological change in EPI will lead to radical innovations e.g.,in completely changing industries' innovation stratgey, plant and equipment , skill, production technique, design and so on. Radical CCS will need new infrastructure to transport CO2. Wesseling et al. (2017), Åhman et al (2016); Denis-Ryan et al. (2016); Griffin et al. (2017)	[0] No direct interaction
Buildings	**Behaviorial response**	**Saving energy, Improvement in Energy efficiency (7.3, 7a, 7b)** ↑ [+2] 🕮🕮🕮🕮 ☺☺☺☺ ★★★ Lifestyle change measures and adoption behavior affect residential energy use and implementation of efficient technologies as residential HVAC systems. Also social influence can drive energy savings in users exposed to energy consumption feedback. Effect of autonomous motivation on energy savings behaviour is greater than that of other more established predictors such as intentions, subjective norms, perceived behavioural control and past behaviour. Use of a hybrid engineering approach using social psychology and economic behaviour models are suggested for Residential peak electricity demand response. However, some take back in energy savings can happen due to rebound effect unless managed appropriately or accounted for welfare improvement. Adjusting Thermostat helps in saving energy . Uptake of energy efficienct appliance by households with introduction of appliance standard, training, promotional material dissemination, desire to save energy bill are helping to change acquisition behaviour. Yue, Yang, and Chen (2013); Somerfeld, Buys, and Vine (2017); Zhao et al. (2017); de Koning et al. (2016); Isenhour and Feng (2016); Sluisveld et al. (2016); Noonan et al. (2015); Allen et al. (2015); Jain et al. (2013a); Hori et al. (2013); Sweeny et al. (2013); Webb et al., (2013); Huebner et al. (2013); Gyamfi, Krumdieck, and Urmee (2013); Chakravarty et al (2013); Santarius (2016); Song et al. (2016); Anda et al. (2014); Roy et al (2018)	**Progressively improve resource efficiency (8.4), Employment opportunties** ↑ [+2] 🕮 ☺ ★ Behaviourial change programmes help in sustaining energy savings through new infrastructuer develoment Anda et al. (2014)	**Innovation and new infrastrcutture (9.2,9.4,9.5)** ↑ [+2] 🕮🕮 ☺☺ ★★ Adoption of smart meter and smart grid following community based social marketing help in infrastructure expansion. People are adopting solar rooftops, white roof/vertical garden/green roofs at much faster rate due to new innovation, regulations. Anda et al. (2014); Roy et al. (2018)	**Sustainable cities (15.6,15.8,15.9)** ↑ [+2] 🕮🕮 ☺☺ ★★ Behaviourial change programmes help in making cities more sustainable. Anda et al. (2014); Roy et al. (2018)
	Accelerating energy efficiency improvement	**Increase in energy savings (7.3)** ↑ [+2] 🕮🕮🕮 ☺☺☺ ★★★★ There is high agreement among researchers based on large number of evidence across various countries that energy efficiency improvement reduce energy consumption and hence lead to energy savings. Efficient cookstove saves bioenergy. Efficient cookstove saves bioenergy.Countries with higher hours of use due to higher ambient temperature or a more carbon intensive electricity grid benefit more from available improvements in energy efficiency and use of refrigerant transition . Berrueta et al. (2017); Cameron, Taylor, and Emmett (2015); Liddell and Guiney (2015); McLeod, Hopfe, and Kwan (2013); Noris et al. (2013); Salvalai et al. (2017); Yang, Yan, and Lam (2014); Kwong, Adam, and Sahari (2014); Holopainen et al. (2014); Bhojvaid Vasundhara et al. (2014); Kim et al. (2017); Shah (2015)	**Employment Opportunities (8.2/8.3/8.5/8.6) / Strong Financial Institutions (8.10)** ↑ / ↓ [+2,-1] 🕮🕮 ☺ ★★ Deploying renewables and energy-efficient technologies, when combined with other targeted monetary and fiscal policies, can help spur innovation and reinforce local, regional, and national industrial and employment objectives. Gross employment effects seem likely to be positive; however, uncertainty remains regarding the net employment effects due to several uncertainties surrounding macro-economic feedback loops playing out at the global level. Moreover, the distributional effects experienced by individual actors may vary significantly. Strategic measures may need to be taken to ensure that a large-scale switch to renewable energy minimizes any negative impacts on those currently engaged in the business of fossil fuels (e.g., government support could help businesses re-tool and workers re-train). To support clean energy and energy efficiency efforts, strengthened financial institutions in developing country communities are necessary for providing capital, credit, and insurance to local entrepreneurs attempting to enact change. (McCollum et al., 2018). Berrueta et al. (2017); McCollum et al. (2018); Aether (2016); Babiker and Eckaus (2007); Bertram et al. (2015); Blyth et al. (2014); Borenstein (2012); Creutzig et al. (2013); Clarke et al. (2014); Dechezleprêtre and Sato (2014); Dinkelman (2011); Fankhauser et al. (2008); Ferroukhi et al. (2016); Frondel et al. (2010); Gohin (2008); Guivarch et al. (2011); Jackson and Senker (2011); Johnson et al. (2015)	**Innovation and new infrastrcutture (9.2,9.4,9.5)** ↑ [+2] 🕮🕮 ☺☺ ★★ Adoption of smart meter and smart grid following community based social marketing help in infrastructure expansion, statutory norms to enhance energy and resource efficiency in building is encouraging green building projects . Anda et al. (2014); Roy et al. (2018)	**Urban Environmental Sustainability (11.3/11.6, 11.b,11.c)** ↑ [+2] 🕮🕮 ☺☺☺ ★★★★ Renewable energy technologies and energy-efficient urban infrastructure solutions (e.g., public transit) can also promote urban environmental sustainability by improving air quality and reducing noise. Efficient transportation technologies powered by renewably-based energy carriers will be a key building block of any sustainable transport system (McCollum et al., 2018). Green buildings help in sutainable construction. McCollum et al. (2018); Bongardt et al. (2013); Creutzig et al. (2012); Grubler and Fisk (2012); Kahn Ribeiro et al. (2012); Raji et al. (2015); Riahi et al. (2012), Kim et al (2017)
	Improved access & fuel switch to modern low-carbon energy	**Meeting energy demand** ↑ [+2] 🕮🕮🕮 ☺☺☺ ★★★ Renewable energies could potentially serve as the main source of meeting energy demand in the rapidly growing developing country cities. Ali e et al. (2015) estimated the potential of solar, wind and biomass renewable energy options to meet part of the electrical demand in Karachi, Pakistan. Creutzig et al. (2014); Connolly et al. (2014); Islar et al. (2017); Mittlefehldt (2016); Bilgily et al. (2017); Ozturk et al. (2017); Mahony and Dufour (2015); Byravan et al. (2017); Abanda et al. (2016); Peng and Lu (2013); Pietzcker (2013); Ali et al. (2015); Li, Yang, and Lam (2014); Yahine and Sauma (2013); Pode (2013); Zulu and Richardson (2013)	**Sustainable economic growth and employment** ↑ [+2] 🕮🕮 ☺☺☺ ★★ Creutzig et al. 2014 assessed the potential for renewable energies in the European region. They found that a European energy transition with a high-level of renewable energy installations in the periphery could act as an economic stimulus, decrease trade deficits, and possibly have positive employment effects. Provision of energy access can play a critical enabling role for new productive activities , livelihoods and employment. Reliable access to modern energy services can have an important influence on productivity and earnings. (McCollum et al., 2018) Creutzig et al. (2014); Byravan et al. (2017); Ali et al. (2015); McCollum et al. (2018); Bernard and Torero (2015); Chakravorty et al. (2014); Grogan and Sadanand (2013); Pueyo et al. (2013); Rao (2013)	**Innovation and new infrastrcutture (9.2,9.4,9.5)** ↑ [+2] 🕮🕮 ☺☺ ★★ Adoption of smart meter and smart grid following community based social marketing help in infrastructure expansion, statutory norms to enhance energy and resource efficiency in building is encouraging green building projects . Introduction of incentives and norms for solar rooftops/white/green roofs in cities are helping to accelerate the expansion of the innovation and infrastructure. Anda et al. (2014); Roy et al. (2018)	**Housing (11.1)** ↑ [+3] 🕮🕮🕮 ☺☺☺ ★★★★ Ensuring access to basic housing services implies that households have access to modern energy forms. (Quote from McCollum et al., 2018), roof top solar in Macau make cities sustainable . Introduction of incentives and norms for solar/white/green rooftops in cities are helping to accelerate the expansion of the infrastructure. McCollum et al. (2018); Bhattacharya et al. (2016); UN (2016); Song et al (2016); Roy et al. (2018)

Transport	**Behavioural response**	**Energy savings (7.3, 7a, 7b)** ↑ [+2] 🕮🕮 ☺☺ ★★ Behavioural response will reduce the volume of transport needs and, by extension, energy demand. Ahmad S., Puppim de Oliveira J.A., 2016; Figueroa M.J., Ribeiro S.K., 2013	**Promote Sustained, inclusive economic growth (8.3)** ↓ [-2] 🕮🕮🕮 ☺☺☺ ★★★ Policy contradictions (e.g. standards, efficient technologies leading to increased electricity prices leading the poor to switch away from clean(er) fuels); unintended outcomes (e.g.redistribution of income generated by carbon taxes) results in contradiction to the primary aims of (productive) job creation and poverty alleviation, and in trade-offs between mitigation adaptation and development policies. Detailed assessment of consequences of mitigation policies requires developing methods and reliable evidence to enable policymakers to more systematically identify how different social groups may be affected by the different available policy options. (Klausbruckner, Annegarn, Henneman, & Rafaj, 2016); (Lucas & Pangbourne, 2014);(Suckall, Tompkins, & Stringer, 2014)	**Build Resilient Infrastructure (9.1)** ↑ / ↓ [+2,-2] 🕮🕮 ☺☺ ★★ As people prefer more mass transportation, integrating train lines, a tram line, BRTs, gondola lift systems, a bicycle-sharing systems and hybrid buses and telecommuting need for new infrastruture increases Dulac (2013); Aamaas and Peters (2017); Martínez-Jaramillo et al. (2017); Xylia et al. (2017)	**Make cities & Human settelments inclusive, safe, resilient (11.2)** ↑ [+2] 🕮🕮 ☺☺ ★★ Climate change threatens to worsen poverty, therefore pro-poor mitigation policies are needed to reduce this threat; for example investing more and better in infrastructure by leveraging private resources and using designs that account for future climate change and the related uncertainty Hallegate et al. (2015); Ahmad and Puppim de Oliveira (2016)
	Accelerating energy efficiency improvement	**Energy savings (7.3, 7a, 7b)** ↑ [+2] 🕮 ☺ ★ Accelrating efficiency in tourism transport reduces energy demand (china) Shukxin et al (2016)	**Promote Sustained, inclusive economic growth (8.3)** ↑ / ↓ [+2,-2] 🕮🕮 ☺☺ ★★ Significant opportunities to slow travel growth and improve efficiency exist and, similarly, alternatives to petroleum exist but have different characteristics in terms of availability, cost, distribution, infrastructure, storage, and public acceptability. Production of new technologies, fuels and infrastructure can favour economic growth, however, efficient financing of increased capital spending and infrastructure is critical. Gouldson et al. (2015); Karkatsouliset al. (2016)	**Build Resilient Infrastructure (9.1)** ↑ / ↓ [+2,-2] 🕮🕮 ☺☺ ★★ Combining promotion of mass transportation, integrating train lines, a tram line, BRTs, gondola lift systems, a bicycle-sharing systems and hybrid buses and telecommuting, reduce traffic and significantly contribute to meet climate targets a comprehensive package of complementary mitigation options is necessary for deep and sustained emission reductions . In sweden public bus fleet is aiming more towards decarbonisation compared to efficiency Dulac (2013); Aamaas and Peters (2017); Martínez-Jaramillo et al. (2017); Xylia et al. (2017)	**Make cities sustainable (11.2,11.3)** ↑ [+2] 🕮 ☺ ★ Two most important elements of making cities sustianble are efficient building and transport (case of Macau). Song et al. (2016)
	Improved access & fuel switch to modern low-carbon energy	**Increase share of renewable (7.2)** ↑ [+2] 🕮🕮 ☺☺ ★★ Biofuel increase share of renewables but can perform poorly if too many countries increase their use of biofuel, whereas electrification performs best when many other countries implement this technology. The strategies are not mutually exclusive and simultaneous implementation of some provides synergies for national energy security. Therefore, important to consider result of material and contextual factors that co-evolve.Electric vehicles using electricity from renewables or low carbon sources combined with e-mobility options such as trolleybuses, metros, trams and electro buses, as well as promote walking and biking, especially for short distances need consideration Månsson (2016); Ajanovic (2015); Wolfram et al. (2017); Alahakoon (2017)	**Promote Sustained, inclusive economic growth (8.3)** ↑ / ↓ [+2,-2] 🕮🕮 ☺☺ ★★ the decarbonisation of the freight sector tends to occur in the second part of the century and that the sector decarbonises by a lower extent than the rest of the economy. Decarbonising road freight on a global scale remains a challenge even when notable progress in biofuels and electric vehicles has been accounted for. Carrara and Longden (2016); Creutzig et al. (2015); IPCC AR5 WG3 (2014)	**Help building inclusive infratsructure (9.1, 9.a)** ↑ [+2] 🕮🕮🕮 ☺☺☺ ★★★ Lack of appropriate infrastructure lead to limited access to job for urban poor (africa, Latin America, India) Gouldson et al. (2015); Figueroa, Fulton and Tiwari (2013); Vasconcellos and Mendonça (2016); Lall et al. (2017)	**Make cities & Human settelments inclusive, safe, resilient (11.2)** ↑ [+2] 🕮🕮 ☺☺ ★★ in rapidly growing cities, the carbon savings from investments at scale, in cost-effective low-carbon measures could be quickly overwhelmed – in as little as 7 years – by the impacts of sustained population and economic growth, highlighting the need to build capacities that enable the exploitation not only of the economically attractive options in the short term but also of those deeper and more structural changes that are likely to be needed in the longer term. With hybrid electric vehicles, plug-in electric vehicles there is emerging new concepts in transportation such as electric highways Gouldson et al. (2015); Figueroa, Fulton and Tiwari (2013); Vasconcellos and Mendonça (2016); Alahakoon (2017)

			INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE		
Replacing coal	**Non-biomass renewables** solar, wind, hydro		↑	**[+3]**	📖📖📖	☺☺☺	★★★★	Decarbonization of the energy system through an up-scaling of renewables will greatly facilitate access to clean, affordable and reliable energy. Hydropower plays an increasingly important role for the global electricity supply. This mitigation option is in line with the targets of SDG7 under the caveat of a transition to modern biomass.	Cherian (2015); Rogelj (2013); Cherian (2015); Jingura and Kamusoko (2016)
	Increased use of biomass		↑	**[+3]**	📖📖📖	☺☺☺	★★★	Increased use of modern biomass will facilitate access to clean, affordable and reliable energy. This mitigation option is in line with the targets of SDG7.	Cherian A. (2015); Jingura R.M., Kamusoko R.(2016), Rogelj (2013)
	Nuclear/Advanced Nuclear		↑	**[1]**	📖📖	☺	★★	Increased use of nuclear power can provide stable baseload power supply and reduce price volatility.	IPCC AR5 WG3 (2014)
	CCS: Bio energy		↑	**[+2]**	📖📖📖	☺☺☺	★★★	Increased use of modern biomass will facilitate access to clean, affordable and reliable energy.	IPCC AR5 WG3 (2014)
Advanced coal	**CCS: Fossil**		↑	**[+2]**	📖📖📖	☺☺☺	★★★	Advanced and cleaner fossil-fuel technology is in line with the targets of SDG7.	IPCC AR5 WG3 (2014)

			INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE		
Replacing coal	**Non-biomass renewables** solar, wind, hydro	**Innovation and Growth (8.1/8.2/8.4)**	~	**[0]**	📖📖	☺☺	★★	Decarbonization of the energy system through an up-scaling of renewables and energy efficiency is consistent with sustained economic growth and resource decoupling. Long-term scenarios point towards slight consumption losses caused by a rapid and pervasive expansion of such energy solutions. Whether sustainable growth, as an overarching concept, is attainable or not is more disputed in the literature. Existing literature is also undecided as to whether or not access to modern energy services causes economic growth (McCollum et al., 2018).	McCollum et al. (2018); Bonan et al. (2014); Clarke et al. (2014); Jackson and Senker (2011); New Climate Economy (2014); OECD (2017); York and McGee (2017)
	Increased use of biomass		↑	**[+1]**	📖	☺	★	Decarbonization of the energy system through an up-scaling of renewables will greatly facilitate access to clean, affordable and reliable energy.	Jingura R.M., Kamusoko R. (2016)
	Nuclear/Advanced Nuclear		↑	**[1]**	📖📖	☺	★★	Local employment impact and reduced price volatility	IPCC AR5 WG3 (2014)
	CCS: Bio energy		↑	**[+1]**	📖	☺	★	See positive impacts of bio-energy use.	
Advanced coal	**CCS: Fossil**	**Innovation and Growth (8.1/8.2/8.4)**	↓	**[-1]**	📖📖📖	☺☺☺	★★★	Lock-in of human and physical capital in the fossil-resources industry	IPCC AR5 WG3 (2014); Vergragt et al. (2011); Markusson et al. (2012); IPCC (2005); Benson et al. (2005); Fankhauser et al. (2008); Shackley and Thompson (2012); Johnson et al. (2015); Bertram et al. (2015)

			INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE		
Replacing coal	**Non-biomass renewables** solar, wind, hydro	**Inclusive and Sustainable Industrialization (9.2/9.4)**	~ / ↓	**[0,-1]**	📖📖	☺☺☺	★★	A rapid up-scaling of renewable energies could necessitate the early retirement of fossil energy infrastructure (e.g., power plants, refineries, pipelines) on a large-scale. The implications of this could in some cases be negative, unless targeted policies can help alleviate the burden on industry (McCollum et al., 2018).	McCollum et al. (2018); Bertram et al. (2015); Fankhauser et al. (2008); Guivarch et al. (2011); Johnson et al. (2015)
	Increased use of biomass		↑	**[+1]**	📖📖	☺☺☺	★★	Access to morden and sustainable energy will be critical to sustain economic growth.	Jingura and Kamusoko (2016); Shahbazet al. (2016)
	Nuclear/Advanced Nuclear	**Innovation and Growth (8.1/8.2/8.4)**	↓	**[-1]**	📖📖	☺☺☺	★★★	Legacy cost of waste and abandoned reactors	IPCC AR5 WG3 (2014); Marra and Palmer (2011); Greenberg, (2013a); Schwenk-Ferrero (2013a); Skipperud et al. (2013); Tyler et al. (2013a)
	CCS: Bio energy		↑	**[+1]**	📖	☺	★	See positive impacts of bio-energy use and CCS/CCU in industrial demand.	
Advanced coal	**CCS: Fossil**		↑	**[+1]**	📖	☺	★	See positive impacts of CCS/CCU in industrial demand.	

