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Chapter 5: Sustainable Development, Poverty Eradication and Reducing Inequalities

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Date of Draft: 23 May 2018

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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]

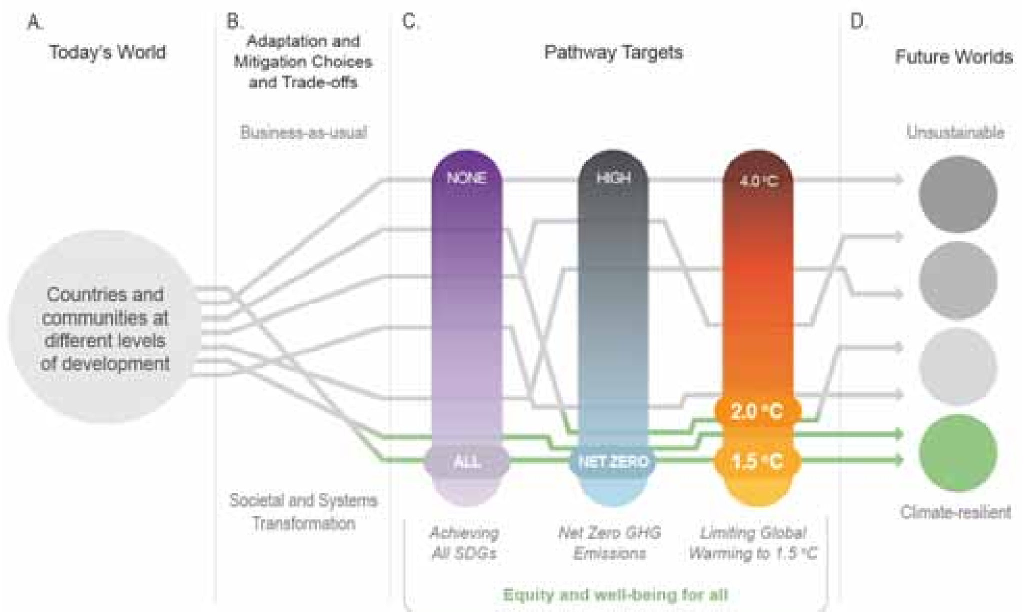

Figure 5.1: Climate-resilient development pathways (CRDPs) (green arrows) between a current world in which countries and commuities exist at different levels of development (A) and future worlds that range from

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

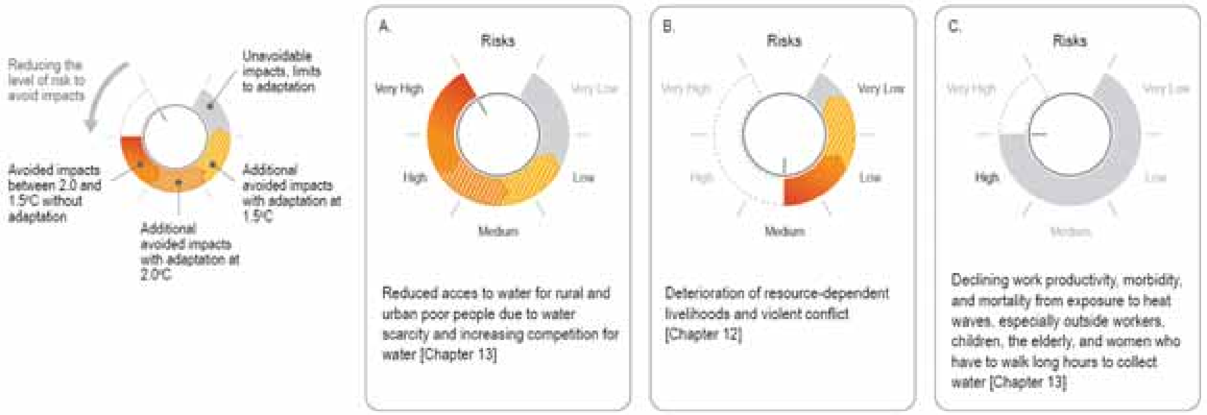
"Loss and Damage" (L&D) has been discussed in international climate negotiations for three decades (INC, 1991; Calliari, 2016; Vanhala and Hestbaek, 2016). A work programme on L&D was established as part of the Cancun Adaptation Framework in 2010 supporting developing countries particularly vulnerable 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]



A. Reduced acces to water for rural and urban poor people due to water scarcity and increasing competition for water [Chapter 13]