			INTERACTION	SCORE	EVIDENCE	AGREEMENT	CONFIDENCE		
Replacing coal	**Non-biomass renewables** solar, wind, hydro	**Disaster Preparedness and Prevention (11.5)**	↑	**[+2]**	📖📖📖	☺☺	★★★	Deployment of renewable energy and improvements in energy efficiency globally will aid climate change mitigation efforts, and this, in turn, can help to reduce the exposure of people to certain types of disasters and extreme events (McCollum et al., 2018).	McCollum et al. (2018); Daut et al. (2013); Hallegatte et al. (2016); IPCC (2014); Riahi et al. (2012); Tully (2006)
	Increased use of biomass			**[0]**				No direct interaction	
	Nuclear/Advanced Nuclear			**[0]**				No direct interaction	
	CCS: Bio energy			**[0]**				No direct interaction	
Advanced coal	**CCS: Fossil**			**[0]**				No direct interaction	

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Agriculture & Livestock	**Behaviourial response: Sustainable healthy diets and reduced food waste**	**Energy Efficiency, universal access (7.1,7.3)** ↑ [+1] 🕮 ☺ ★ Reducing global food supply chain losses have several important secondary benefits like conserving energy. Kummu et al. (2012)	**Sustained and inclusive economic growth (8.2)** ↑ [+1] 🕮🕮🕮 ☺☺☺ ★★★ 23–24% of total cropland and fertilisers are used to produce losses. So reduction in food losses will help to diversify these valuable resources into other productive activities. Kummu et al. (2012); Hiç et al. (2016)	**Infrastructure building and promotion of inclusive industrialization (9.1/ 9.2)** ↑ [+1] 🕮🕮🕮 ☺☺☺ ★★★ By targeting infrastructure,processing and distribution losses wastage in food systems can be minimized. 23–24% of total cropland and fertilisers are used to produce losses. So reduction in food losses will help to diversify these valuable resources into other productive activities. Beddington et al. (2012); Ingram (2011); Lamb et al. (2016); Kummu et al. (2012); Hiç et al. (2016)	**[0]** No interaction
	Land based greenhouse gas reduction and soil carbon sequestration	**Sustainable and modern energy (7.b)** ↑ [+1] 🕮🕮🕮 ☺☺☺ ★★★ Conventional agricultural biotechnology methods such as energy-efficient farming can help in sequestration of soil carbon. Modern biotechnologies like green-energy, N-efficient GM crops can also help in C-sequestration. Biotech crops allow farmers to use less and environmental friendly energy and practice soil carbon sequestration.Biofuels, both from traditional and GMO crops such as sugarcane, oilseed, rapeseed, and jatropha can be produced. Green energy programs through plantations of perennial non edible oil-seed producing plants and production of biodiesel for direct use in the energy sector, or blending biofuels with fossil fuels in certain proportions thereby minimizing use of fossil fuels (Quoted from Lakshmi et. al (2015)). Genetically modified crops reduces demand fossil fuel-based inputs. Mtui (2011); Johnson et al. (2007); Lakshmi et. al (2015); Sarin et al. (2007); Treasury (2009); Lua et al. (2009); Jain and Sharma (2010); Lybbert and Sumner (2010)	**Sustainable Growth (8.2)** ↑ / ↓ [+2,-1] 🕮🕮 ☺☺ ★★ Many developing countries including Gulf States will benefit from CSA given the central role of agriculture in their economic and social development (Quoted from Behnassi, M., Boussaid,M., &Gopichandran, R. (2014)). Low commodity prices have reduced the incentive to invest in yield growth and have led to declining farm labour and farm capital investment.(Quoted from Lamb, A., et al. (2016)) Behnassi, Boussaid and Gopichandran (2014); Lamb, et al. (2016)	**Infrastructure building, promotion of inclusive industrialization and innovation (9.1/** ↑ / ↓ [+2,-2] 🕮🕮🕮 ☺☺☺ ★★★ Reduced research support and delayed industrialization will have an adverse effect on food security and nourishment of children. Organic farming technologies utilizing bio-based fertilizers (composted humus and animal manure) are some of the conventional biotechnological options for reducing artificial fertilizer use (Lakshmi et al., 2015). CSA requires huge financial investment and institutional innovation. CSA is committed to new ways of engaging in participatory research and partnerships with producers (Steenwerth, 2014). Technologies used on-farm and during food processing to increase productivity which also helps in adaptation and/or mitigation are new, so convincing potential customers are difficult. Also Low awareness of CSA and inaccessible language, high costs, lack of verified impact of technologies, hard to reach and train farmers, low consumer demand, unequal distribution of costs/benefits across supply chains are barriers of CSA technology adoption (Long, Blok, and Coninx (2016). Low commodity prices have reduced the incentive to invest in yield growth and have led to declining investment in research and development (Lamb et al., 2016). Evenson (1999); Lakshmi et. al (2015); Behnassi, Boussaid and Gopichandran (2014); Steenwerth et al. (2014); Long, Blok and Coninx (2016); Lamb et al. (2016)	**[0]** no direct interaction
	Greenhouse gas reduction from improved livestock production and manure management systems	**Energy Efficiency (7.3)** ↑ [+1] & J « Scenarios where zero human-edible concentrate feed is use for livestocks non-renewable energy use reduces by 36% Schader et al. (2015)	**Sustainable Economic Growth (8.4)** ↑ [+1] & J « Exploiting the increasingly decoupled interactions between crops and livestock could be beneficial for promoting structural changes in the livestock sector and is a prerequisite for the sustainable growth of the sector. (Quoted from Herrero, M., & Thornton, P. K. (2013) Herrero and Thornton (2013)	**Technological upgradation and Innovation (9.2)** ↑ [+2] 🕮🕮🕮 ☺☺☺ ★★★ Complete genome maps for poultry and cattle now exist, and these open up the way to possible advances in evolutionary biology, animal breeding and animal models for human diseases. Genomic selection should be able to at least double the rate of genetic gain in the dairy industry. (Quoted from Thornton, P. K. (2010)) Nanotechnology, biogas technology, separation technologies are a disruptive technology that enhance biogas production from anaerobic digesters or to reduce odours. Thornton (2010); Sansoucy (1995); Burton (2007)	**[0]** No direct interaction
Forest	**Reduced deforestation, REDD+**	**Energy Efficiency (7.3)** ↑ / ↓ [+1,-1] 🕮 ☺ ★ Consider the entire sinks and reservoirs of greenhouse gas while developing the nationally appropriate mitigations actions. For countries with a significant contribution of forest degradation (and GHG emissions)from wood fuels, this should be considered (Quoted from Lima, M. G. B., Kissinger, G., Visseren-Hamakers, I. J., Braña-Varela, J., & Gupta, A. (2017)). Biomass for energy is recognized as often being inefficient, and is often harvested in an unsustainable manner, but is a renewable energy source Lima et al. (2017); Katila et al. (2017)	**Sustainable Economic Growth (8.4)** ↑ [+1] 🕮 ☺ ★ Efforts by the Government of Zambia to reduce emissions byREDD+, have contributed erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Partnerships betwwen local forest managers, community enterprises and private sector companies can support local economies and livelihoods, and boost regional and national economic growth. Turpie, Warr and Ingram (2015); Epstein and Theuer (2017); Katila et al. (2017)	**Infrastructure building ,promotion of inclusive industrialization (9.1/ 9.2/9.5)** ↑ / ↓ [+1,-1] 🕮 ☺ ★ Expanding road net works are recognized as one of the main drivers of deforesting and forest degradation, diminishing forest benefits to communities, On the other hand, roads can enhance market access, thereby boosting local benefits (SDG 1) from the commercialization of forest products.(Quoted from Katila, P., et al. (2017)). Efforts by the Government of Zambia to reduce emissions byREDD+, have contributed erosion control, ecotourism and pollination valued at 2.5% of the country's GDP. Katila et al. (2017); Turpie, Warr and Ingram (2015); Epstein and Theuer (2017)	**[0]** No direct interaction
	Afforestation and reforestation	**Energy Conservation (7.3/7.b)** ↑ [+1] 🕮 ☺ ★ The US Forest Service estimates that an average NYC street tree (urban afforestation) produces $209 in annual benefits, which is primarily driven by aesthetic ($90 per tree) and energy savings (from shade) benefits ($47.63 per tree) Jones et al. (2018)	**Decent job creation and Sustainable economic growth (8.3/8.4)** ↑ [+2] 🕮🕮 ☺☺ ★★ Many tree plantations worldwide have higher growth rates which can provide higher rates of returns for investors. Agroforestry initiatives that offer significant opportunities for projects to provide benefits to smallholder farmers can also help address land degradation through community based efforts in more marginal areas. Mangroves reduce impacts of disasters (cyclones/storms/floods) enhance water quality, fisheries, tourism business, and livelihoods. Zomer et al. (2008); Kibria (2015)	**[0]** No direct interaction	**Improving air quality, green and public spaces (11.6,11.7, 11a, 11b)** ↑ [+2] 🕮🕮🕮🕮 ☺☺☺☺ ★★★★ Many urban tree plantations world wide are done with focus on multiple benefits like air quality improvement, cultural preference for green nature, healthy community interaction besides temperature control and biodiversity enhancement goals. Pei et al (2018); McKinney (2018); Kowarik (2018); Wei (2018); Chen et al (2018); McPherson et al (2018)
	Behaviourial response (responsible sourcing)	**Universal access (7.3)** ↑ [+1] 🕮 ☺ ★ The trade of wood pellets from clean wood waste should be facilitated with less administrative barriers for the import by the EU, in order to have this new option seriously accounted for as a future resource for energy. (Quoted from Sikkema, R., et al. (2014)). Recommends further harmonization of legal harvesting, sustainable sourcing and cascaded use requirements for woody biomass for energy with the current requirements of voluntary SFM certification schemes. Sikkema et al. (2014)	**Decent job creation and Sustainable economic growth (8.3/8.4)** ↑ [+2] 🕮 ☺ ★ Some standards seek primarily to coordinate global trade, many purport to promote ecological sustainability and social justice or to institutionalize “corporate social responsibility” (CSR) e.g. labour standards developed in the wake of sweatshop and child labour scandals. Environmental standards for pollution control etc. Indonesian factories may seek advantages through non-price competition—perhaps by highlighting decent working conditions or the existence of a union—or to see trade associations or government promoting the country as a responsible sourcing location. Bartley, T. (2010)	**Technological upgradation and Innovation,promotion of inclusive industrialization (9.1/** ↑ [+2] 🕮🕮 ☺☺ ★ Capacity for processing certified timber is often underutilized, due the limited supply available. As a result, manufacturing firms that are seeking to tap into green markets often turn to other sources of timber.(Quoted from Bartley, T. (2010)). Responsible sourcing, when integrated into business practices, can enable retailers to better manage brand value and reputation by avoiding negative public relations, as well as maintaining and enhancing brand integrity (Huang et al., 2013). Bartley, T. (2010), Huang, W., Wilkes, A., Sun, X., & Terheggen, A. (2013)	**Improving air quality, green and public spaces, peri urban spaces (11.6,11.7, 11a, 11b)** ↑ [+2] 🕮🕮🕮🕮 ☺☺☺☺ ★★★★ Many urban tree plantations world wide are done with focus on multiple benefits like air quality improvement, cultural preference for green nature, healthy community interaction besides temperature control and biodiversity enhancement goals. People's preference for urban forest gardens are encouraging new urban green spaces, tree selection helps in building resilience to disaster. Pei et al (2018); McKinney (2018); Kowarik (2018); Wei (2018); Chen et al (2018); McPherson et al (2018)
Oceans	**Ocean iron fertilization**	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction
	Blue carbon	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction
	Enhanced Weathering	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction	**[0]** No direct interaction

Glossary

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Notes: TSU compiled version. Note that subterms are in italics beneath main terms.

1.5°C-consistent emissions pathways
See Pathways.

1.5°C warmer worlds
Projected worlds in which global warming has reached and, unless otherwise indicated, been limited to 1.5°C above pre-industrial levels. There is no single 1.5°C warmer world and projections of 1.5°C warmer worlds look different depending on whether it is considered on a near-term transient trajectory or at climate equilibrium after several millennia, and, in both cases, if it occurs with or without overshoot. Within the 21st century, several aspects play a role for the assessment of risk and potential impacts in 1.5°C warmer worlds: the possible occurrence, magnitude and duration of an overshoot, the way in which emissions reductions are achieved, the ways in which policies might be able to influence the resilience of human and natural systems, and the nature of the regional and sub-regional risks. Beyond the 21st century, several elements of the climate system would continue to change even if the global mean temperatures remain stable, including further increases of sea level.

2030 Agenda for Sustainable Development
A UN resolution in September 2015 adopting a plan of action for people, planet and prosperity in a new global development framework anchored in 17 Sustainable Development Goals (UN, 2015).

See also Sustainable Development Goals (SDGs).

Acceptability of policy or system change
The extent to which a policy or system change is evaluated unfavourably or favourably, or rejected or supported, by members of the general public (public acceptability) or politicians or governments (political acceptability). Acceptability may vary from totally unacceptable/fully rejected to totally acceptable/fully supported; individuals may differ in how acceptable policies or system changes are believed to be.

Adaptability
See Adaptive capacity.

Adaptation
In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Incremental adaptation
Adaptation that maintains the essence and integrity of a system or process at a given scale. [Footnote: This definition builds from the definition used in Park et al. (2012).]

Transformational adaptation
Adaptation that changes the fundamental attributes of a socio-ecological system in anticipation of climate change and its impacts.

Adaptation limits
The point at which an actor’s objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.

Hard adaptation limit - No adaptive actions are possible to avoid intolerable risks.
Soft adaptation limit - Options are currently not available to avoid intolerable risks through adaptive action.

See also Adaptation options, Adaptive capacity, and Maladaptive actions (Maladaptation).

Adaptation behaviour
See Human behaviour.

Adaptation limits
See Adaptation.

Adaptation options
The array of strategies and measures that are available and appropriate for addressing adaptation. They include a wide range of actions that can be categorized as structural, institutional, ecological or behavioural.

See also Adaptation, Adaptive capacity, and Maladaptive actions (Maladaptation).

Adaptation pathways
See Pathways.

Adaptive capacity
The ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. [Footnote: This glossary entry builds from definitions used in previous IPCC reports and the Millennium Ecosystem Assessment (MEA, 2005).]

See also Adaptation, Adaptation options, and Maladaptive actions (Maladaptation).

Adaptive governance
See Governance.

Aerosol
A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 μm that reside in the atmosphere for at least several hours. The term aerosol, which includes both the particles and the suspending gas, is often used in this report in its plural form to mean aerosol particles. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: through both interactions that scatter and/or absorb radiation and through interactions with cloud microphysics and other cloud properties, or upon deposition on snow or ice covered surfaces thereby altering their albedo and contributing to climate feedback. Atmospheric aerosols, whether natural or anthropogenic, originate from two different pathways: emissions of primary particulate matter (PM), and formation of secondary PM from gaseous precursors. The bulk of aerosols are of natural origin. Some scientists use group labels that refer to the chemical composition, namely: sea salt, organic carbon, black carbon (BC), mineral species (mainly desert dust), sulphate, nitrate, and ammonium. These labels are, however, imperfect as aerosols combine particles to create complex mixtures.

See also Short-lived climate forcers (SLCF), and Black carbon (BC).

Afforestation
Planting of new forests on lands that historically have not contained forests. [Footnote: For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000), information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).]

See also Reforestation, Deforestation, and Reducing Emissions from Deforestation and Forest Degradation (REDD+).

Agreement
In this report, the degree of agreement within the scientific body of knowledge on a particular finding is assessed based on multiple lines of evidence (e.g., mechanistic understanding, theory, data, models, expert judgement) and expressed qualitatively (Mastrandrea et al., 2010).

See also Evidence, Confidence, Likelihood, and Uncertainty.

Air pollution
Degradation of air quality with negative effects on human health, the natural or built environment, due to the introduction by natural processes or human activity in the atmosphere of substances (gases, aerosols) which have a direct (primary pollutants) or indirect (secondary pollutants) harmful effect.

See also Aerosol, and Short-lived climate forcers (SLCF).

Albedo
The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow-covered surfaces have a high albedo, the surface albedo of soils ranges from high to low, and vegetation-covered surfaces and the oceans have a low albedo. The Earth's planetary albedo changes mainly through varying cloudiness, snow, ice, leaf area and land cover changes.

Ambient persuasive technology
Technological systems and environments that are designed to change human cognitive processing, attitudes and behaviours without the need for the user’s conscious attention.

Anomaly
The deviation of a variable from its value averaged over a reference period.

See also Reference period.

Anthropocene
The 'Anthropocene' is a proposed new geological epoch resulting from significant human-driven changes to the structure and functioning of the Earth System, including the climate system. Originally

proposed in the Earth System science community in 2000, the proposed new epoch is undergoing a formalization process within the geological community based on the stratigraphic evidence that human activities have changed the Earth System to the extent of forming geological deposits with a signature that is distinct from those of the Holocene, and which will remain in the geological record. Both the stratigraphic and Earth System approaches to defining the Anthropocene consider the mid-20th Century to be the most appropriate starting date, although others have been proposed and continue to be discussed. The Anthropocene concept has been taken up by a diversity of disciplines and the public to denote the substantive influence humans have had on the state, dynamics and future of the Earth System.

See also Holocene.

Anthropogenic
Resulting from or produced by human activities.

See also Anthropogenic emissions, and Anthropogenic removals.

Anthropogenic emissions
Emissions of greenhouse gases (GHGs), precursors of GHGs and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land use changes (LULUC), livestock production, fertilisation, waste management, and industrial processes.

See also Anthropogenic, and Anthropogenic removals.

Anthropogenic removals
Anthropogenic removals refer to the withdrawal of GHGs from the atmosphere as a result of deliberate human activities. These include enhancing biological sinks of CO_2 and using chemical engineering to achieve long term removal and storage. Carbon capture and storage (CCS) from industrial and energy-related sources, which alone does not remove CO_2 in the atmosphere, can reduce atmospheric CO_2 if it is combined with bioenergy production (BECCS).

See also Anthropogenic emissions, Bioenergy with carbon dioxide capture and storage (BECCS), and Carbon dioxide capture and storage (CCS).

Artificial intelligence (AI)
Computer systems able to perform tasks normally requiring human intelligence, such as visual perception and speech recognition.

Atmosphere
The gaseous envelope surrounding the earth, divided into five layers — the troposphere which contains half of the earth's atmosphere, the stratosphere, the mesosphere, the thermosphere, and the exosphere, which is the outer limit of the atmosphere. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93 % volume mixing ratio), helium and radiatively active greenhouse gases (GHGs) such as carbon dioxide (CO_2) (0.04% volume mixing ratio) and ozone (O_3). In addition, the atmosphere contains the GHG water vapour (H_2O), whose amounts are highly variable but typically around 1% volume mixing ratio. The atmosphere also contains clouds and aerosols.

See also Troposphere, Stratosphere, Greenhouse gas (GHG), and Hydrological cycle.

Atmosphere-ocean general circulation model (AOGCM)
See Climate model.

Attribution
See Detection and attribution.

Baseline scenario
In much of the literature the term is also synonymous with the term business-as-usual (BAU) scenario, although the term BAU has fallen out of favour because the idea of business as usual in century-long socio-economic projections is hard to fathom. In the context of transformation pathways, the term baseline scenarios refers to scenarios that are based on the assumption that no mitigation policies or measures will be implemented beyond those that are already in force and/or are legislated or planned to be adopted. Baseline scenarios are not intended to be predictions of the future, but rather counterfactual constructions that can serve to highlight the level of emissions that would occur without further policy effort. Typically, baseline scenarios are then compared to mitigation scenarios that are constructed to meet different goals for greenhouse gas (GHG) emissions, atmospheric concentrations or temperature change. The term baseline scenario is often used interchangeably with reference scenario and no policy scenario.

See also Emission scenario, and Mitigation scenario.

Biochar
Stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Biochar may be added to soils to improve soil functions and to reduce greenhouse gas emissions from biomass and soils, and for carbon sequestration. [Footnote: This definition builds from IBI (2018)]

Biodiversity
Biological diversity means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (UN, 1992).

Bioenergy
Energy derived from any form of biomass or its metabolic by-products.

See also Biomass and Biofuel.

Bioenergy with carbon dioxide capture and storage (BECCS)
Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. Note that depending on the total emissions of the BECCS supply chain, carbon dioxide can be removed from the atmosphere.

See also Bioenergy, and Carbon dioxide capture and storage (CCS).

Biofuel
A fuel, generally in liquid form, produced from biomass. Biofuels currently include bioethanol from sugarcane or maize, biodiesel from canola or soybeans, and black liquor from the paper-manufacturing process.

See also Biomass, and Bioenergy.

Biomass
Living or recently-dead organic material.

See also Bioenergy, and Biofuel.

Biophilic urbanism
Designing cities with green roofs, green walls and green balconies to bring nature into the densest parts of cities in order to provide green infrastructure and human health benefits.

See also Green infrastructure.

Black carbon (BC)
Operationally defined aerosol species based on measurement of light absorption and chemical reactivity and/or thermal stability. It is sometimes referred to as soot. BC is mostly formed by the incomplete combustion of fossil fuels, biofuels, and biomass but it also occurs naturally. It stays in the atmosphere only for days or weeks. It is the most strongly light-absorbing component of particulate matter (PM) and has a warming effect by absorbing heat into the atmosphere and reducing the albedo when deposited on snow or ice.

See also Aerosol.

Blue carbon
Blue carbon is the carbon captured by living organisms in coastal (e.g., mangroves, salt marshes, seagrasses) and marine ecosystems, and stored in biomass and sediments.

Burden sharing (also referred to as Effort sharing)
In the context of mitigation, burden sharing refers to sharing the effort of reducing the sources or enhancing the sinks of greenhouse gases (GHGs) from historical or projected levels, usually allocated by some criteria, as well as sharing the cost burden across countries.

Business as usual (BAU)
See Baseline scenario.

Carbon budget
This term refers to three concepts in the literature: (1) an assessment of carbon cycle sources and sinks on a global level, through the synthesis of evidence for fossil-fuel and cement emissions, land-use change emissions, ocean and land CO_2 sinks, and the resulting atmospheric CO_2 growth rate. This is referred to as the global carbon budget; (2) the estimated cumulative amount of global carbon dioxide emissions that that is estimated to limit global surface temperature to a given level above a

reference period, taking into account global surface temperature contributions of other GHGs and climate forcers; (3) the distribution of the carbon budget defined under (2) to the regional, national, or sub-national level based on considerations of equity, costs or efficiency.

See also Remaining carbon budget.

Carbon cycle
The term used to describe the flow of carbon (in various forms, e.g., as carbon dioxide (CO_2), carbon in biomass, and carbon dissolved in the ocean as carbonate and bicarbonate) through the atmosphere, hydrosphere, terrestrial and marine biosphere and lithosphere. In this report, the reference unit for the global carbon cycle is $GtCO_2$ or GtC (Gigatonne of carbon = 1 GtC = 10^{15} grams of carbon. This corresponds to 3.667 $GtCO_2$).

Carbon dioxide (CO_2)
A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land use changes (LUC) and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a Global Warming Potential (GWP) of 1.

See also Greenhouse gas (GHG). See also Land use and land-use change. See also Global Warming Potential (GWP).

Carbon dioxide capture and storage (CCS)
A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. Sometimes referred to as Carbon Capture and Storage. See also Carbon dioxide capture and utilisation (CCU), Bioenergy with carbon dioxide capture and storage (BECCS), and Sequestration.

Carbon dioxide capture and utilisation (CCU)
A process in which CO_2 is captured and then used to produce a new product. If the CO_2 is stored in a product for a climate-relevant time horizon, this is referred to as carbon dioxide capture, utilisation and storage (CCUS). Only then, and only combined with CO_2 recently removed from the atmosphere, can CCUS lead to carbon dioxide removal. CCU is sometimes referred to as Carbon dioxide capture and use.

See also Carbon dioxide capture and storage (CCS).

Carbon dioxide capture, utilisation and storage (CCUS)
See Carbon dioxide capture and utilisation (CCU).

Carbon dioxide removal (CDR)
Carbon Dioxide Removal methods refer to processes that remove CO_2 from the atmosphere by either increasing biological sinks of CO_2 or using chemical processes to directly bind CO_2. CDR is classified as a special type of mitigation.

See also Mitigation (of climate change), Greenhouse gas removal (GGR), Negative emissions, Sink.

Carbon intensity
The amount of emissions of carbon dioxide (CO_2) released per unit of another variable such as Gross Domestic Product (GDP), output energy use or transport.

Carbon neutrality
Achieving net zero carbon dioxide emissions at a global scale through the balance of residual carbon dioxide emissions with the same amount of carbon dioxide removal.

See also Climate neutrality.

Carbon price
The price for avoided or released carbon dioxide (CO_2) or CO_2-equivalent emissions. This may refer to the rate of a carbon tax, or the price of emission permits. In many models that are used to assess the economic costs of mitigation, carbon prices are used as a proxy to represent the level of effort in mitigation policies.

Carbon sequestration
The process of storing carbon in a carbon pool.

See also Blue carbon, Carbon dioxide capture and storage (CCS), Uptake, and Sink.

Carbon sink
See Sink.

Clean Development Mechanism (CDM)
A mechanism defined under Article 12 of the Kyoto Protocol through which investors (governments or companies) from developed (Annex B) countries may finance greenhouse gas (GHG) emission reduction or removal projects in developing countries (Non-Annex B), and receive Certified Emission Reduction Units (CERs) for doing so. The CERs can be credited towards the commitments of the respective developed countries. The CDM is intended to facilitate the two objectives of promoting sustainable development (SD) in developing countries and of helping industrialized countries to reach their emissions commitments in a cost-effective way.

Climate
Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate-compatible development (CCD)
A form of development building on climate strategies that embrace development goals and development strategies that integrate climate risk management, adaptation and mitigation. Source: (Mitchell and Maxwell, 2010)

Climate change
Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes.

See also Climate variability, Global warming, Ocean acidification, and Detection and attribution.

Climate change commitment
Climate change commitment is defined as the unavoidable future climate change resulting from inertia in the geophysical and socio-economic systems. Different types of climate change commitment are discussed in the literature (see subterms). Climate change commitment is usually quantified in terms of the further change in temperature, but it includes other future changes, for example in the hydrological cycle, in extreme weather events, in extreme climate events, and in sea level.

Constant composition commitment
The constant composition commitment is the remaining climate change that would result if atmospheric composition and hence radiative forcing were held fixed at a given value. It results from the thermal inertia of the ocean and slow processes in the cryosphere and land surface.

Zero emissions commitment
The zero emissions commitment is the climate change commitment that would result from setting anthropogenic emissions to zero. It is determined by both inertia in physical climate system components (ocean, cryosphere, land surface) and carbon cycle inertia.

Constant emissions commitment
The constant emissions commitment is the committed climate change that would result from keeping anthropogenic emissions constant.

Feasible scenario commitment
The feasible scenario commitment is the climate change that corresponds to the lowest emission scenario judged feasible.

Infrastructure commitment
The infrastructure commitment is the climate change that would result if existing greenhouse gas and aerosol emitting infrastructure were used until the end of its expected lifetime.

Climate extreme (extreme weather or climate event)
The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable. For simplicity, both extreme weather events and extreme climate events are referred to collectively as 'climate extremes.'

See also Extreme weather event.

Climate feedback
An interaction in which a perturbation in one climate quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced. The initial perturbation can either be externally forced or arise as part of internal variability.

Climate governance
See Governance.

Climate justice
See Justice.

Climate model
A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrizations are involved. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate and for operational purposes, including monthly, seasonal and interannual climate predictions.

See also Earth system model (ESM).

Climate neutrality
Concept of a state in which human activities result in no net effect on the climate system. Achieving such a state would require balancing of residual emissions with emission (carbon dioxide) removal as well as accounting for regional or local biogeophysical effects of human activities that, for example, affect surface albedo or local climate.

See also Carbon neutrality.

Climate projection
A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases (GHGs) and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions

concerning, for example, future socioeconomic and technological developments that may or may not be realized.

Climate-resilient development pathways (CRDPs)
Trajectories that strengthen sustainable development and efforts to eradicate poverty and reduce inequalities while promoting fair and cross-scalar adaptation to and resilience in a changing climate. They raise the ethics, equity, and feasibility aspects of the deep societal transformation needed to drastically reduce emissions to limit global warming (e.g., to 1.5°C) and achieve desirable and liveable futures and well-being for all.

Climate-resilient pathways
Iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with climate change.

See also Pathways, Climate-resilient development pathways (CRDPs), Development pathways, and Transformation pathways.

Climate services
Climate services refers to information and products that enhance users' knowledge and understanding about the impacts of climate change and/or climate variability so as to aid decision-making of individuals and organizations and enable preparedness and early climate change action. Products can include climate data products.

Climate sensitivity
Climate sensitivity refers to the change in the annual global mean surface temperature in response to a change in the atmospheric CO_2 concentration or other radiative forcing.

Equilibrium climate sensitivity
Refers to the equilibrium (steady state) change in the annual global mean surface temperature following a doubling of the atmospheric carbon dioxide (CO_2) concentration. As a true equilibrium is challenging to define in climate models with dynamic oceans, the equilibrium climate sensitivity is often estimated through experiments in AOGCMs where CO_2 levels are either quadrupled or doubled from pre-industrial levels and which are integrated for 100-200 years. The climate sensitivity parameter (units: °C $(W\ m^{-2})^{-1}$) refers to the equilibrium change in the annual global mean surface temperature following a unit change in radiative forcing.

Effective climate sensitivity
An estimate of the global mean surface temperature response to a doubling of the atmospheric carbon dioxide (CO_2) concentration that is evaluated from model output or observations for evolving non-equilibrium conditions. It is a measure of the strengths of the climate feedbacks at a particular time and may vary with forcing history and climate state, and therefore may differ from equilibrium climate sensitivity.

Transient climate response
The change in the global mean surface temperature, averaged over a 20-year period, centered at the time of atmospheric CO_2 doubling, in a climate model simulation in which CO_2 increases at 1% yr^{-1} from pre-industrial. It is a measure of the strength of climate feedbacks and the timescale of ocean heat uptake.

Climate-smart agriculture (CSA)
Climate-smart agriculture (CSA) is an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate. CSA aims to tackle three main objectives: sustainably increasing agricultural productivity and incomes; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions, where possible (source: FAO).

Climate system
The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land-use change.

Climate target
Climate target refers to a temperature limit, concentration level, or emissions reduction goal used towards the aim of avoiding dangerous anthropogenic interference with the climate system. For example, national climate targets may aim to reduce greenhouse gas emissions by a certain amount over a given time horizon, for example those under the Kyoto Protocol.

Climate variability
Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

See also Climate change.

Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC)
Common but Differentiated Responsibilities and Respective Capabilities (CBDR–RC) is a key principle in the United Nations Framework Convention on Climate Change (UNFCCC) that recognises the different capabilities and differing responsibilities of individual countries in tacking climate change. The principle of CBDR–RC is embedded in the 1992 UNFCCC treaty, The convention states: "… the global nature of climate change calls for the widest possible cooperation by all countries and their participation in an effective and appropriate international response, in accordance with their common but differentiated responsibilities and respective capabilities and their social and economic conditions." Since then the CBDR-RC principle has guided the UN climate negotiations.

CO_2 equivalent (CO_2-eq) emission
The amount of carbon dioxide (CO_2) emission that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a greenhouse gas (GHG) or a mixture of GHGs. There are a number of ways to compute such equivalent emissions and choose appropriate time horizons. Most typically, the CO_2-equivalent emission is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for a 100 year time horizon. For a mix of GHGs it is obtained by summing the CO_2-equivalent emissions of each gas. CO_2-equivalent emission is a common scale for comparing emissions of different GHGs but does not imply equivalence of the

corresponding climate change responses. There is generally no connection between CO_2-equivalent emissions and resulting CO_2-equivalent concentrations.

Conference of the Parties (COP)
The supreme body of UN conventions, such as the United Nations Framework Convention on Climate Change (UNFCCC), comprising parties with a right to vote that have ratified or acceded to the convention.

See also United Nations Framework Convention on Climate Change (UNFCCC).

Confidence
The robustness of a finding based on the type, amount, quality and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement across multiple lines of evidence. In this report, confidence is expressed qualitatively (Mastrandrea et al., 2010). See Section 1.6 for the list of confidence levels used.

See also Agreement, Evidence, Likelihood, and Uncertainty.

Co-benefits
The positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits for society or the environment. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefits.

Conservation agriculture
A coherent group of agronomic and soil management practices that reduce the disruption of soil structure and biota.

Constant composition commitment
See Climate change commitment.

Constant emissions commitment
See Climate change commitment.

Coping capacity
The ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term. [Footnote: This glossary entry builds from the definition used in UNISDR (2009) and IPCC (2012a).]

See also Resilience.

Cost-benefit analysis
Monetary assessment of all negative and positive impacts associated with a given action. Cost-benefit analysis enables comparison of different interventions, investments or strategies and reveal how a

given investment or policy effort pays off for a particular person, company or country. Cost-benefit analyses representing society's point of view are important for climate change decision making, but there are difficulties in aggregating costs and benefits across different actors and across timescales.

See also Discounting.

Cost-effectiveness
A measure of the cost at which policy goal or outcome is achieved. The lower the cost the greater the cost-effectiveness.

See also Integrated models.

Coupled Model Intercomparison Project (CMIP)
The Coupled Model Intercomparison Project (CMIP) is a climate modelling activity from the World Climate Research Programme (WCRP) which coordinates and archives climate model simulations based on shared model inputs by modelling groups from around the world. The CMIP3 multi-model data set includes projections using SRES scenarios. The CMIP5 data set includes projections using the Representative Concentration Pathways. The CMIP6 phase involves a suite of common model experiments as well as an ensemble of CMIP-endorsed model intercomparison projects (MIPs).

Cumulative emissions
The total amount of emissions released over a specified period of time.

See also Carbon budget, and Transient climate response to cumulative CO_2 emissions (TCRE).

Deforestation
Conversion of forest to non-forest. For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). [Footnote: See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).]

See also Afforestation, Reforestation, and Reducing Emissions from Deforestation and Forest Degradation (REDD+).

Demand and supply-side measures

Demand-side measures
Policies and programmes for influencing the demand for goods and/or services. In the energy sector, demand-side management aims at reducing the demand for electricity and other forms of energy required to deliver energy services.

Supply-side measures
Policies and programmes for influencing how a certain demand for goods and/or services is met. In the energy sector, for example, supply-side mitigation measures aim at reducing the amount of greenhouse gas emissions emitted per unit of energy produced.

See also Mitigation measures.

Demand-side measures
See Demand and supply-side measures.

Detection
See Detection and attribution.

Detection and attribution
Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%. Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with a formal assessment of confidence.

Discounting
A mathematical operation that aims to make monetary (or other) amounts received or expended at different times (years) comparable across time. The discounter uses a fixed or possibly time-varying discount rate from year to year that makes future value worth less today (if the discount rate is positive). The choice of discount rate(s) is debated as it is a judgement based on hidden and/or explicit values.

Discount rate
See Discounting.

(Internal) Displacement
Internal displacement refers to the forced movement of people within the country they live in. Internally displaced persons (IDPs) are "Persons or groups of persons who have been forced or obliged to flee or to leave their homes or places of habitual residence, in particular as a result of or in order to avoid the effects of armed conflict, situations of generalized violence, violations of human rights or natural or human-made disasters, and who have not crossed an internationally recognized State border." (UNCHR, 1998).

See also Migration.

Distributive equity
See Equity.

Distributive justice
See Justice.

Downscaling
Downscaling is a method that derives local- to regional-scale (up to 100 km) information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods [are based on observations and] develop statistical relationships that link the large-scale atmospheric variables with local/ regional climate variables. In all cases, the quality of the driving model remains an important limitation on quality of the downscaled information. The two methods can be combined, e.g., applying empirical/statistical downscaling to the output of a regional climate model, consisting of a dynamical downscaling of a global climate model."

Drought
A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term (see Box 3-3), therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion. For example, shortage of precipitation during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought), and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in precipitation. A period with an abnormal precipitation deficit is defined as a meteorological drought.

See also Soil moisture.

Megadrought
A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more.

Decarbonisation
The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport.

Decoupling
Decoupling (in relation to climate change) is where economic growth is no longer strongly associated with consumption of fossil fuels. Relative decoupling is where both grow but at different rates. Absolute decoupling is where economic growth happens but fossil fuels decline.

Deliberative governance
See Governance.

Development pathways
See Pathways.

Direct air carbon dioxide capture and storage (DACCS)
Chemical process by which CO_2 is captured directly from the ambient air, with subsequent storage. Also known as direct air capture and storage (DACS).

Disaster
Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.

See also Hazard.

Disaster risk management (DRM)
Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices, with the explicit purpose of increasing human security, well-being, quality of life, and sustainable development.

Disruptive innovation
Disruptive innovation is demand-led technological change that leads to significant system change and is characterized by strong exponential growth.

Double dividend
The extent to which revenues generated by policy instruments, such as carbon taxes or auctioned (tradeable) emission permits can (1) contribute to mitigation and (2) offset part of the potential welfare losses of climate policies through recycling the revenue in the economy by reducing other distortionary taxes.

Early warning systems (EWS)
The set of technical, financial and institutional capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare to act promptly and appropriately to reduce the possibility of harm or loss. Dependent upon context, EWS may draw upon scientific and/or Indigenous knowledge. EWS are also considered for ecological applications e.g., conservation, where the organisation itself is not threatened by hazard but the ecosystem under conservation is (an example is coral bleaching alerts), in agriculture (for example, warnings of ground frost, hailstorms) and in fisheries (storm and tsunami warnings). This glossary entry builds from the definitions used in UNISDR (2009) and IPCC (2012a).