B. Deterioration of resource-dependent livelihoods and violent conflict [Chapter 12]

C. Declining work productivity, morbidity, and mortality from exposure to heat waves, especially outside workers, children, the elderly, and women who have to walk long hours to collect water [Chapter 13]

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]

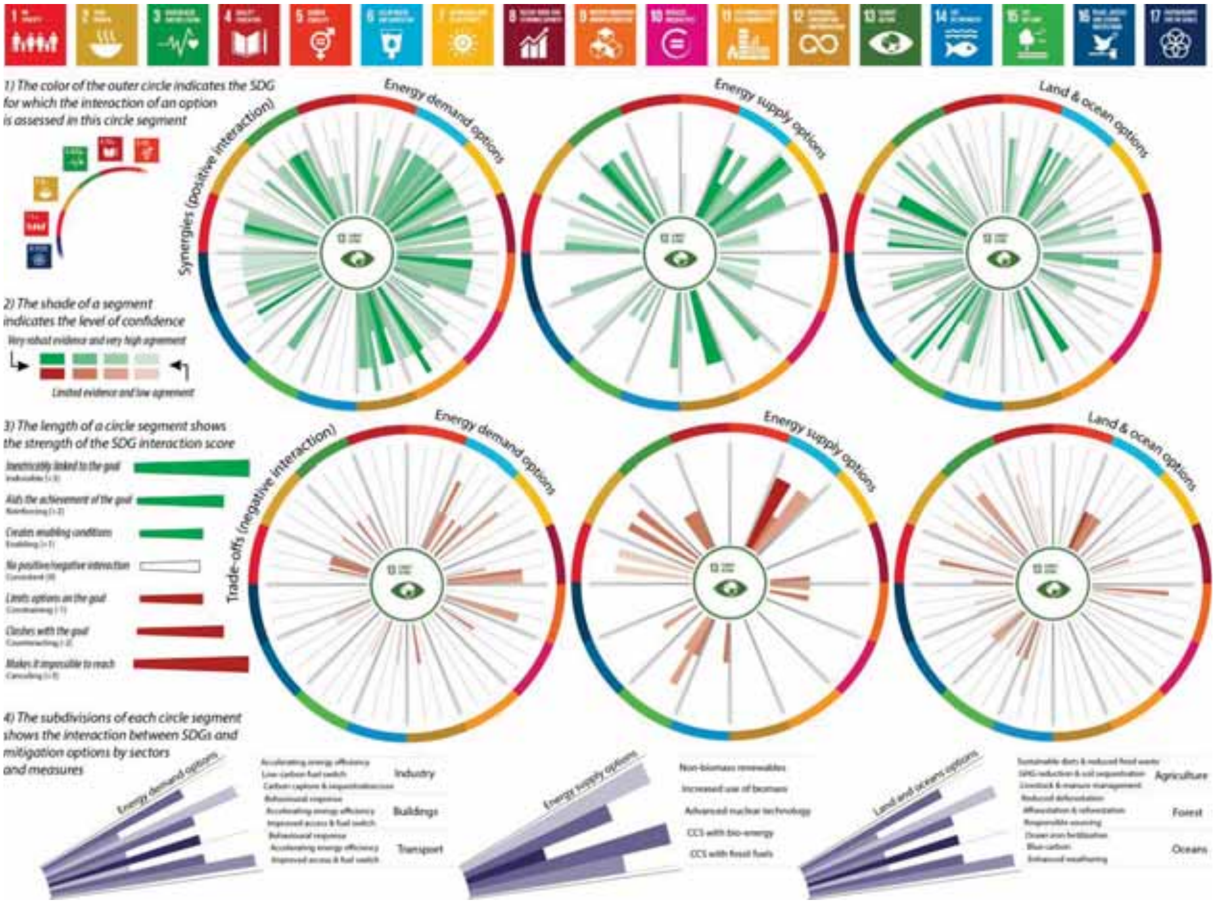


Figure 5.3: **Synergies and trade-offs and gross Sustainable Development Goal (SDG)-interaction with individual mitigation options.** The top three wheels represent synergies and the bottom three wheels show trade-offs. The colours on the border of the wheels correspond to the SDGs listed above, starting 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]