Earth system feedbacks
See Climate feedback.

Earth system model (ESM)
A coupled atmosphere–ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric CO_2 or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included.

See also Climate model.

Ecosystem
An ecosystem is a functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment.

See also Ecosystem services.

Ecosystem services
Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or biodiversity maintenance, (2) provisioning services such as food or fibre, (3) regulating services such as climate regulation or carbon sequestration, and (4) cultural services such as tourism or spiritual and aesthetic appreciation.

Effective climate sensitivity
See Climate sensitivity.

Effective radiative forcing
See Radiative forcing.

Electric vehicle (EV)
A vehicle whose propulsion is powered fully or mostly by electricity.

Battery electric vehicle (BEV)
A vehicle whose propulsion is entirely electric without any internal combustion engine.

Plug-in hybrid electric vehicle (PHEV)
A vehicle whose propulsion is mostly electric with batteries re-charged from an electric source but extra power and distance are provided by a hybrid internal combustion engine.

El niño-southern oscillation (ENSO)
The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere–ocean phenomenon, with preferred time scales of two to about seven years, is known as the El Niño-Southern Oscillation (ENSO). It is often measured by the surface pressure anomaly difference between Tahiti and Darwin and/or the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This phenomenon has a great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and

in many other parts of the world, through global teleconnections. The cold phase of ENSO is called La Niña.

Emission scenario

A plausible representation of the future development of emissions of substances that are radiatively active (e.g., greenhouse gases (GHGs), aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and land use) and their key relationships. Concentration scenarios, derived from emission scenarios, are often used as input to a climate model to compute climate projections.

See also Baseline scenario, Mitigation scenario, Representative Concentration Pathways (RCPs) (under Pathways), Shared socio-economic pathways (SSPs) (under Pathways), Scenario, Socio-economic scenario, and Transformation pathway.

Emissions trading

A market-based instrument aiming at meeting a mitigation objective in an efficient way. A cap on GHG emissions is divided in tradeable emission permits that are allocated by a combination of auctioning and handing out free allowances to entities within the jurisdiction of the trading scheme. Entities need to surrender emission permits equal to the amount of their emissions (e.g., tonnes of CO_2). An entity may sell excess permits to entities that can avoid the same amount of emissions in a cheaper way. Trading schemes may occur at the intra-company, domestic, or international level (e.g., the flexibility mechanisms under the Kyoto Protocol and the EU-EUTS) and may apply to carbon dioxide (CO_2), other greenhouse gases (GHGs), or other substances.

Emission trajectories

A projected development in time of the emission of a greenhouse gas (GHG) or group of GHGs, aerosols, and GHG precursors.

See also Pathways.

Enabling conditions

Conditions that affect the feasibility of adaptation and mitigation options, and can accelerate and scale-up systemic transitions that would limit temperature increase to 1.5°C and enhance capacities of systems and societies to adapt to the associated climate change, while achieving sustainable development, eradicating poverty and reducing inequalities. Enabling conditions include finance, technological innovation, strengthening policy instruments, institutional capacity, multi-level governance, and changes in human behaviour and lifestyles. They also include inclusive processes, attention to power asymmetries and unequal opportunities for development and reconsideration of values.

See also Feasibility.

Energy efficiency

The ratio of output or useful energy or energy services or other useful physical outputs obtained from a system, conversion process, transmission or storage activity to the input of energy (measured as $kWh\ kWh^{-1}$, tonnes kWh^{-1} or any other physical measure of useful output like tonne-km transported). Energy efficiency is often described by energy intensity. In economics, energy intensity describes the ratio of economic output to energy input. Most commonly energy efficiency is measured as input energy over a physical or economic unit, i.e. kWh USD^{-1} (energy intensity), kWh tonne^{-1}. For buildings, it is often measured as kWh m^{-2}, and for vehicles as km liter^{-1}or liter km^{-1}. Very often in policy "energy efficiency" is intended as the measures to reduce energy demand through technological options such as insulating buildings, more efficient appliances, efficient lighting, efficient vehicles, etc.

Energy security
The goal of a given country, or the global community as a whole, to maintain an adequate, stable and predictable energy supply. Measures encompass safeguarding the sufficiency of energy resources to meet national energy demand at competitive and stable prices and the resilience of the energy supply; enabling development and deployment of technologies; building sufficient infrastructure to generate, store and transmit energy supplies and ensuring enforceable contracts of delivery.

Enhanced weathering
Enhancing the removal of carbon dioxide from the atmosphere through dissolution of silicate and carbonate rocks by grinding these minerals to small particles and actively applying them to soils, coasts or oceans.

(Model) Ensemble
A group of parallel model simulations characterising historical climate conditions, climate predictions, or climate projections. Variation of the results across the ensemble members may give an estimate of modelling-based uncertainty. Ensembles made with the same model but different initial conditions only characterize the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model differences. Perturbed parameter ensembles, in which model parameters are varied in a systematic manner, aim to assess the uncertainty resulting from internal model specifications within a single model. Remaining sources of uncertainty unaddressed with model ensembles are related to systematic model errors or biases, which may be assessed from systematic comparisons of model simulations with observations wherever available.

See also Climate projection.

Equality
A principle that ascribes equal worth to all human beings, including equal opportunities, rights, and obligations, irrespective of origins

Inequality
Uneven opportunities and social positions, and processes of discrimination within a group or society, based on gender, class, ethnicity, age, and (dis)ability, often produced by uneven development. Income inequality refers to gaps between highest and lowest income earners within a country and between countries.

See also Equity, Ethics, and Fairness.

Equilibrium climate sensitivity
See Climate sensitivity.

Equity
Equity is the principle of fairness in burden sharing and is a basis for understanding how the impacts and responses to climate change, including costs and benefits, are distributed in and by society in more or less equal ways. It is often aligned with ideas of equality, fairness and justice and applied with respect to equity in the responsibility for, and distribution of, climate impacts and policies across society, generations, and gender, and in the sense of who participates and controls the processes of decision making.

Distributive equity
Equity in the consequences, outcomes, costs and benefits of actions or policies. In the case of climate change or climate policies for different people, places and countries, including equity aspects of sharing burdens and benefits for mitigation and adaptation.

Gender equity
Ensuring equity in that women and men have the same rights, resources and opportunities. In the case of climate change gender equity recognizes that women are often more vulnerable to the impacts of climate change and may be disadvantaged in the process and outcomes of climate policy.

Inter-generational equity
Equity between generations that acknowledges that the effects of past and present emissions, vulnerabilities and policies impose costs and benefits for people in the future and of different age groups.

Procedural equity
Equity in the process of decision making including recognition and inclusiveness in participation, equal representation, bargaining power, voice and equitable access to knowledge and resources to participate.

See also Equality, Ethics and Fairness.

Ethics
Ethics involves questions of justice and value. Justice is concerned with right and wrong, equity and fairness, and, in general, with the rights to which people and living beings are entitled. Value is a matter of worth, benefit, or good.

See also Equality, Equity, and Fairness.

Evidence
Data and information used in the scientific process to establish findings. In this report, the degree of evidence reflects the amount, quality, and consistency of scientific/technical information on which the Lead Authors are basing their findings.

See also Agreement, Confidence, Likelihood, and Uncertainty.

Exposure
The presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.

See also Hazard, Risk, and Vulnerability.

Extratropical Cyclone
Any cyclonic-scale storm that is not a tropical cyclone. Usually refers to a middle- or high-latitude migratory storm system formed in regions of large horizontal temperature variations. Sometimes called extratropical storm or extratropical low.

See also Tropical cyclone.

Extreme weather or climate event
See Climate extreme (extreme weather or climate event).

Extreme weather event
An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).

See also Heat wave, and Climate extreme (extreme weather or climate event)

Fairness
Impartial and just treatment without favouritism or discrimination in which each person is considered of equal worth with equal opportunity.

See also Equity, Equality and Ethics.

Feasible scenario commitment
See Climate change commitment.

Feasibility
The degree to which climate goals and response options are considered possible and/or desirable. Feasibility depends on geophysical, ecological, technological, economic, social and institutional conditions for change. Conditions underpinning feasibility are dynamic, spatially variable, and may vary between different groups.

See also Enabling conditions.

Feedback
See Climate feedback.

Flexible governance
See Governance.

Flood
The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas that are not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.

Food security
A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2001).

Food wastage
Food wastage encompasses food loss (the loss of food during production and transportation) and food waste (the waste of food by the consumer) (FAO, 2013).

Forcing
See Radiative forcing.

Forest
A vegetation type dominated by trees. Many definitions of the term forest are in use throughout the world, reflecting wide differences in biogeophysical conditions, social structure and economics. For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). [Footnote: See also information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013) and the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).]

See also Afforestation, Deforestation, and Reforestation.

Fossil fuels
Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.

Framework Convention on Climate Change
See United Nations Framework Convention on Climate Change (UNFCCC).

Gender equity
See Equity.

General purpose technologies (GPT)
General Purpose Technologies can be or are used pervasively in a wide range of sectors in ways that fundamentally change the modes of operation of those sectors (Helpman, 1998). Examples include the steam engine, power generator and motor, ICT, and biotechnology.

Geoengineering
In this report, separate consideration is given to the two main approaches considered as 'geoengineering' in some of the literature: solar radiation modification (SRM) and carbon dioxide removal (CDR). Because of this separation, the term 'geoengineering' is not used in this report. See also Carbon dioxide removal (CDR) and Solar radiation modification (SRM).

Glacier
A perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallisation of snow and showing evidence of past or present flow. A glacier typically gains mass by accumulation of snow, and loses mass by melting and ice discharge into the sea or a lake if the glacier terminates in a body of water. Land ice masses of continental size (>50 000 km^2) are referred to as ice sheets.

See also Ice sheet.

Global climate model (also referred to as general circulation model, both abbreviated as GCM)
See Climate model.

Global mean surface temperature (GMST)
Area-weighted global average of land surface air temperature over land and sea surface temperatures, unless otherwise specified, normally expressed relative to a specified reference period.

See also Land surface air temperature, and Sea surface temperature (SST).

Global warming
An increase in global mean surface temperature (GMST) averaged over a 30-year period, relative to 1850-1900 unless otherwise specified. For periods shorter than 30 years, global warming refers to the estimated average temperature over the 30 years centred on that shorter period, accounting for the impact of any temperature fluctuations or trend within those 30 years.

See also Climate change, Climate variability, and Global mean surface temperature (GMST).

Governance
A comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures. Whereas government is defined strictly in terms of the nation-state, the more inclusive concept of governance recognizes the contributions of various levels of government (global, international, regional, sub-national and local) and the contributing roles of the private sector, of nongovernmental actors, and of civil society to addressing the many types of issues facing the global community.

Adaptive governance
An emerging term in the literature for the evolution of formal and informal institutions of governance that prioritize social learning in planning, implementation and evaluation of policy through iterative social learning to steer the use and protection of natural resources, ecosystem services and common pool natural resources, particularly in situations of complexity and uncertainty.

Climate governance
Purposeful mechanisms and measures aimed at steering social systems towards preventing, mitigating, or adapting to the risks posed by climate change (Jagers and Stripple, 2003).

Deliberative governance
Deliberative governance involves decision making through inclusive public conversation which allows opportunity for developing policy options through public discussion rather than collating individual preferences through voting or referenda (although the later governance mechanisms can also be proceeded and legitimated by public deliberation processes).

Flexible governance
Strategies of governance at various levels, which prioritize the use of social learning and rapid feedback mechanisms in planning and policy making, often through incremental, experimental and iterative management processes.

Governance capacity
The ability of governance institutions, leaders, and non-state and civil society to plan, co-ordinate, fund, implement, evaluate and adjust policies and measures over the short, medium and long term, adjusting for uncertainty, rapid change and wide ranging impacts and multiple actors and demands.

Multi-level governance
Multi-level governance refers to negotiated, non-hierarchical exchanges between institutions at the transnational, national, regional and local levels. Multi-level governance identifies relationships among governance processes at these different levels. Multi-level governance does include negotiated relationships among institutions at different institutional levels and also a vertical 'layering' of governance processes at different levels. Institutional relationships take place directly between, transnational, regional and local levels, thus bypassing the state level (Peters and Pierre, 2001).

Participatory governance
A governance system that enables direct public engagement in decision-making using a variety of techniques for example, referenda, community deliberation, citizen juries or participatory budgeting. The approach can be applied in formal and informal institutional contexts from national to local, but is usually associated with devolved decision making. [Footnote: This definition builds from Fung and Olin Wright (2003) and Sarmiento and Tilly (2018).]

Governance capacity
See Governance.

Green infrastructure
The interconnected set of natural and constructed ecological systems, green spaces and other landscape features. It includes planted and indigenous trees, wetlands, parks, green open spaces and original grassland and woodlands, as well as possible building and street level design interventions that incorporate vegetation. Green infrastructure provides services and functions in the same way as conventional infrastructure. This definition builds from Culwick and Bobbins (2016).

Greenhouse gas (GHG)
Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4)

and ozone (O_3) are the primary GHGs in the earth's atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the GHGs sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

See also Carbon dioxide (CO_2), Methane (CH_4), and Ozone (O_3).

Greenhouse gas removal (GGR)
Withdrawal of a GHG and/or a precursor from the atmosphere by a sink.

See also Carbon dioxide removal (CDR), and Negative emissions.

Gross domestic product (GDP)
The sum of gross value added, at purchasers' prices, by all resident and non-resident producers in the economy, plus any taxes and minus any subsidies not included in the value of the products in a country or a geographic region for a given period, normally one year. GDP is calculated without deducting for depreciation of fabricated assets or depletion and degradation of natural resources.

Gross fixed capital formation (GFCF)
One component of the GDP that corresponds to the total value of acquisitions, minus disposals of fixed assets during one year by the business sector, governments and households, plus certain additions to the value of non-produced assets (such as subsoil assets or major improvements in the quantity, quality or productivity of land).

Halocarbons
A collective term for the group of partially halogenated organic species, which includes the chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), halons, methyl chloride and methyl bromide. Many of the halocarbons have large Global Warming Potentials. The chlorine and bromine-containing halocarbons are also involved in the depletion of the ozone layer.

Hazard
The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

See also Disaster, Exposure, Risk, and Vulnerability.

Heating, ventilation, and air conditioning (HVAC)
Heating, ventilation and air conditioning technology is used to control temperature and humidity in an indoor environment, be it in buildings or in vehicles, providing thermal comfort and healthy air quality to the occupants. HVAC systems can be designed for an isolated space, an individual building or a distributed heating and cooling network within a building structure or a district heating system. The latter provides economies of scale and also scope for integration with solar heat, natural seasonal cooling/heating etc.

Heat wave
A period of abnormally hot weather. Heat waves and warm spells have various and in some cases overlapping definitions.

See also Extreme weather event.

Holocene
The Holocene is the current interglacial geological epoch, the second of two epochs within the Quaternary period, the preceding being the Pleistocene. The International Commission on Stratigraphy defines the start of the Holocene at 11,650 years before 1950.

See also Anthropocene.

Human behaviour
The way in which a person acts in response to a particular situation or stimulus. Human actions are relevant at different levels, from international, national, and sub-national actors, to NGO, firm-level actors, and communities, households, and individual actions.

Adaptation behaviour
Human actions that directly or indirectly affect the risks of climate change impacts.

Mitigation behaviour
Human actions that directly or indirectly influence mitigation.

Human behavioural change
A transformation or modification of human actions. Behaviour change efforts can be planned in ways that mitigate climate change and/or reduce negative consequences of climate change impacts.

Human rights
Rights that are inherent to all human beings, universal, inalienable, and indivisible, typically expressed and guaranteed by law. They include the right to life, economic, social, and cultural rights, and the right to development and self-determination (based upon the definition by the UN Office of the High Commissioner).

Procedural rights
Rights to a legal procedure to enforce substantive rights.

Substantive rights
Basic human rights, including the right to the substance of being human such as life itself, liberty and happiness.

Human security
A condition that is met when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity. In the context of climate change, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests and to live with dignity.

Human system
Any system in which human organizations and institutions play a major role. Often, but not always, the term is synonymous with society or social system. Systems such as agricultural systems, urban systems, political systems, technological systems, and economic systems are all human systems in the sense applied in this report.

Hydrological cycle
The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condenses to form clouds, precipitates as rain or snow, which on land can be intercepted by trees and vegetation, potentially accumulates as snow or ice, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, flows out into the oceans, and ultimately evaporates again from the ocean or land surface. The various systems involved in the hydrological cycle are usually referred to as hydrological systems.

Ice sheet
A mass of land ice of continental size that is sufficiently thick to cover most of the underlying bed, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast flowing ice streams or outlet glaciers, in some cases into the sea or into ice shelves floating on the sea. There are only two ice sheets in the modern world, one on Greenland and one on Antarctica. During glacial periods there were others.

See also Glacier.

Impacts (consequences, outcomes)
The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability. Impacts generally refer to effects on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial.

See also Adaptation, Exposure, Hazard, Loss and Damage, and loss and damages, and Vulnerability.

(climate change) Impact assessment
The practice of identifying and evaluating, in monetary and/or non-monetary terms, the effects of climate change on natural and human systems.

Incremental adaptation
See Adaptation.

Indigenous knowledge
Indigenous knowledge refers to the understandings, skills and philosophies developed by societies with long histories of interaction with their natural surroundings. For many Indigenous peoples, Indigenous knowledge informs decision-making about fundamental aspects of life, from day-to-day

activities to longer term actions. This knowledge is integral to cultural complexes, which also encompass language, systems of classification, resource use practices, social interactions, values, ritual and spirituality. These distinctive ways of knowing are important facets of the world's cultural diversity. This definition builds on UNESCO (2018).

Indirect land-use change
See Land-use change.

Industrial revolution
A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels, initially coal, and hence emission of carbon dioxide (CO_2).

See also Pre-industrial.

Industrialized/developed/developing countries
There are a diversity of approaches for categorizing countries on the basis of their level of development, and for defining terms such as industrialized, developed, or developing. Several categorizations are used in this report. (1) In the United Nations system, there is no established convention for designating of developed and developing countries or areas. (2) The United Nations Statistics Division specifies developed and developing regions based on common practice. In addition, specific countries are designated as Least Developed Countries (LCD), landlocked developing countries, small island developing states, and transition economies. Many countries appear in more than one of these categories. (3) The World Bank uses income as the main criterion for classifying countries as low, lower middle, upper middle, and high income. (4) The UNDP aggregates indicators for life expectancy, educational attainment, and income into a single composite Human Development Index (HDI) to classify countries as low, medium, high, or very high human development.

Inequality
See Equality.

Information and communication technology (ICT)
An umbrella term that includes any information and communication device or application, encompassing: computer systems, network hardware and software, cellphone, etc.

Infrastructure commitment
See Climate change commitment.

Institution
Institutions are rules and norms held in common by social actors that guide, constrain and shape human interaction. Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations - such as parliaments, regulatory agencies, private firms, and community bodies - develop and act in response to institutional frameworks and the incentives they

frame. Institutions can guide, constrain and shape human interaction through direct control, through incentives, and through processes of socialization.

See also Institutional capacity.

Institutional capacity

Institutional capacity comprises building and strengthening individual organisations and providing technical and management training to support integrated planning and decision-making processes between organisations and people, as well as empowerment, social capital, and an enabling environment, including the culture, values and power relations (Willems and Baumert, 2003).

Integrated assessment

A method of analysis that combines results and models from the physical, biological, economic and social sciences and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.

See also Integrated assessment model (IAM).

Integrated assessment model (IAM)

Integrated assessment models (IAMs) integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments.

One class of IAM used in respect of climate change mitigation may include representations of: multiple sectors of the economy, such as energy, land use and land use change; interactions between sectors; the economy as a whole; associated GHG emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social and technological development and the evolution of the climate system.

Another class of IAM additionally includes representations of the costs associated with climate change impacts, but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost-benefit framework and have been used to estimate the social cost of carbon.

Integrated water resources management (IWRM)

A process which promotes the coordinated development and management of water, land and related resources in order to maximise economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.

Inter-generational equity

See Equity.

Inter-generational justice

See Justice.

Internal variability

See Climate variability.

Internet of Things (IoT)
The network of computing devices embedded in everyday objects such as cars, phones and computers, connected via the internet, enabling them to send and receive data.

Iron fertilisation
See Ocean fertilisation.

Irreversibility
A perturbed state of a dynamical system is defined as irreversible on a given timescale, if the recovery timescale from this state due to natural processes is substantially longer than the time it takes for the system to reach this perturbed state.

See also Tipping point.

Justice
Justice is concerned with ensuring that people get what is due to them setting out the moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society.

Climate justice
Justice that links development and human rights to achieve a human-centred approach to addressing climate change, safeguarding the rights of the most vulnerable people and sharing the burdens and benefits of climate change and its impacts equitably and fairly. This definitions builds upon the one used by the Mary Robinson Foundation - Climate Justice.

Distributive justice
Justice in the allocation of economic and non-economic costs and benefits across society.

Inter-generational justice
Justice in the distribution of economic and non-economic costs and benefits across generations.

Procedural justice
Justice in the way outcomes are brought about including who participates and is heard in the processes of decision making.

Social justice
Just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity, and support according to principles of justice and fairness.

See also Equity, Ethics, Fairness, and Human rights.

Kyoto Protocol
The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty adopted in December 1997 in Kyoto, Japan, at the Third Session of the Conference of the Parties (COP3) to the UNFCCC. It contains legally binding commitments, in addition to those included in the UNFCCC. Countries included in Annex B of the Protocol (mostly OECD countries and countries with economies in transition) agreed to reduce their anthropogenic greenhouse gas (GHG) emissions (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6)) by at least 5%

below 1990 levels in the first commitment period (2008-2012). The Kyoto Protocol entered into force on 16 February 2005 and as of May 2018 had 192 Parties (191 States and the European Union). A second commitment period was agreed in December 2012 at COP18, known as the Doha Amendment to the Kyoto Protocol, in which a new set of Parties committed to reduce GHG emissions by at least 18% below 1990 levels in the period from 2013 to 2020. However, as of May 2018, the Doha Amendment had not received sufficient ratifications to enter into force.

See also United Nations Framework Convention on Climate Change (UNFCCC), and Paris Agreement.

Land surface air temperature
The near-surface air temperature over land, typically measured at 1.25-2 m above the ground using standard meteorological equipment.

Land use
Land use refers to the total of arrangements, activities and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation and city dwelling). In national greenhouse gas inventories, land use is classified according to the IPCC land use categories of forest land, cropland, grassland, wetland, settlements, other.

See also Land-use change.

Land-use change (LUC)
Land-use change involves a change from one land use category to another.

Indirect land-use change (iLUC)
Refers to market-mediated or policy-driven shifts in land use that cannot be directly attributed to land use management decisions of individuals or groups. For example, if agricultural land is diverted to fuel production, forest clearance may occur elsewhere to replace the former agricultural production.

Land use, land-use change and forestry (LULUCF)
In the context of national greenhouse gas (GHG) inventories under the UNFCCC, LULUCF is a GHG inventory sector that covers anthropogenic emissions and removals of GHG from carbon pools in managed lands, excluding non-CO_2 agricultural emissions. Following the 2006 IPCC Guidelines for National GHG Inventories, “anthropogenic” land-related GHG fluxes are defined as all those occurring on “managed land”, i.e., “where human interventions and practices have been applied to perform production, ecological or social functions”. Since managed land may include CO_2 removals not considered as “anthropogenic” in some of the scientific literature assessed in this report (e.g., removals associated with CO_2 fertilisation and N deposition), the land-related net GHG emission estimates included in this report are not necessarily directly comparable with LULUCF estimates in National GHG Inventories.

See also Afforestation, Deforestation, Reforestation and the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000).

Land use, land-use change and forestry (LULUCF)
See Land use, land-use change and forestry (LULUCF).

Lifecycle assessment (LCA)
Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product or service throughout its life cycle. This definition builds from ISO (2018).

Likelihood
The chance of a specific outcome occurring, where this might be estimated probabilistically. Likelihood is expressed in this report using a standard terminology (Mastrandrea et al., 2010). See Section 1.6 for the list of likelihood qualifiers used.

See also Agreement, Evidence, Confidence, and Uncertainty.

Livelihood
The resources used and the activities undertaken in order to live. Livelihoods are usually determined by the entitlements and assets to which people have access. Such assets can be categorised as human, social, natural, physical, or financial.

Local knowledge
Local knowledge refers to the understandings and skills developed by individuals and populations, specific to the places where they live. Local knowledge informs decision-making about fundamental aspects of life, from day-to-day activities to longer term actions. This knowledge is a key element of the social and cultural systems which influence observations of, and responses to climate change; it also informs governance decisions. This definition builds on UNESCO (2018)

Lock-in
A situation in which the future development of a system, including infrastructure, technologies, investments, institutions, and behavioural norms, is determined or constrained (“locked in”) by historic developments.

Long-lived climate forcers (LLCF)
Long-lived climate forcers refer to a set of well-mixed greenhouse gases with long atmospheric lifetimes. This set of compounds includes carbon dioxide and nitrous oxide, together with some fluorinated gases. They have a warming effect on climate. These compounds accumulate in the atmosphere at decadal to centennial timescales, and their effect on climate hence persists for decades to centuries after their emission. On timescales of decades to a century already emitted emissions of long-lived climate forcers can only be abated by greenhouse gas removal (GGR).

See also Short-lived climate forcers (SLCF).

Loss and Damage, and losses and damages
Research has taken Loss and Damage (capitalized letters) to refer to political debate under the UNFCCC following the establishment of the Warsaw Mechanism on Loss and Damage in 2013, which is to “address loss and damage associated with impacts of climate change, including extreme events and slow onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change.” Lowercase letters (losses and damages) have been taken to refer broadly to harm from (observed) impacts and (projected) risks (see Mechler et al., 2018).

Maladaptive actions (Maladaptation)
Actions that may lead to increased risk of adverse climate-related outcomes, including via increased GHG emissions, increased vulnerability to climate change, or diminished welfare, now or in the future. Maladaptation is usually an unintended consequence.

Market exchange rates (MER)
The rate at which a currency of one country can be exchanged with the currency of another country. In most economies such rates evolve daily while in others there are official conversion rates that are adjusted periodically.

See also Purchasing power parity (PPP).

Market failure
When private decisions are based on market prices that do not reflect the real scarcity of goods and services but rather reflect market distortions, they do not generate an efficient allocation of resources but cause welfare losses. A market distortion is any event in which a market reaches a market clearing price that is substantially different from the price that a market would achieve while operating under conditions of perfect competition and state enforcement of legal contracts and the ownership of private property. Examples of factors causing market prices to deviate from real economic scarcity are environmental externalities, public goods, monopoly power, information asymmetry, transaction costs, and non-rational behaviour.

Measurement, reporting and verification (MRV)

Measurement
"The process of data collection over time, providing basic datasets, including associated accuracy and precision, for the range of relevant variables. Possible data sources are field measurements, field observations, detection through remote sensing and interviews." Source: UN REDD

Reporting
"The process of formal reporting of assessment results to the UNFCCC, according to predetermined formats and according to established standards, especially the Intergovernmental Panel on Climate Change (IPCC) Guidelines and GPG (Good Practice Guidance)." Source: UN REDD

Verification
"The process of formal verification of reports, for example, the established approach to verify national communications and national inventory reports to the UNFCCC." Source: UN REDD

Megadrought
See Drought.

Methane (CH_4)
One of the six greenhouse gases (GHGs) to be mitigated under the Kyoto Protocol and is the major component of natural gas and associated with all hydrocarbon fuels. Significant emissions occur as a result of animal husbandry and agriculture and their management represents a major mitigation option.

Migration
The International Organization for Migration (IOM) defines migration as "The movement of a person or a group of persons, either across an international border, or within a State. It is a population movement, encompassing any kind of movement of people, whatever its length, composition and causes; it includes migration of refugees, displaced persons, economic migrants, and persons moving for other purposes, including family reunification." (IOM, 2018).

Migrant
The International Organization for Migration (IOM) defines a migrant as "any person who is moving or has moved across an international border or within a State away from his/her habitual place of residence, regardless of (1) the person's legal status; (2) whether the movement is voluntary or involuntary; (3) what the causes for the movement are; or (4) what the length of the stay is." (IOM, 2018).

See also (Internal) Displacement.

Millennium Development Goals (MDGs)
A set of eight time-bound and measurable goals for combating poverty, hunger, disease, illiteracy, discrimination against women and environmental degradation. These goals were agreed at the UN Millennium Summit in 2000 together with an action plan to reach the goals by 2015.

Mitigation (of climate change)
A human intervention to reduce emissions or enhance the sinks of greenhouse gases. Note that this encompasses carbon dioxide removal (CDR) options.

Mitigation behaviour
See Human behaviour.

Mitigation measures
In climate policy, mitigation measures are technologies, processes or practices that contribute to mitigation, for example renewable energy (RE) technologies, waste minimization processes, public transport commuting practices.

See also Policies (for mitigation and adaptation).

Mitigation option
A technology or practice that reduces GHG emissions or enhances sinks.

Mitigation pathways
See Pathways.

Mitigation scenario
A plausible description of the future that describes how the (studied) system responds to the implementation of mitigation policies and measures.

See also Emission scenario, Pathways, Socio-economic scenarios, and Stabilisation (of GHG or CO_2-equivalent concentration).

Monitoring and evaluation (M&E)
Monitoring and evaluation refers to mechanisms put in place at national to local scales to respectively monitor and evaluate efforts to reduce greenhouse gas emissions and/or adapt to the impacts of climate change with the aim of systematically identifying, characterizing and assessing progress over time.

Motivation (of an individual)
An individual’s reason or reasons for acting in a particular way; individuals may consider various consequences of actions, including financial, social, affective, and environmental consequences. Motivation can arise from outside (extrinsic) or inside (intrinsic) the individual.

Multi-level governance
See Governance.

Narratives
Qualitative descriptions of plausible future world evolutions, describing the characteristics, general logic and developments underlying a particular quantitative set of scenarios. Narratives are also referred to in the literature as “storylines”.

See also Scenario, Scenario storyline and Pathways.

Nationally Determined Contributions (NDCs)
A term used under the United Nations Framework Convention on Climate Change (UNFCCC) whereby a country that has joined the Paris Agreement outlines its plans for reducing its emissions. Some countries NDCs also address how they will adapt to climate change impacts, and what support they need from, or will provide to, other countries to adopt low-carbon pathways and to build climate resilience. According to Article 4 paragraph 2 of the Paris Agreement, each Party shall prepare, communicate and maintain successive NDCs that it intends to achieve. In the lead up to 21st Conference of the Parties in Paris in 2015, countries submitted Intended Nationally Determined Contributions (INDCs). As countries join the Paris Agreement, unless they decide otherwise, this INDC becomes their first Nationally Determined Contribution (NDC).

See also United Nations Framework Convention on Climate Change (UNFCCC), and Paris agreement.

Negative emissions
Removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, i.e. in addition to the removal that would occur via natural carbon cycle processes. For CO_2, negative emissions can be achieved with direct capture of CO_2 from ambient air, bioenergy with carbon capture and sequestration (BECCS), afforestation, reforestation, biochar, ocean alkalinization, among others.

See also Net negative emissions, Net-zero emissions, Carbon dioxide removal (CDR), and Greenhouse gas removal (GGR).

Net negative emissions
A situation of net negative emissions is achieved when, as result of human activities, more greenhouse gases are removed from the atmosphere than are emitted into it. Where multiple greenhouse gases are involved, the quantification of negative emissions depends on the climate metric chosen to compare emissions of different gases (such as Global warming potential, Global temperature change potential, and others, as well as the chosen time horizon).

See also Negative emissions, Net-zero emissions and Net-zero CO_2 emissions.

Net-zero CO_2 emissions
Conditions in which any remaining anthropogenic carbon dioxide (CO_2) emissions are balanced globally by anthropogenic CO_2 removals. Net-zero CO_2 emissions are also referred to as carbon neutrality.

See also Net-zero emissions, Carbon neutrality and Net negative emissions.

Net-zero emissions
Net-zero emissions are achieved when emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals. Where multiple greenhouse gases are involved, the quantification of net-zero emissions depends on the climate metric chosen to compare emissions of different gases (such as Global warming potential, global temperature change potential, and others, as well as the chosen time horizon).

See also Net-zero CO_2 emissions, Negative emissions, Net negative emission, and Carbon neutrality

Nitrous oxide (N_2O)
One of the six greenhouse gases (GHGs) to be mitigated under the Kyoto Protocol. The main anthropogenic source of N_2O is agriculture (soil and animal manure management), but important contributions also come from sewage treatment, fossil fuel combustion, and chemical industrial processes. N_2O is also produced naturally from a wide variety of biological sources in soil and water, particularly microbial action in wet tropical forests.

Non-overshoot pathways
See Pathways.

Ocean acidification (OA)
Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide (CO_2) from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity (IPCC, 2011, p. 37).

Ocean fertilisation
Deliberate increase of nutrient supply to the near-surface ocean in order to enhance biological production through which additional carbon dioxide from the atmosphere is sequestered. This can be achieved by the addition of micro-nutrients or macro-nutrients. Ocean fertilisation is regulated by the London Protocol.

Overshoot
The temporary exceedance of a specified level of global warming, such as 1.5°C. Overshoot implies a peak followed by a decline in global warming, achieved through anthropogenic removal of CO_2 exceeding remaining CO_2 emissions globally.

See also Pathways (Subterms: Overshoot pathways, Non-overshoot Pathways).

Overshoot pathways
See Pathways.

Ozone (O_3)
Ozone, the triatomic form of oxygen (O_3), is a gaseous atmospheric constituent. In the troposphere, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.

Paris Agreement
The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) was adopted on December 2015 in Paris, France, at the 21st session of the Conference of the Parties (COP) to the UNFCCC. The agreement, adopted by 196 Parties to the UNFCCC, entered into force on 4 November 2016 and as of May 2018 had 195 Signatories and was ratified by 177 Parties. One of the goals of the Paris Agreement is “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”, recognising that this would significantly reduce the risks and impacts of climate change. Additionally, the Agreement aims to strengthen the ability of countries to deal with the impacts of climate change. The Paris Agreement is intended to become fully effective in 2020.

See also United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, and Nationally Determined Contributions (NDCs).

Participatory governance
See Governance.

Pathways
The temporal evolution of natural and/or human systems towards a future state. Pathway concepts range from sets of quantitative and qualitative scenarios or narratives of potential futures to solution-oriented decision-making processes to achieve desirable societal goals. Pathway approaches typically focus on biophysical, techno-economic, and/or socio-behavioural trajectories and involve various dynamics, goals, and actors across different scales.

1.5°C-consistent pathway
A pathway of emissions of greenhouse gases and other climate forcers that provides an approximately one-in-two to two-in-three chance, given current knowledge of the climate response, of global warming either remaining below 1.5°C or returning to 1.5°C by around 2100 following an overshoot.

Adaptation pathways
A series of adaptation choices involving trade-offs between short-term and long-term goals and values. These are processes of deliberation to identify solutions that are meaningful to people in the context of their daily lives and to avoid potential maladaptation.

Development pathways
Development pathways are trajectories based on an array of social, economic, cultural, technological, institutional, and biophysical features that characterise the interactions between human and natural systems and outline visions for the future, at a particular scale.

Mitigation pathways
A mitigation pathway is a temporal evolution of a set of mitigation scenario features, such as greenhouse gas emissions and socio-economic development.

Overshoot pathways
Pathways that exceed the stabilization level (concentration, forcing, or temperature) before the end of a time horizon of interest (e.g., before 2100) and then decline towards that level by that time. Once the target level is exceeded, removal by sinks of greenhouse gases is required.
See also Overshoot.

Non-overshoot pathways
Pathways that stay below the stabilization level (concentration, forcing, or temperature) during the time horizon of interest (e.g., until 2100).

Representative concentration pathways (RCPs)
Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover (Moss et al., 2008). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasizes the fact that not only the long-term concentration levels, but also the trajectory taken over time to reach that outcome are of interest (Moss et al., 2010). RCPs were used to develop climate projections in CMIP5.

RCP2.6
One pathway where radiative forcing peaks at approximately 3 W m^{-2} and then declines to be limited at 2.6 W m^{-2} in 2100 (the corresponding Extended Concentration Pathway, or ECP, has constant emissions after 2100).

RCP4.5 and RCP6.0
Two intermediate stabilisation pathways in which radiative forcing is limited at approximately 4.5 W m^{-2} and 6.0 W m^{-2} in 2100 (the corresponding ECPs have constant concentrations after 2150).

RCP8.5
One high pathway which leads to >8.5 W m^{-2} in 2100 (the corresponding ECP has constant emissions after 2100 until 2150 and constant concentrations after 2250).

See also CMIP, and Shared socio-economic pathways (SSPs).

Shared socio-economic pathways (SSPs)
Shared socio-economic pathways (SSPs) were developed to complement the RCPs with varying socio-economic challenges to adaptation and mitigation (O’Neill et al., 2014). Based on five narratives, the SSPs describe alternative socio-economic futures in the absence of climate policy intervention, comprising sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil–fueled development (SSP5), and a middle-of-the-road development (SSP2) (O’Neill, 2000;

O'Neill et al., 2017; Riahi et al., 2017). The combination of SSP-based socio-economic scenarios and Representative Concentration Pathway (RCP)-based climate projections provides an integrative frame for climate impact and policy analysis.

Transformation pathways
Trajectories describing consistent sets of possible futures of greenhouse gas (GHG) emissions, atmospheric concentrations, or global mean surface temperatures implied from mitigation and adaptation actions associated with a set of broad and irreversible economic, technological, societal, and behavioural changes. This can encompass changes in the way energy and infrastructure are used and produced, natural resources are managed and institutions are set up and in the pace and direction of technological change (TC).