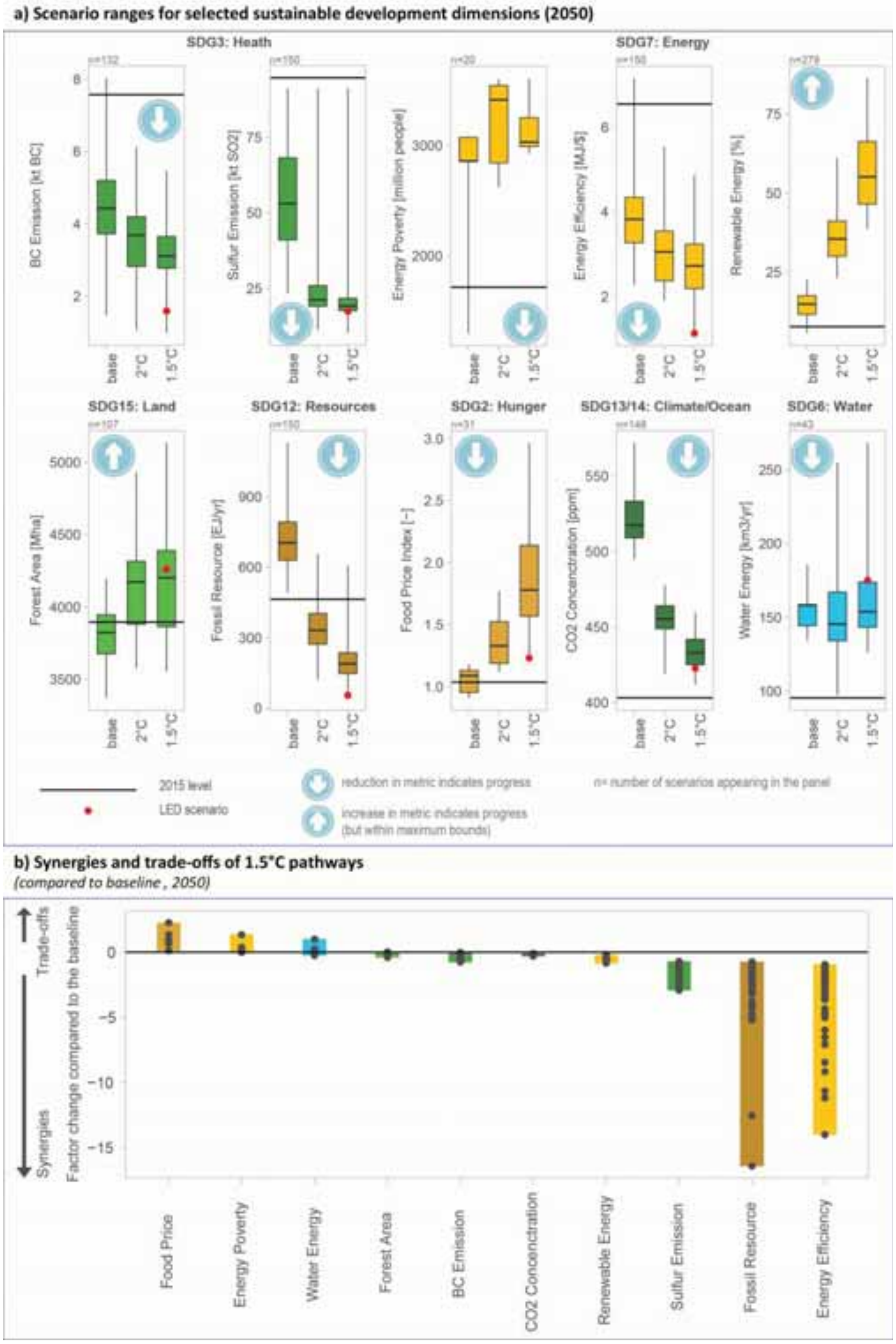


Figure 5.4: **Sustainable development implications of mitigation actions in 1.5°C pathways**. **Panel (a)** shows ranges for 1.5°C pathways for selected sustainable development dimensions compared to the ranges of 2°C pathways and baseline pathways. The panel (a) depicts interquartile and the full range 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]