See also Scenario, Scenario storyline, Emission scenario, Mitigation scenario, Baseline scenario, Stabilisation (of GHG or CO_2-equivalent concentration), and Narratives.

Peri-urban areas
Peri-urban areas are those parts of a city that appear to be quite rural but are in reality strongly linked functionally to the city in its daily activities.

Permafrost
Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years.

pH
pH is a dimensionless measure of the acidity of a solution given by its concentration of hydrogen ions ($[H^+]$). pH is measured on a logarithmic scale where $pH = -\log_{10}[H^+]$. Thus, a pH decrease of 1 unit corresponds to a 10-fold increase in the concentration of H^+, or acidity.

Policies (for climate change mitigation and adaptation)
Policies are taken and/or mandated by a government - often in conjunction with business and industry within a single country, or collectively with other countries - to accelerate mitigation and adaptation measures. Examples of policies are support mechanisms for renewable energy supplies, carbon or energy taxes, fuel efficiency standards for automobiles, etc.

Political economy
The set of interlinked relationships between people, the state, society and markets as defined by law, politics, economics, customs and power that determine the outcome of trade and transactions and the distribution of wealth in a country or economy.

Poverty
Poverty is a complex concept with several definitions stemming from different schools of thought. It can refer to material circumstances (such as need, pattern of deprivation or limited resources), economic conditions (such as standard of living, inequality or economic position) and/or social relationships (such as social class, dependency, exclusion, lack of basic security or lack of entitlement).

See also Poverty eradication.

Poverty eradication
A set of measures to end poverty in all its forms everywhere.

See also Sustainable Development Goals (SDGs).

Precursors

Atmospheric compounds that are not greenhouse gases (GHGs) or aerosols, but that have an effect on GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.

See also Aerosol, and Greenhouse gas (GHG).

Pre-industrial
The multi-century period prior to the onset of large-scale industrial activity. The reference period 1850-1900 is used to approximate pre-industrial global mean surface temperature (GMST) in this report.

See also Industrial revolution.

Procedural equity
See Equity.

Procedural justice
See Justice.

Procedural rights
See Human rights.

Projection
A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realized.

See also Climate projection, Scenario, and Pathways.

Purchasing power parity (PPP)
The purchasing power of a currency is expressed using a basket of goods and services that can be bought with a given amount in the home country. International comparison of, for example, gross domestic products (GDP) of countries can be based on the purchasing power of currencies rather than on current exchange rates. PPP estimates tend to lower the gap between the per capita GDP in industrialised and developing countries.

See also Market exchange rate (MER).

Radiative forcing

Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) at the tropopause or top of atmosphere due to a change in an driver of climate change, such as a change in the concentration of carbon dioxide or the output of the Sun. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is termed the effective radiative forcing. Radiative forcing is not to be confused with cloud radiative forcing, which describes an unrelated measure of the impact of clouds on the radiative flux at the top of the atmosphere.

Reasons for concern (RFCs)

Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of climate change may be dangerous (in the language of Article 2 of the UNFCCC) by aggregating risks from various sectors, considering hazards, exposures, vulnerabilities, capacities to adapt, and the resulting impacts.

Reducing Emissions from Deforestation and Forest Degradation (REDD+)

An effort to create financial value for the carbon stored in forests, offering incentives for developing countries to reduce emissions from forested lands and invest in low-carbon paths to sustainable development (SD). It is therefore a mechanism for mitigation that results from avoiding deforestation. REDD+ goes beyond deforestation and forest degradation, and includes the role of conservation, sustainable management of forests and enhancement of forest carbon stocks. The concept was first introduced in 2005 in the 11th Session of the Conference of the Parties (COP) in Montreal and later given greater recognition in the 13th Session of the COP in 2007 at Bali and inclusion in the Bali Action Plan which called for 'policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries (REDD) and the role of conservation, sustainable management of forests and enhancement of forest carbon stock in developing countries'. Since then, support for REDD has increased and has slowly become a framework for action supported by a number of countries.

Reference period

The period relative to which anomalies are computed.

See also Anomalies.

Reference scenario

See Baseline scenario.

Reforestation

Planting of forests on lands that have previously contained forests but that have been converted to some other use. [Footnote: For a discussion of the term forest and related terms such as afforestation, reforestation and deforestation, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000), information provided by the United Nations Framework Convention on Climate Change (UNFCCC, 2013), the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).]

See also Deforestation, and Afforestation, and Reducing Emissions from Deforestation and Forest Degradation (REDD+).

Region
A region is a relatively large-scale land or ocean area characterized by specific geographical and climatological features. The climate of a land-based region is affected by regional and local scale features like topography, land use characteristics and large water bodies, as well as remote influences from other regions, in addition to global climate conditions. The IPCC defines a set of standard regions for analyses of observed climate trends and climate model projections (see Fig. 3.2; AR5, SREX).

Remaining carbon budget
Cumulative global CO_2 emissions from the start of 2018 to the time that CO_2 emissions reach net-zero that would result in a given level of global warming.

See also Carbon budget.

Representative concentration pathways (RCPs)
See Pathways

Resilience
The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.[Footnote: This definition builds from the definition used by Arctic Council (2013).]

See also Hazard, Risk, and Vulnerability.

Risk
The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and wellbeing, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence.

Risk assessment
The qualitative and/or quantitative scientific estimation of risks.

See also Risk, Risk management, and Risk perception.

Risk management
Plans, actions, strategies or policies to reduce the likelihood and/or consequences of risks or to respond to consequences.

See also Risk, Risk assessment, and Risk perception.

Risk perception
The subjective judgment that people make about the characteristics and severity of a risk.

See also Risk, Risk assessment, and Risk management.

Runoff
The flow of water over the surface or through the subsurface, which typically originates from the part of liquid precipitation and/or snow/ice melt that does not evaporate or refreeze, and is not transpired.

See also Hydrological cycle.

Scenario
A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change (TC), prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

See also Baseline scenario, Emission scenario, Mitigation scenario and Pathways.

Scenario storyline
A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution. Also referred to as ‘narratives’ in the scenario literature.

See also Narratives.

Sea ice
Ice found at the sea surface that has originated from the freezing of seawater. Sea ice may be discontinuous pieces (ice floes) moved on the ocean surface by wind and currents (pack ice), or a motionless sheet attached to the coast (land-fast ice). Sea ice concentration is the fraction of the ocean covered by ice. Sea ice less than one year old is called first-year ice. Perennial ice is sea ice that survives at least one summer. It may be subdivided into second-year ice and multi-year ice, where multiyear ice has survived at least two summers.

Sea level change (sea level rise/sea level fall)
Sea level can change, both globally and locally (relative sea level change) due to (1) a change in ocean volume as a result of a change in the mass of water in the ocean, (2) changes in ocean volume as a result of changes in ocean water density, (3) changes in the shape of the ocean basins and changes in the Earth’s gravitational and rotational fields, and (4) local subsidence or uplift of the land. Global mean sea level change resulting from change in the mass of the ocean is called barystatic. The amount of barystatic sea level change due to the addition or removal of a mass of water is called its sea level equivalent (SLE). Sea level changes, both globally and locally, resulting from changes in water density are called steric. Density changes induced by temperature changes only are called thermosteric, while density changes induced by salinity changes are called halosteric. Barystatic and

steric sea level changes do not include the effect of changes in the shape of ocean basins induced by the change in the ocean mass and its distribution.

Sea surface temperature (SST)
The sea surface temperature is the subsurface bulk temperature in the top few meters of the ocean, measured by ships, buoys, and drifters. From ships, measurements of water samples in buckets were mostly switched in the 1940s to samples from engine intake water. Satellite measurements of skin temperature (uppermost layer; a fraction of a millimeter thick) in the infrared or the top centimeter or so in the microwave are also used, but must be adjusted to be compatible with the bulk temperature.

Sendai Framework for Disaster Risk Reduction
The Sendai Framework for Disaster Risk Reduction 2015-2030 outlines seven clear targets and four priorities for action to prevent new, and to reduce existing disaster risks. The voluntary, non-binding agreement recognizes that the State has the primary role to reduce disaster risk but that responsibility should be shared with other stakeholders including local government, the private sector and other stakeholders, with the aim for the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries.

Sequestration
See Uptake.

Shared socio-economic pathways (SSPs)
See Pathways.

Short-lived climate forcers (SLCF)
Short-lived climate forcers refers to a set of compounds that are primarily composed of those with short lifetimes in the atmosphere compared to well-mixed greenhouse gases, and are also referred to as near-term climate forcers. This set of compounds includes methane, which is also a well-mixed greenhouse gas, as well as ozone and aerosols, or their precursors, and some halogenated species that are not well-mixed greenhouse gases. These compounds do not accumulate in the atmosphere at decadal to centennial timescales, and so their effect on climate is predominantly in the first decade after their emission, although their changes can still induce long-term climate effects such as sea-level change. Their effect can be cooling or warming. A subset of exclusively warming short-lived climate forcers is referred to as short-lived climate pollutants.

See also Long-lived climate forcers (LLCF).

Short-lived climate pollutants (SLCP)
See Short-lived climate forcers (SLCF).

Sink
A reservoir (natural or human, in soil, ocean, and plants) where a greenhouse gas, an aerosol or a precursor of a greenhouse gas is stored. Note that UNFCCC Article 1.8 refers to a sink as any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere.

See also Sequestration, and Uptake.

Small Island Developing States (SIDS)
Small Island Developing States (SIDS), as recognised by the United Nations OHRLLS (Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States), are a distinct group of developing countries facing specific social, economic and environmental vulnerabilities (UN-OHRLLS, 2011). They were recognized as a special case both for their environment and development at the Rio Earth Summit in Brazil in 1992. Fifty eight countries and territories are presently classified as SIDS by the UN OHRLLS, with 38 being UN member states and 20 being Non-UN Members or Associate Members of the Regional Commissions (UN-OHRLLS, 2018).

Social costs
The full costs of an action in terms of social welfare losses, including external costs associated with the impacts of this action on the environment, the economy (GDP, employment) and on the society as a whole.

Social cost of carbon (SCC)
The net present value of aggregate climate damages (with overall harmful damages expressed as a number with positive sign) from one more tonne of carbon in the form of carbon dioxide (CO_2), conditional on a global emissions trajectory over time.

Social inclusion
A process of improving the terms of participation in society, particularly for people who are disadvantaged, through enhancing opportunities, access to resources, and respect for rights (UN, 2016).

Social justice
See Justice.

Social learning
A process of social interaction through which people learn new behaviours, capacities, values, and attitudes.

Social value of mitigation activities (SVMA)
Social, economic and environmental value of mitigation activities that include, in addition to their climate benefits, their co-benefits to adaptation and sustainable development objectives.

Social-ecological systems
An integrated system that includes human societies and ecosystems, in which humans are part of nature. The functions of such a system arise from the interactions and interdependence of the social and ecological subsystems. The system’s structure is characterized by reciprocal feedbacks, emphasising that humans must be seen as a part of, not apart from, nature. [Footnote: This definition

builds from Arctic Council (2016) and Berkes and Folke (1998).]

Societal (social) transformation
See Transformation.

Socio-economic scenario
A scenario that describes a possible future in terms of population, gross domestic product (GDP), and other socio-economic factors relevant to understanding the implications of climate change.

See also Reference scenario, Emission scenario, Mitigation scenario and Pathways.

Socio-technical transitions
Socio-technical transitions are where technological change is associated with social systems and the two are inextricably linked.

Soil carbon sequestration (SCS)
Land management changes which increase the soil organic carbon content, resulting in a net removal of CO_2 from the atmosphere.

Soil moisture
Water stored in the soil in liquid or frozen form. Root-zone soil moisture is of most relevance for plant activity.

Solar radiation management
See Solar radiation modification (SRM).

Solar radiation modification (SRM)
Solar radiation modification refers to the intentional modification of the Earth's shortwave radiative budget with the aim of reducing warming. Artificial injection of stratospheric aerosols, marine cloud brightening and land surface albedo modification are examples of proposed SRM methods. SRM does not fall within the definitions of mitigation and adaptation (IPCC, 2012b, p. 2). Note that in the literature SRM is also referred to as solar radiation management or albedo enhancement.

Stabilisation (of GHG or CO_2-equivalent concentration)
A state in which the atmospheric concentrations of one greenhouse gas (GHG) (e.g., carbon dioxide) or of a CO_2-equivalent basket of GHGs (or a combination of GHGs and aerosols) remains constant over time.

Stranded assets
Assets exposed to devaluations or conversion to ‘liabilities’ because of unanticipated changes in their initially expected revenues due to innovations and/or evolutions of the business context, including changes in public regulations at the domestic and international levels.

Stratosphere
The highly stratified region of the atmosphere above the troposphere extending from about 10 km (ranging from 9 km at high latitudes to 16 km in the tropics on average) to about 50 km altitude.

See also Atmosphere, and Troposphere.

Subnational actor
Subnational actors include state/provincial, regional, metropolitan and local/municipal governments as well as non-party stakeholders, such as civil society, the private sector, cities and other subnational authorities, local communities and indigenous peoples.

Substantive rights
See Human rights.

Supply-side measures
See Demand and supply-side measures.

Surface temperature
See Global mean surface temperature (GMST), Land surface air temperature, and Sea surface temperature (SST).

Sustainability
A dynamic process that guarantees the persistence of natural and human systems in an equitable manner.

Sustainable development (SD)
Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987) and balances social, economic and environmental concerns.

See also Sustainable Development Goals (SDGs) and Development pathways (under Pathways).

Sustainable Development Goals (SDGs)
The 17 global goals for development for all countries established by the United Nations through a participatory process and elaborated in the 2030 Agenda for Sustainable Development, including ending poverty and hunger; ensuring health and wellbeing, education, gender equality, clean water and energy, and decent work; building and ensuring resilient and sustainable infrastructure, cities and consumption; reducing inequalities; protecting land and water ecosystems; promoting peace, justice and partnerships; and taking urgent action on climate change.

See also Sustainable development (SD).

SDG-interaction score
A seven-point scale (Nilsson et al., 2016) used to rate interactions between mitigation options and the SDGs. Scores range from +3 (indivisible) to -3 (cancelling), with a zero score indicating ‘consistent’

but with neither a positive or negative interaction. The scale, as applied in this report, also includes: direction (whether the interaction is uni- or bi-directional), and confidence as assessed per IPCC guidelines.

Technology transfer
The exchange of knowledge, hardware and associated software, money and goods among stakeholders, which leads to the spread of technology for adaptation or mitigation. The term encompasses both diffusion of technologies and technological cooperation across and within countries.

Tipping point
A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated. For the climate system, it refers to a critical threshold when global or regional climate changes from one stable state to another stable state.

See also Irreversibility.

Transformation
A change in the fundamental attributes of natural and human systems.

Societal (social) transformation
A profound and often deliberate shift initiated by communities toward sustainability, facilitated by changes in individual and collective values and behaviours, and a fairer balance of political, cultural, and institutional power in society.

Transformation pathways
See Pathways.

Transformational adaptation
See Adaptation.

Transformative change
A system wide change. This requires more than technological change to consideration of social and economic factors that with technology can bring about rapid change at scale.

Transient climate response
See Climate sensitivity.

Transient climate response to cumulative CO_2 emissions (TCRE)
The transient global average surface temperature change per unit cumulative CO_2 emissions, usually 1000 GtC. TCRE combines both information on the airborne fraction of cumulative CO_2 emissions (the fraction of the total CO_2 emitted that remains in the atmosphere, which is determined by carbon cycle processes) and on the transient climate response (TCR).

See also Transient climate response (TCR) (under Climate sensitivity).

Transit-oriented development (TOD)
An approach urban development that maximizes the amount of residential, business and leisure space within walking distance of efficient public transport, so as to enhance mobility of citizens, the viability of public transport and the value of urban land in mutually supporting ways.

Transition
The process of changing from one state or condition to another in a given period of time. Transition can be in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change.

Tropical cyclone
The general term for a strong, cyclonic-scale disturbance that originates over tropical oceans. Distinguished from weaker systems (often named tropical disturbances or depressions) by exceeding a threshold wind speed. A tropical storm is a tropical cyclone with one-minute average surface winds between 18 and 32 m s^{-1}. Beyond 32 m s^{-1}, a tropical cyclone is called a hurricane, typhoon, or cyclone, depending on geographic location.

See also Extratropical cyclone.

Troposphere
The lowest part of the atmosphere, from the surface to about 10 km in altitude at mid-latitudes (ranging from 9 km at high latitudes to 16 km in the tropics on average), where clouds and weather phenomena occur. In the troposphere, temperatures generally decrease with height.

See also Atmosphere, and Stratosphere.

Uncertainty
A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, incomplete understanding of critical processes, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts) (see IPCC, 2004; Mastrandrea et al., 2010; Moss and Schneider, 2000).

See also Confidence, and Likelihood.

United Nations Framework Convention on Climate Change (UNFCCC)
The UNFCCC was adopted in May 1992 and opened for signature at the 1992 Earth Summit in Rio de Janeiro. It entered into force in March 1994 and as of May 2018 had 197 Parties (196 States and the European Union). The Convention's ultimate objective is the "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The provisions of the Convention are pursued and implemented by two treaties: the Kyoto Protocol and the Paris Agreement.

See also Kyoto Protocol, and Paris Agreement.

Uptake
The addition of a substance of concern to a reservoir.
See also Carbon sequestration and Sink.

Vulnerability
The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

See also Exposure, Hazard, and Risk.

Water cycle
See Hydrological cycle.

Wellbeing
A state of existence that fulfils various human needs, including material living conditions and quality of life, as well as the ability to pursue one’s goals, to thrive, and feel satisfied with one’s life. Ecosystem well-being refers to the ability of ecosystems to maintain their diversity and quality.

Zero emissions commitment
See Climate change commitment.

References

Arctic Council (2013). "Glossary of terms," in Arctic Resilience Interim Report 2013 (Stockholm, Sweden: Stockholm Environment Institute and Stockholm Resilience Centre), viii.

Arctic Council (2016). Arctic Resilience Report 2016. , eds. M. Carson and G. Peterson Stockholm Sweden: Stockholm Environment Institute and Stockholm Resilience Centre.

Berkes, F., and Folke, C. (1998). Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. New York: Cambridge University Press.

Culwick, C., and Bobbins, K. (2016). A Framework for a Green Infrastructure Planning Approach in the Gauteng City-Region. Johannesburg: GCRO.

FAO (2001). "Glossary," in The State of Food Insecurity in the World 2001 (Food and Agriculture Organisation of the United Nations (FAO)).

FAO (2013). Food wastage footprint. Impacts on natural resources. Summary Report. Rome, Italy: Food and Agriculture Organisation of the United Nations.

Fung, A and E.O Wright, 2003, Deepened Democracy: Institutional innovation in Empowered Participatory Governance. Verso, London.

Helpman, E. (1998). General Purpose Technologies and Economic Growth. , ed. E. Helpman Cambridge, MA, USA: MIT Press.

IBI (2018). Frequently Asked Questions About Biochar: What is biochar? Available at: http://www.biochar-international.org/biochar/faqs#question1.
IOM (2018). Key Migration Terms. Available at: https://www.iom.int/key-migration-terms.

IPCC (2000). Land Use, Land-Use Change, and Forestry: A Special Report of the IPCC. , eds. R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo, and D. J. Dokken Cambridge, UK.

IPCC (2003). Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types. , eds. J. Penman, M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, et al. Hayama, Kanagawa, Japan.

IPCC (2004). IPCC Workshop on Describing Scientific Uncertainties in Climate Change to Support Analysis of Risk of Options. Workshop Report. , eds. M. R. Manning, M. Petit, D. Easterling, J. Murphy, A. Patwardhan, H.-H. Rogner, et al. Geneva, Switzerland.

IPCC (2011). Workshop Report of the Intergovernmental Panel on Climate Change Workshop on Impacts of Ocean Acidification on Marine Biology and Ecosystems. , eds. C. B. Field, V. Barros, T. F. Stocker, D. Qin, K. J. Mach, G.-K. Plattner, et al. Stanford, California, United States of America: IPCC Working Group II Technical Support Unit, Carnegie Institution.

IPCC (2012a). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of IPCC Intergovernmental Panel on Climate Change. , eds. C. B. Field, V. Barros, T. F. Stocker, Q. Dahe, D. J. Dokken, K. L. Ebi, et al. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press doi:9781107607804.

IPCC (2012b). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). , eds. C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, et al. Cambridge, UK and New York, NY, USA: Cambridge University Press.

ISO (2018). ISO 14044:2006. Environmental management - Life cycle assessment - Requirements and guidelines. Available at: https://www.iso.org/standard/38498.html [Accessed May 31, 2018].

Jagers, S. C., and Stripple, J. (2003). Climate Governance Beyond the State. Glob. Gov. 9, 385–399.

Mastrandrea, M. D., Field, C. B., Stocker, T. F., Edenhofer, O., Ebi, K. L., Frame, D. J., et al. (2010). Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Geneva, Switzerland.

MEA (2005). “Appendix D: Glossary,” in Ecosystems and Human Well-being: Current States and Trends. Findings of the Condition and Trends Working Group, Vol. 1, eds. R. Hassan, R. Scholes, and N. Ash (Washington DC, USA: Island Press), 893–900.

Mechler, R., Bouwer, L., Schinko, T., Surminski, S., and Linnerooth-Bayer, J. (2018). Loss and Damage from Climate Change. Concepts, Methods and Policy Options. Springer Heidelberg.

Mitchell, T., and Maxwell, S. (2010). Defining climate compatible development.

Moss, R., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., et al. (2008). Towards new scenarios for analysis of emissions, climate change, impacts and response strategies. Geneva, Switzerland.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., et al. (2010). The next generation of scenarios for climate change research and assessment. Nature 463, 747–756.

Moss, R., and Schneider, S. (2000). “Uncertainties in the IPCC TAR: Recommendations to Lead Authors for More Consistent Assessment and Reporting,” in, eds. R. Pachauri, T. Taniguchi, and K. Tanaka (Geneva, Switzerland), 33–51.

Nilsson, M., Griggs, D., and Visback, M. (2016). Map the interactions between Sustainable Development Goals. Nature 534, 320–322. doi:10.1038/534320a.

O’Neill, B. (2000). The Jury is still out on global warming potentials. Clim. Change 44, 427–443. doi:10.1023/A:1005582929198.

O’Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., et al. (2017). The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180. doi:10.1016/j.gloenvcha.2015.01.004.

O’Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., et al. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Clim. Change 122, 387–400. doi:10.1007/s10584-013-0905-2.

Park, S. E., Marshall, N. A., Jakku, E., Dowd, A. M., Howden, S. M., Mendham, E., et al. (2012). Informing adaptation responses to climate change through theories of transformation. Glob. Environ. Chang. 22, 115–126. doi:10.1016/j.gloenvcha.2011.10.003.

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O’Neill, B. C., Fujimori, S., et al. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Chang. 42, 153–168. doi:10.1016/j.gloenvcha.2016.05.009.

UN-OHRLLS (2011). Small Island Developing States: Small Islands Big(ger) Stakes. New York, NY: Office for the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States (UN-OHRLLS).

UN-OHRLLS (2018). Small Island Developing States: Country Profiles.

UN (1992). Convention on Biological Diversity - Article 2: Use of Terms.

UN (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. New York.

UN (2016). “Identifying social inclusion and exclusion,” in Leaving no one behind: the imperative of inclusive development. Report on the World Social Situation 2016 ST/ESA/362. (New York, NY, USA), 17–31.

UNCHR (1998). Guiding Principles on Internal Displacement.

UNESCO (2018). Local and Indigenous Knowledge Systems. Available at: http://www.unesco.org/new/en/natural-sciences/priority-areas/links/related-information/what-is-local-and-indigenous-knowledge/ [Accessed May 15, 2018].

UNFCCC (2013). Reporting and accounting of LULUCF activities under the Kyoto Protocol. Available at: http://unfccc.int/methods/lulucf/items/4129.php.

UNISDR (2009). 2009 UNISDR Terminology on Disaster Risk Reduction. Geneva, Switzerland.
Willems, S., and Baumert, K. (2003). Institutional Capacity and Climate Actions. Paris, France.

Changes to the Underlying Scientific-Technical Assessment to ensure consistency with the approved Summary for Policymakers

1. Background

Consistent with Section 4.5 of Appendix A to the Principles Governing IPCC Work, Coordinating Lead Authors have identified some changes to the underlying report to ensure consistency with the language used in the approved Summary for Policymakers or to provide additional clarification as agreed at the Joint Working Group Session. These changes do not alter any substantive findings of the final draft of the underlying report as distributed to governments on 29 August 2018.
Note that the final draft of the underlying report is also subject to copy-editing and corrections in proof as normally applied to scientific reports.

2. Changes to be made to the underlying report

The following table lists those changes that will be made in the underlying report following the line by line approval of its Summary for Policymakers.
Note that page and line numbers for the SPM are based on the numbering used in the revised final draft as distributed to Governments on 30 September 2018; page and line numbers for the underlying report are based on the numbering used in the final draft as distributed to Governments on 29 August 2018.

SPM Page:Line or Section	Chapter	Chapter Page:Line	Summary
5:20	1	4:30	Reconcile confidence assessment to medium for general statement about past emissions committing us to 1.5C on all timescales.
4:8	1	7:40	Avoid the use of 1.5C-consistent pathways throughout Chapter 1, clarifying whether statements are referring to no-or-limited-overshoot versus high-overshoot in all cases.
14:2	1	32:1	CDR is considered distinct from the above mitigation activities", or some equivalent usage that does not imply explicitly that CDR is considered a type of mitigation. Propagate throughout chapter.
7	1	1:46	Revise figure in FAQ and associated TA description including table of parameters in simple model used to ensure precise consistency with final production version of SPM1. Revisions are of the order of individual line thicknesses and hence do not affect the visual impact and message of the figure.
5:22-23	1	26:11	“Around 2040” was revised to “likely between 2030 and 2052” requires traceability to the chapter. Insert on page 26, line 11, following “immediately”: “Applying a similar approach to the multi-dataset average GMST used in this report, now at 1.04°C, increasing at 0.215°C per decade, and accounting for correlated uncertainties between estimated warming level and warming rate, gives a one-standard-error range for warming reaching 1.5°C of 2030 to 2052.
13:40	2	13:12	At end of sentence after "both CO2 and non-CO2 emissions" add "(see glossary)" due to trickleback of new footnote on non-CO2 emissions that's related to the final C1.2 but is related to the non-CO2 discussion that occurs here in the FGD SPM.
3:24	2	8:53	after "emission pathway" add "(see glossary)" due to trickleback of new definition that may now be added to glossary
C2.3	2	55	Table 2.6: split to distinguish "no or low overshoot" and "high overshoot" pathways
C2.3	2	55	Table 2.7: split to distinguish "no or low overshoot" and "high overshoot" pathways

C2.2	2	Page 51-57	Section 2.4.2: Include ranges for subset of pathways consistent with their use in SPM
C2.3	2	Page 57-67	Section 2.4.3: Include ranges for subset of pathways consistent with their use in SPM
C1	2	4	2030 emissions, interquartile emission ranges and year ranges estimated from Table 2.4 need adding to ES
C1	2	23	2010 emissions, interquartile emission ranges and year ranges calcuated from from Table 2.4 need adding to Section 2.3
C1.3	2	22	Insert surface air temperture based remaining budgets into Table 2.2 through extra rows at 0.53C and 1.03. These remaining carbon budgets for 0.53°C are 840, 560, and 420 GtCO2 for a 33, 50, and 66% probability, respectively, given a historical GSAT warming of 0.97°C (and thus 1.5°C from 1850-1900); and 2030, 1500, and 1170 GtCO2 for a 33, 50 and 66% probability, respectively, for 1.03°C (or 2°C from 1850-1900).
C1.3	2	17:21	41GtCO2 needs to be 43 +/-3 GtCO2 - and add high confidence
C1.3	2	17	show AR5 budget and ranges from 2018 start of with surface air temperture from new table row
C1.3	2	5	show AR5 budget and ranges from 2018 start of with surface air temperture from new table row in ES
C1.3 (footnote)	2	17	introduce framing of total carbon budget context in 2.2.2 and historic emissions to date from Table 2.1 and give medium confidence to historic emissions toi date. Matching footnote 1 for C1.3
C1.3 - footnote 2	2	17	explain reason for 300 GtCO2 difference from AR5 and level of confidence
C1.3	2	17	Add sentence on ar5 difference in Executive Summary, explicitly mentioning the 300GTCO2
C1.3	2	20:53	Add "more thereafter" to ES feedbacks estimate
C.13	2	18	Update Figure 2.3 for baselines from both budget estimates
C1.3	2Annex	99	Replace figure 2.A.3 illustrating teo types of temperture change
C1.3	2	5:33	Add "more thereafter" to ES feedbacks estimate
C1.3	2	5:34	Exchange 50% uncertanity range in budgets with absolute uncertanity range
SPM3a	2	29	Include scenario selection in caption Figure 2.5
14: 27	2	75: 10	Replace "avoiding the need" with "reducing the reliance"
19:36-37, 48	2	78: 37	Add the following sentence at the end of the 1st paragragh of section 2.5.2.1: "Explicit carbon pricing is briefly addressed here to the extent it pertains to the scope of Chapter 2. For detailed policy issues about carbon pricing see Section 4.4.5."
19:36-37, 48	2	79:1-3	Delete last sentence "Considering incomplete…… (see section 4.4.5.2)."
19:36-37, 48	2	79:39-44	Move sentences "In addition, the revenue recycling effect…….is achieved (Sands, 2018)." to p.80 line 16 and insert them right after "(Sonnenschein et al., 2018)."
19:36-37, 48	2	80:10	Replace "price of carbon" with "carbon price"
19:36-37, 48	2	80:21	Delete "woulde need to" and add "s" to "increase"
19:36-37, 48	2	80:24	Replace "the price of carbon" with "carbon pricing"
19:20	2	83:25	Add "including conditional" to ("NDC") in the caption. ie. ("NDC", including conditional NDCs)
25:35	2	24:5	Change 1.5°C-consistent pathway to 1.5°C pathway
SPM3b	2	25:Table 2.3	Adjust wording in description of SSP narratives for consistency with SPM3b

C3	2	2.3.4	Adjust ranges to pathways limiting warming with no or limited overshoot
C1	2	2.3.2	Adjust ranges to pathways limiting warming with no or limited overshoot
C1, D1	2	2.3.5	Adjust ranges to pathways limiting warming with no or limited overshoot
25:35	2	27:1	Change 1.5°C-consistent pathway to 1.5°C pathway
25:35	2	28:35	Change 1.5°C-consistent pathway to 1.5°C pathway
25:35	2	28:54	Change 1.5°C-consistent pathway to 1.5°C pathway
25:35	2	39:11	Change 1.5°C-consistent pathway to 1.5°C pathway
25:35	2	39:37	Change 1.5°C-consistent pathway to 1.5°C pathway
25:35	2	44:22	Change 1.5°C-consistent pathway to 1.5°C pathway
25:35	2	46:8	Change 1.5°C-consistent pathway to 1.5°C pathway
C1.3	2	17	give footnote explaining that the table left column is globally surface air temperature from a base of either GMST or surface air temperature
C1.3	2	48	Update Figure 2.10 with budgets mentioned in SPM.
C2.3	2	54	Figure 2.16: split to distinguish "no or low overshoot" and "high overshoot" pathways
C2.3	2	56	Figure 2.17: split to distinguish "no or low overshoot" and "high overshoot" pathways
C2.2	2	6	Update ranges in ES to pathway definitions used in SPM
C2.3	2	6	Update ranges in ES to pathway definitions used in SPM
	3	131:2	Figure 3.20 & Figure 3.21 add confidence to embers bars
	3	131:2 & 133:1	Correct caption of Figure 3.20 & 3.21 to match approved version of SPM2 caption
	3	131:2 / 132:28	Titles, Figure caption and subtitles in embers figures in Ch 3 need to be modified to match the SPM version.
7:38 (B4.2)	3	p8 (ES), p52	Changes to allow indicative range to be given in (new) B2.1. Text that allows indicative range for GMSLR for 1.5C at 2100. Reword ES accordingly.
7:38 (B4.1)	3	p8	Reword final line of ES statement on GMSLR on threshold temperatures.
9:6 (B2.3)	3	p9, p165, p136	Reword ES statement andsubsection summary on peramfrost to include projected range; amend range given in on 3.5.2.5 RFC1
9:14 (B3.1)	3	p 8, p50	Clarify timescale on sea ice recovery (decadal) in summary of subsection and ES
9:14 (B3.1)	3	p 8, p50	Add definition for ice-free Arctic in section and ES (as footnote). AR5 "nearly ice-free when the sea ice extent is less than 106 km2 for at least five consecutive years."
10:39 (B5.7)	3	p 140-1	Update confidence associated with RCF5 (medium)
B3.2	3	p.68:23	Change 7 to 6.5% (and consider ES statement p. 9: l10)
	3	6:27	Replace "Changes in temperature extremes and heavy precipitation indices are detectable in observations for the 1991-2010 period compared with 1960-1979, when a global warming of approximately 0.5°C occurred (*high confidence*). The observed tendencies over that time frame are consistent with attributed changes since the mid-20th century (*high confidence*) {3.3.1, 3.3.2, 3.3.3}." with "Trends in intensity and frequency of some climate and weather extremes have been detected over time spans during which about 0.5^{o}C of global warming occurred (*medium confidence*). This assessment is based on several lines of evidence, including attribution studies for changes in extremes since 1950. {3.2, 3.3.1, 3.3.2, 3.3.3, 3.3.4}."
	3	6-31	Add: "Several regional changes in climate are assessed to occur with global warming up to 1.5°C compared to pre-industrial levels, including warming of extreme temperatures in many regions (*high confidence*), increases in frequency, intensity and/or amount of heavy precipitation in several regions (*high confidence*), and an increase in intensity or frequency of droughts in some regions (*medium confidence*). {3.3.1, 3.3.2, 3.3.3, 3.3.4, Table 3.2}"

	3	7:5	Replace "Substantial changes in regional climate occur between 1.5°C and 2°C [...]" with "Climate models project robust^FOOTNOTE#5 differences in regional climate between present-day and global warming of 1.5^FOOTNOTE#6, and between 1.5°C and 2°C#6"; FOOTNOTE#5: "Robust is here used to mean that at least two thirds of climate models show the same sign of changes at the grid point scale, and that differences in large regions are statistically significant [...]."; FOOTNOTE#6: "Projected changes in impacts between different levels of global warming are determined with respect to changes in global mean surface air temperature" (This is not striclty a trickle back since it was proposed by the authors prior to the approval session following comments on the FGD version of the SPM, but it is required to support changes in SPM; Exception: "mean" in "global mean surface air temperature" was added as a result of a comment from the floor)
	3	7:24	Replace "Tropical cyclones are projected to increase in intensity (with associated increases in heavy precipitation) although not in frequency (low confidence, limited evidence)" with "Tropical cyclones are projected to decrease in frequency but with an increase in the number of very intense cyclones (limited evidence, low confidence).Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (medium confidence)"
	3	7:25	Add "Heavy precipitation when aggregated at global scale is projected to be higher at 2.0°C than at 1.5°C of global warming (*medium confidence*)."
	3	7:26	Replace "drought and risks associated with water availability" with "drought, precipitation deficits, and risks associated with water availability"
	3	17:12	Add "It should also be noted that attributed changes in extremes since 1950 that were reported in the IPCC AR5 report (IPCC, 2013) generally correspond to changes in global warming of about 0.5°C (see 3.SM.1)"
	3	19:19	Add "This in particular also applies to attributed changes in extremes since 1950 that were reported in the IPCC AR5 report (IPCC, 2013; see also 3.SM.1)"
	3	38:28	Add "These analyses suggest that increases in drought, dryness or precipitation deficits are projected at 1.5°C or 2°C global warming in some regions compared to the pre-industrial or present-day conditions, as well as between these two global warming levels, although there is substantial variability in signals depending on the considered indices or climate models (Lehner et al. 2017, Schleussner et al. 2017, Greve et al. 2018) (*medium confidence*). Generally, the clearest signals are found for the Mediterranean region (*medium confidence*)."
	3	59 (Table 3.2, row "drought and dryness")	Add in column "projected changes at 1.5°C [...]": " Increases in drought, dryness or precipitation deficits projected in some regions compared to the pre-industrial or present-day conditions, but susbtantial variability in signals depending on considered indices or climate model (*medium confidence*)."

	3	59 (Table 3.2, row "drought and dryness")	Add in column "projected changes at 2°C [...]": " Increases in drought, dryness or precipitation deficits projected in some regions compared to the pre-industrial or present-day conditions, but susbtantial variability in signals depending on considered indices or climate model (*medium confidence*)."
	3	63 (Table 3.2, row "tropical and extra-tropical cyclones")	The text for the "observed change" column should stay the same. However, the remaining text (currently a single column for 1.5 degrees C of warming, 2 degrees C of warming and differences between 1.5 and 2 degrees C of warming) should be removed. Text should then be added to the three different columns as follows: changes at 1.5°C [...] "Increases in heavy precipitation associated with tropical cyclones (medium confidence)"; changes at 2°C [...] "Further increases in heavy precipitation associated with tropical cyclones (medium confidence)"; Differences between 2°C and 1.5° [...] "Heavy precipitation associated with tropical cyclones is projected to be higher at 2°C compared to 1.5°C global warming (medium confidence); Limited evidence that the global number of tropical cyclones will be lower under 2°C of global warming compared to under 1.5°C of warming, but an increase in the number of very intense cyclones (low confidence)".
SPM2	3	131	Figure 3-20 - Change text: 'Risks for specific natural, managed and human systems' to 'Risks and/or impacts for specific natural, managed and human systems'
SPM2	3	131	Figure 3-20 -Text describing colours here needs to be same as that is SPM figure (which it currently is)
SPM2	3	131	Figure 3-20 - Delete the text "Assessment of risks at 2°C or higher are beyond the scope of the present assessment" as in SPSM2
SPM2	3	131	Figure 3-20 - Remove 2.5°C from both y-axes as in SPM-2
SPM2	3	131	Figure 3-20 - Remove text '0.87°C' and add grey band labelled '2006–2016' in top and bottom figures – like in SPM-2.
SPM2	3	131	Figure 3-20 - Remove text: "The average global surface temperature was converted to GMST for marine related embers (warm water corals, mangroves, and small scale fisheries, low latitude) by adjusting for the small difference between GMST and SST across a range of CMIP5 climate models" - Just like in SPM2
SPM2	3	131	Figure 3-20 - Change text: 'y axes (top and bottom) need to be: 'Global mean surface temperature change above pre-industrial levels (oC).' Just like in SPM2
SPM2	3	131	Figure 3-20 - Edge of all embers above 0.87°C need to be dashed as in SPM-2 figure.