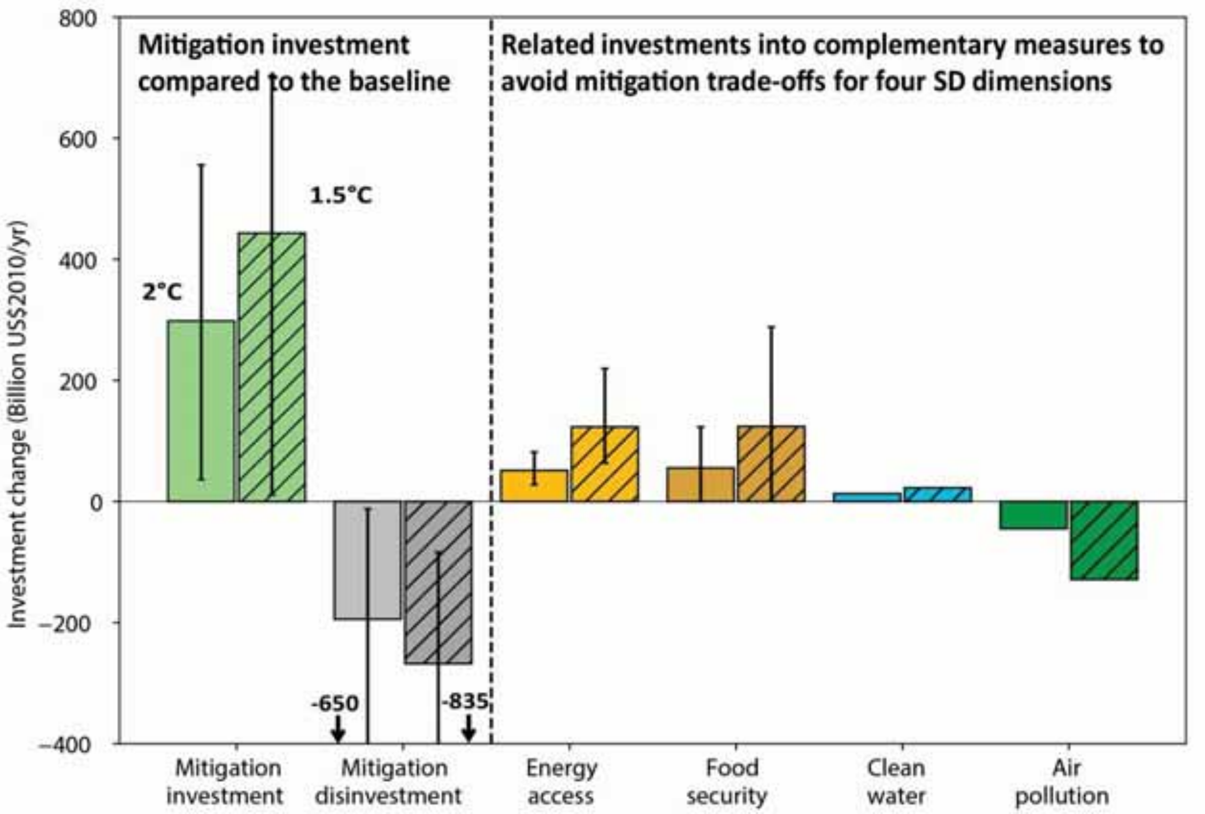


Figure 5.5: **Investment into mitigation up until 2030 and implications for investments for four sustainable development dimensions**. Cross-hatched bars show the median investment in 1.5°C pathways across results from different models, and solid bars for 2°C pathways, respectively. Whiskers on bars 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]

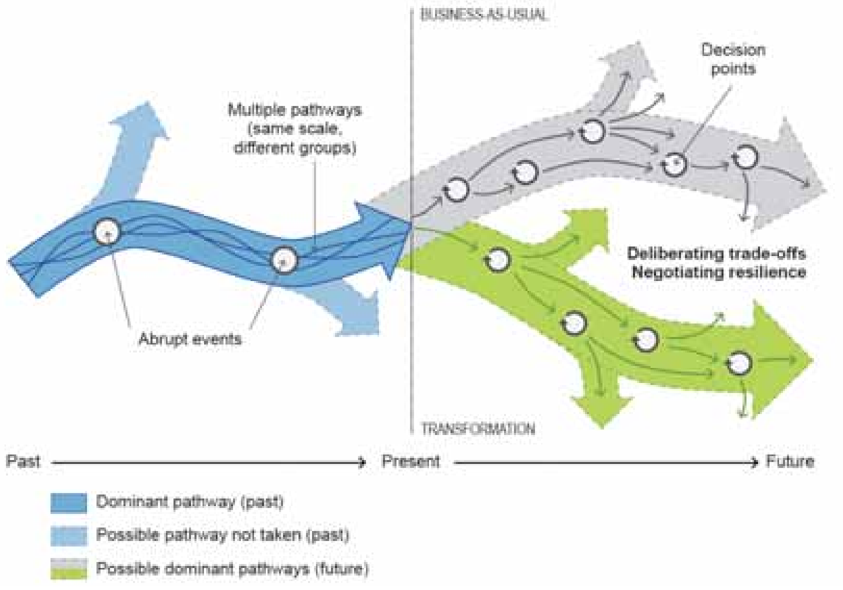


Figure 5.6: Pathways into the future, with path dependencies and iterative problem-solving and decision-making (after Fazey et al. (2016).

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℃ and ensuring equity and well-being for human populations and ecosystems in a 1.5℃ 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.

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.

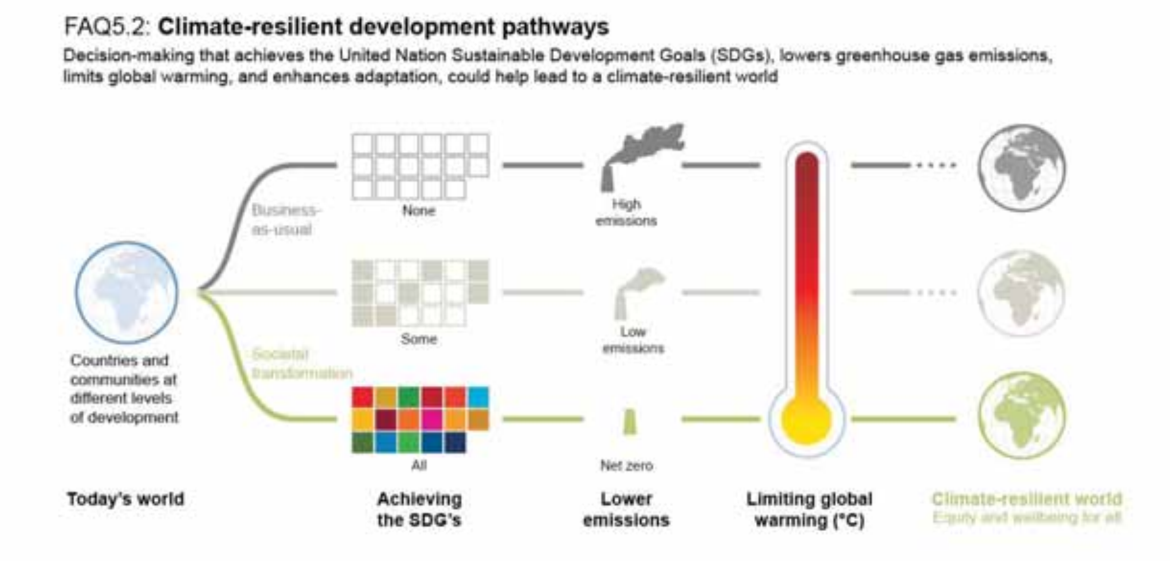
The Paris Agreement states that it "will be implemented to reflect equity… in the light of different national circumstances" and calls for "rapid reductions" of greenhouse gases to be achieved "on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty". Similarly, 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.

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Chapter 1: Framing and Context