SPM2	3	131	Figure 3-20 - Add confidence levels as letters as per figure SPM-2. The lines connect the transition temperatures - as in SPM2.
SPM2	3	88	Figure 3-18 - Change text: 'Risks and adaptation limits for specific marine and coastal organisms, ecosystems and sectors' to 'Risks and/or impacts for specific marine and coastal organisms, ecosystems and sectors'
SPM2	3	88	Figure 3-18 -Text describing colours here needs to be same as that is SPM figure (which it currently is)
SPM2	3	88	Figure 3-18 -Delete the text "Assessment of risks at 2°C or higher are beyond the scope of the present assessment" as in SPSM2
SPM2	3	88	Figure 3-18 - Remove 2.5^{o}C from both y-axes as in SPM2
SPM2	3	88	Figure 3-18 - Remove text '0.87^{o}C' and add grey band labelled '2006–2016' in top and bottom figures – like in SPM-2.
SPM2	3	88	Figure 3-18 - Change text: 'y axes (top and bottom) need to be: 'Global mean surface temperature change above pre-industrial levels (oC).' Just like in SPM2
SPM2	3	88	Figure 3-18 - Edge of all embers above 0.87^{O}C need to be dashed as in SPM-2 figure.
SPM2	3	88	Figure 3-18 - Add confidence levels as letters as per figure SPM-2. The lines connect the transition temperatures - as in SPM2.
SPM2	3	132	Figure 3-21 - Change text: 'Risks associated with Reasons for Concern' to 'Risks and/or impacts associated with Reasons for Concern'
SPM2	3	132	Figure 3-21 - Text describing colours here needs to be same as that is SPM figure (which it currently is)
SPM2	3	132	Figure 3-21 - Remove 2.5^{o}C from both y-axes as in SPM2
SPM2	3	132	Figure 3-21 - Remove text '0.87^{o}C' and add grey band labelled '2006–2016' in top and bottom figures – like in SPM-2.
SPM2	3	132	Figure 3-21 - Change text: 'y axes (top and bottom) need to be: 'Global mean surface temperature change above pre-industrial levels (oC).' Just like in SPM2
SPM2	3	132	Figure 3-21 - Edge of all embers above 0.87^{O}C need to be dashed as in SPM-2 figure.
SPM2	3	132	Figure 3-21 - Add confidence levels as letters as per figure SPM-2. The lines connect the transition temperatures - as in SPM2.
SPM2	3	131	Figure 3-21 - Delete the text "Assessment of risks at 2°C or higher are beyond the scope of the present assessment" as in SPSM2
	3	3-11:6-13	Change "Any increase in global temperature (e.g., +0.5°C) is expected to affect human health (high confidence). Risks are lower at 1.5°C than at 2°C for heat-related morbidity and mortality (very high confidence), particularly in urban areas because of urban heat island effects (high confidence). Risks of ozone-related mortality would also be lower at 1.5°C than at 2°C of global warming assuming that emissions related to the formation of ozone remain the same (high confidence), and the same applies to risks of undernutrition (medium confidence). Risks are projected to change for some vector-borne diseases, such as malaria and dengue fever (high confidence), with positive or negative trends

			occurring depending on the disease, region and extent of change (high confidence). Incorporating estimates of adaptation into projections reduces the magnitude of risks (high confidence). {3.4.7, 3.4.7.1} " to "Any increase in global warming is projected to affect human health, with primarily negative consequences (high confidence). Lower risks are projected at 1.5°C than at 2°C for heat-related morbidity and mortality (very high confidence) and for ozone-related mortality if emissions needed for ozone formation remain high (high confidence). Urban heat islands often amplify the impacts of heatwaves in cities (high confidence). Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5°C to 2°C, including potential shifts in their geographic range (high confidence). {3.4.7, 3.4.8, 3.5.5.8}"
	3	3-10:7-8	Change "Global warming of 1.5°C (as opposed to 2ºC) is projected to reduce climate induced impacts on crop yield and nutritional content in some regions (high confidence)." to "Limiting warming to 1.5°C, compared with 2ºC, is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America; and in the CO2 dependent, nutritional quality of rice and wheat (high confidence)."
	3	3-10:12-13	Change "Risks of food shortages are lower in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon at 1.5oC of global warming when compared to 2°C (medium confidence)." to "Reductions in projected food availability are larger at 2ºC than at 1.5°C of global warming in the Sahel, southern Africa, the Mediterranean, central Europe, and the Amazon (medium confidence). "
	3	3-9:45-46	Change "Risks to water scarcity are greater at 2°C than at 1.5°C of global warming in some regions (medium confidence)." to "Depending on future socioeconomic conditions, limiting global warming to 1.5°C, compared to 2°C, may reduce the proportion of the world population exposed to a climate-change induced increase in water stress by up to 50%, although there is considerable variability between regions (medium confidence). "
	3	3-9:46 to 3:10:1-3	Delete the text "Limiting global warming to 1.5°C would approximately halve the fraction of world population expected to suffer water scarcity as compared to 2°C, although there is considerable variability between regions (medium confidence). Socioeconomic drivers, however, are expected to have a greater influence on these risks than the changes in climate (medium confidence)"
	3	3-11:28-32	Change "Globally, the projected impacts on economic growth in a 1.5°C warmer world are larger than those of the present-day (about 1°C), with the largest impacts expected in the tropics and the Southern Hemisphere subtropics (limited evidence, low confidence). At 2°C substantially lower economic growth is projected for many developed and developing countries (limited evidence, medium confidence), with the potential to also limit economic damages at 1.5°C of global warming." to "Risks to global aggregated economic growth due to climate change impacts are projected to be lower at 1.5°C than at 2°C by the end of this century (medium confidence). This excludes the costs of mitigation, adaptation investments and the benefits of adaptation. Countries in the tropics and Southern Hemisphere subtropics are projected to experience the largest impacts on economic

			growth due to climate change should global warming increase from 1.5°C to 2 °C (medium confidence)."
	3	3-7:37-41	Change "Some regions are projected to experience multiple compound climate-related risks at 1.5°C that will increase with warming of 2°C and higher (high confidence). Some regions are projected to be affected by collocated and/or concomitant changes in several types of hazards. Multi-sector risks are projected to overlap spatially and temporally, creating new (and exacerbating current) hazards, exposures, and vulnerabilities that will affect increasing numbers of people and regions with additional warming." to "Exposure to multiple and compound climate-related risks increases between 1.5°C and 2°C of global warming, with greater proportions of people both exposed and susceptible to poverty in Africa and Asia (high confidence). For global warming from 1.5°C to 2°C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (medium confidence) "
9:6 (B2.3)	3	p9, p165, p136	Reword ES statement andsubsection summary on peramfrost to include projected range; amend range given in on 3.5.2.5 RFC1 as well as in Table 3.7 (p 3 -151)
A3.2	3		The ES FGD text used to read 'Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, medium confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.' in ES. In the SPM, the statement A3.2 reads A3.2. Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (high confidence). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (high confidence). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8}". To make the ES consistent, the statement should be edited to read "Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot (high confidence). The size and duration of an overshoot will also affect future impacts (e.g. irreversible loss of some ecosystems, high confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.'
B3 and B3.1	3		Edit ES statement to make the confidence levels consistent with the SPM and specify the exact numbers as in the SPM. This means to edit from "Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (medium confidence). The number of species projected to lose over half of their

			climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (high confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.' to 'Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (high confidence). The number of species projected to lose over half of their climatically determined geographic range at 2°C warming (18% of insects, 16% of plants, 8% of vertebrates) is projected to be reduced to 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming (medium confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.'. It will also be important to ensure that the confidence levels in the underlying text also match this.
A3.2	3		For consistency with A2, in the ES the statement 'Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (high confidence).' should be edited to read Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of some ecosystems (high confidence).' Also check underlying text.

A3.2	3		The ES FGD text used to read 'Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, medium confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.' in ES. In the SPM, the statement A3.2 reads A3.2. Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (high confidence). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (high confidence). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8}". To make the ES consistent, the statement should be edited to read "Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot (high confidence). The size and duration of an overshoot will also affect future impacts (e.g. irreversible loss of some ecosystems, high confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.'
B3 and B3.1	3		Edit ES statement to make the confidence levels consistent with the SPM and specify the exact numbers as in the SPM. This means to edit from "Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (medium confidence). The number of species projected to lose over half of their climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (high confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.' to 'Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (high confidence). The number of species projected to lose over half of their climatically determined geographic range at 2°C warming (18% of insects, 16% of plants, 8% of vertebrates) is projected to be reduced to 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming (medium confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.'. It will also be important to ensure that the confidence levels in the underlying text also match this.

A3.2	3		For consistency with A2, in the ES the statement 'Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (high confidence).' should be edited to read Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of some ecosystems (high confidence).' Also check underlying text.
B3.2	3		The SPM wording is B3.2. "Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1ºC of global warming, compared with 13% (interquartile range 8–20%) at 2°C (medium confidence). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (medium confidence). {3.4.3.1, 3.4.3.5}" and the FGD ES wording was 'The terrestrial area affected by ecosystem transformation (13%) at 2°C, which is approximately halved at 1.5°C global warming (high confidence)' . In the ES, this latter sentence needs to be edited to read "The global terrestrial land area projected to be affected by ecosystem transformation (13%, interquartile range 8–20%) at 2°C, is approximately halved at 1.5°C global warming to 4% (interquartile range 2–7%) (medium confidence)."
A3.2	3		The ES FGD text used to read 'Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, medium confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.' in ES. In the SPM, the statement A3.2 reads A3.2. Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (high confidence). Some impacts may be long-lasting or irreversible, such as

			the loss of some ecosystems (high confidence). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8}". To make the ES consistent, the statement should be edited to read "Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot (high confidence). The size and duration of an overshoot will also affect future impacts (e.g. irreversible loss of some ecosystems, high confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.'
B3 and B3.1	3		Edit ES statement to make the confidence levels consistent with the SPM and specify the exact numbers as in the SPM. This means to edit from "Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (medium confidence). The number of species projected to lose over half of their climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (high confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.' to 'Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (high confidence). The number of species projected to lose over half of their climatically determined geographic range at 2°C warming (18% of insects, 16% of plants, 8% of vertebrates) is projected to be reduced to 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming (medium confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.'. It will also be important to ensure that the confidence levels in the underlying text also match this.
A3.2	3		For consistency with A2, in the ES the statement 'Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (high confidence).' should be edited to read Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of some ecosystems (high confidence).' Also check underlying text.

B3.2	3		The SPM wording is B3.2. "Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1ºC of global warming, compared with 13% (interquartile range 8–20%) at 2°C (medium confidence). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (medium confidence). {3.4.3.1, 3.4.3.5}" and the FGD ES wording was 'The terrestrial area affected by ecosystem transformation (13%) at 2°C, which is approximately halved at 1.5°C global warming (high confidence)' . In the ES, this latter sentence needs to be edited to read "The global terrestrial land area projected to be affected by ecosystem transformation (13%, interquartile range 8–20%) at 2°C, is approximately halved at 1.5°C global warming to 4% (interquartile range 2–7%) (medium confidence)."
B3.3	3		In ES add B3.3, add and will proceed with further warming' after "High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (high confidence)" .
A3.2	3		The ES FGD text used to read 'Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot. The size and duration of an overshoot will also affect future impacts (e.g. loss of ecosystems, medium confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.' in ES. In the SPM, the statement A3.2 reads A3.2. Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (high confidence). Some impacts may be long-lasting or irreversible, such as the loss of some ecosystems (high confidence). {3.2, 3.4.4, 3.6.3, Cross-Chapter Box 8}". To make the ES consistent, the statement should be edited to read "Future risks at 1.5°C will depend on the mitigation pathway and on the possible occurrence of a transient overshoot (high confidence). The impacts on natural and human systems would be greater where mitigation pathways temporarily overshoot 1.5°C and return to 1.5°C later in the century, as compared to pathways that stabilizes at 1.5°C without an overshoot (high confidence). The size and duration of an overshoot will also affect future impacts (e.g. irreversible loss of some ecosystems, high confidence). Changes in land use resulting from mitigation choices could have impacts on food production and ecosystem diversity {Sections 3.6.1 and 3.6.2, Cross-Chapter boxes 7 and 8 in this Chapter}.'
B3 and B3.1	3		Edit ES statement to make the confidence levels consistent with the SPM and specify the exact numbers as in the SPM. This means to edit from "Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (medium confidence). The number of species projected to lose over half of their climatically determined geographic range (about 18% of insects, 16% of plants, 8% of vertebrates) is reduced by 50% (plants, vertebrates) or 66% (insects) at 1.5°C versus 2°C of warming (high confidence). Risks associated with other biodiversity-related factors such

			as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.' to 'Risks of local species losses and, consequently, risks of extinction are much less in a 1.5°C versus a 2°C warmer world (high confidence). The number of species projected to lose over half of their climatically determined geographic range at 2°C warming (18% of insects, 16% of plants, 8% of vertebrates) is projected to be reduced to 6% of insects, 8% of plants and 4% of vertebrates at 1.5°C warming (medium confidence). Risks associated with other biodiversity-related factors such as forest fires, extreme weather events, and the spread of invasive species, pests, and diseases, are also reduced at 1.5°C versus 2°C of warming (high confidence), supporting greater persistence of ecosystem services {3.4.3.2, 3.5.2}.'. It will also be important to ensure that the confidence levels in the underlying text also match this.
A3.2	3		For consistency with A2, in the ES the statement 'Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of many ecosystems (high confidence).' should be edited to read Overshooting poses large risks for natural and human systems, especially if the temperature at peak warming is high, because some risks may be long-lasting and irreversible, such as the loss of some ecosystems (high confidence).' Also check underlying text.
B3.2	3		The SPM wording is B3.2. "Approximately 4% (interquartile range 2–7%) of the global terrestrial land area is projected to undergo a transformation of ecosystems from one type to another at 1ºC of global warming, compared with 13% (interquartile range 8–20%) at 2°C (medium confidence). This indicates that the area at risk is projected to be approximately 50% lower at 1.5°C compared to 2°C (medium confidence). {3.4.3.1, 3.4.3.5}" and the FGD ES wording was 'The terrestrial area affected by ecosystem transformation (13%) at 2°C, which is approximately halved at 1.5°C global warming (high confidence)' . In the ES, this latter sentence needs to be edited to read "The global terrestrial land area projected to be affected by ecosystem transformation (13%, interquartile range 8–20%) at 2°C, is approximately halved at 1.5°C global warming to 4% (interquartile range 2–7%) (medium confidence)."

B3.3	3		In ES add B3.3, add and will proceed with further warming' after "High-latitude tundra and boreal forests are particularly at risk of climate change-induced degradation and loss, with woody shrubs already encroaching into the tundra (high confidence)" .
B5.7	3		In ES the text read 'There are multiple lines of evidence that there has been a substantial increase since AR5 in the levels of risk associated with four of the five Reasons for Concern (RFCs) for global warming levels of up to 2°C (high confidence). The word 'assessed' should be inserted before 'risk'
B5.7	3		Replace RFC text with text in SPM
6:26	4	33:42	Replace '>70%' with 'to between 75 and 90% (interquartile range)'
13:6	4	Across the chapter	Replace '1.5°C-consistent pathways' with 'pathways limiting global warming to 1.5°C with no or limited overshoot'.
14:9	4	Across the chapter	Replace '2°C-consistent pathways' with 'pathways limiting global warming to below 2°C'. [**NOTE: In the approved SPM this is in C2.7, seocnd sentence, as an example.**]
22:40	4	87:6	Change 'over 2015-2035' to 'between 2016-2035'. [**NOTE: In the approved SPM this is in the line under D4.3**]
22:49-50	4	13:35	Change 'threefold' to '3-4 times' [**NOTE: This bullet is C2.7 in the approved SPM]**
25:20	4	44:35	In the context of 1.5°C pathways {Chapter 2}, they serve to offset residual emissions that take longer to abate or to reduce emissions after overshooting the 1.5°C carbon budget' CHANGE TO 'In the context of 1.5°C pathways {Chapter 2}, they serve to offset residual emissions and, in most cases, achieve net-negative emissions to return to 1.5°C from an overshoot.'
SPM3b	4		Update Table 4.1: update numbers to be consistent with SPM
C2.3	4		Update Table 4.1 for pathway classification used in SPM
12:14	5	15:17-18	Include Table 3.5 in traceability count (see Chapter 3……)
SPM4	5		Update Figure 5.2: red coloured circle segment corresponding to SDG9 in, circle Trade-offs (negative interaction) energy demand options, to be replaced by white
25:3	Glossary	25:22	Global mean surface temperature (GMST) - replace glossary definition with version in SPM Box 1: Estimated global average of near-surface air temperatures over land and sea-ice, and sea surface temperatures over ice-free ocean regions, with changes normally expressed as departures from a value over a specified reference period. When estimating changes in GMST, near-surface air temperature over both land and oceans are also used.

			[FOOTNOTE] FOOTNOTE: Past IPCC reports, reflecting the literature, have used a variety of approximately equivalent metrics of GMST change.
25:3	Glossary	N/A (New)	Add the following definition for Global mean surface air temperature (GSAT) - Global average of near-surface air temperatures over land and oceans. Changes in GSAT are often used as a measure of global temperature change in climate models but are not observed directly.
25:8	Glossary	42:16	Pre-industrial - replace glossary definition with version in SPM Box 1: The multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (GMST).
25:12	Glossary	25:29	Global warming - replace glossary definition with version in SPM Box 1: The estimated increase in global mean surface temperature (GMST) averaged over a 30-year period, or the 30-year period centered on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue.
25:20	Glossary	8:49	Carbon dioxide removal (CDR) - replace glossary definition with version in SPM Box 1: Anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities.
25:20	Glossary	36:24	Mitigation (of climate change) - Remove "Note that this encompasses carbon dioxide removal (CDR) options."
25:20	Glossary		Negative emissions - Remove "For CO_2, negative emissions can be achieved with direct capture of CO_2 from ambient air, bioenergy with carbon capture and sequestration (BECCS), afforestation, reforestation, biochar, ocean alkalinization, among others."
25:31	Glossary	39:1	Overshoot - change name of term to 'Temperature overshoot' to be consistent with SPM Box 1