Technical Annex 1.A

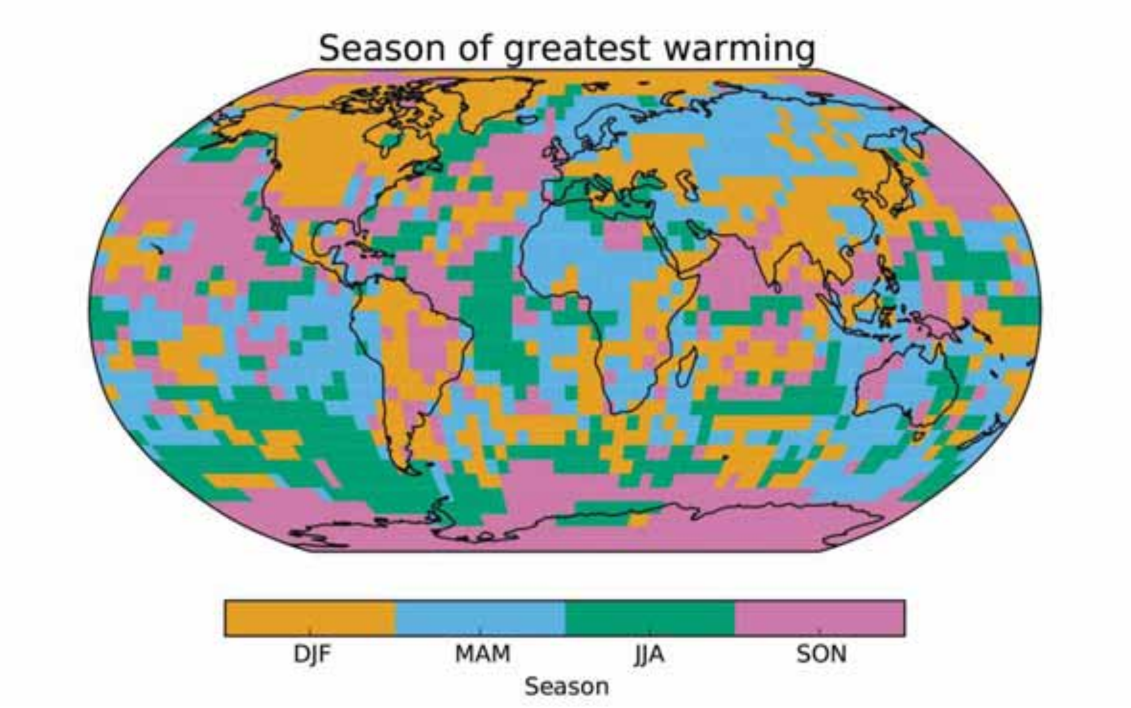
This Annex provides technical details of the calculations behind the figures in the chapter, as well as some supporting figures provided for sensitivity analysis or to provide support to the main assessment.

Table of Content

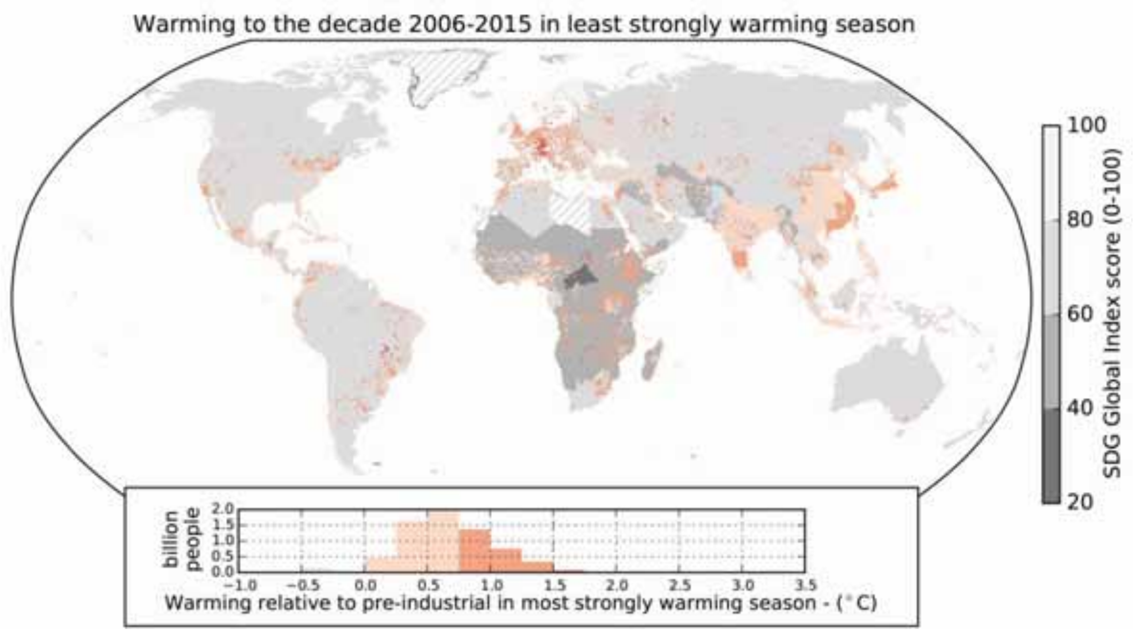
Annex 1.A.1: supporting material for for Figure 1.1

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.



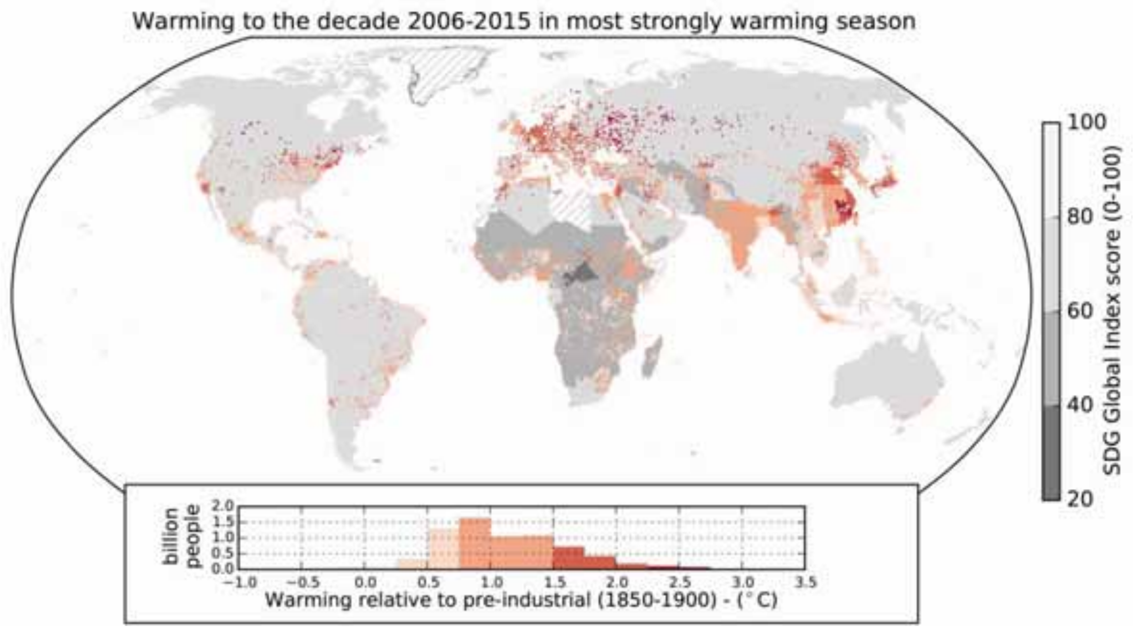
Technical Annex 1.A, Figure 1: Season of greatest human-induced warming over 2006-2015 relative to 1850-1900 for the data shown in Figure 1.1.



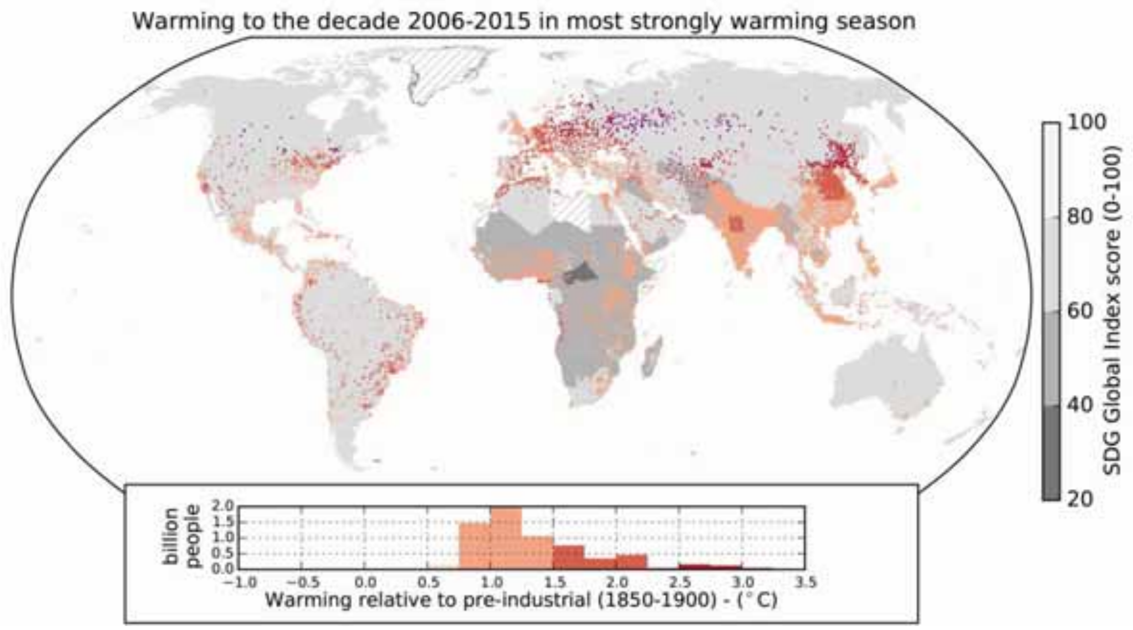
Technical Annex 1.A, Figure 2: As for Figure 1.1 but with scatter points coloured by warming in the season with least warming over the 2006-2015 period.

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.

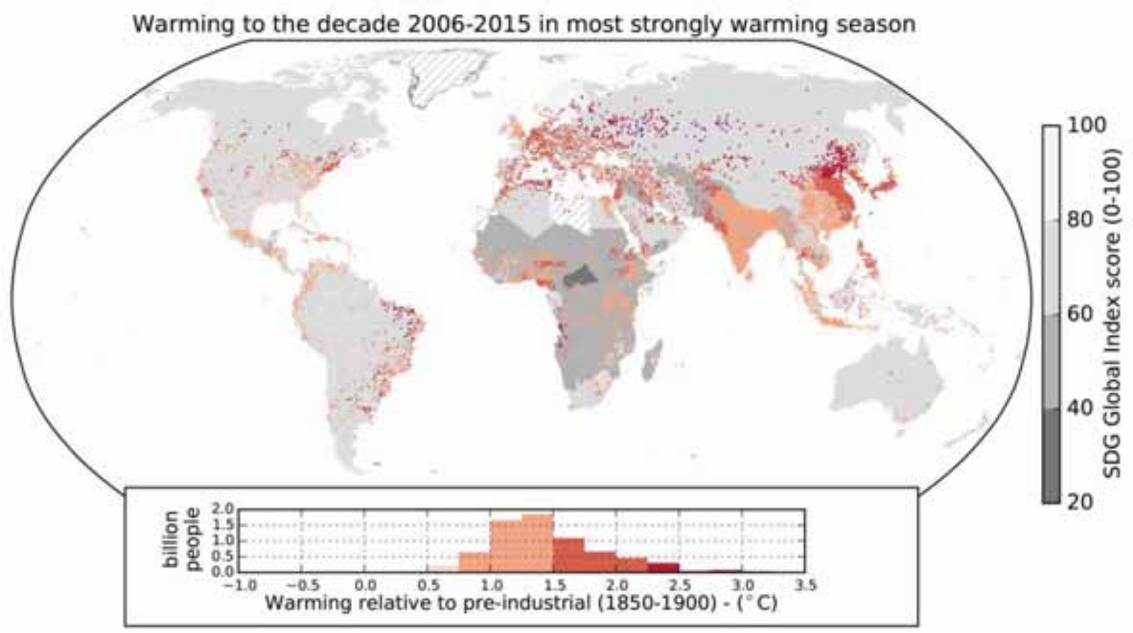
The SDG Global Index Score is a quantitative measure of progress towards the 17 sustainable development goals (Sachs et al., 2017). The goals cross-cut the three dimensions of sustainable development – environmental sustainability, economic growth, and social inclusion. It has a range of 0-100, 100 corresponding 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.

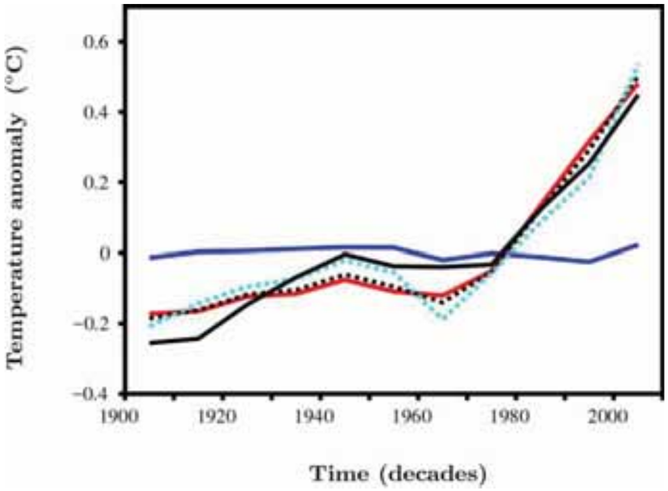
The pink "Holocene" shading is derived from the "Standard5x5Grid" reconstruction of Marcott et al. (2013) (expressed relative to 1850-1900 using the HadCRUT4 anomaly between this reference period and the 1961-90 base period of the data). The vertical extent of the solid shading is determined by the maximum 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).

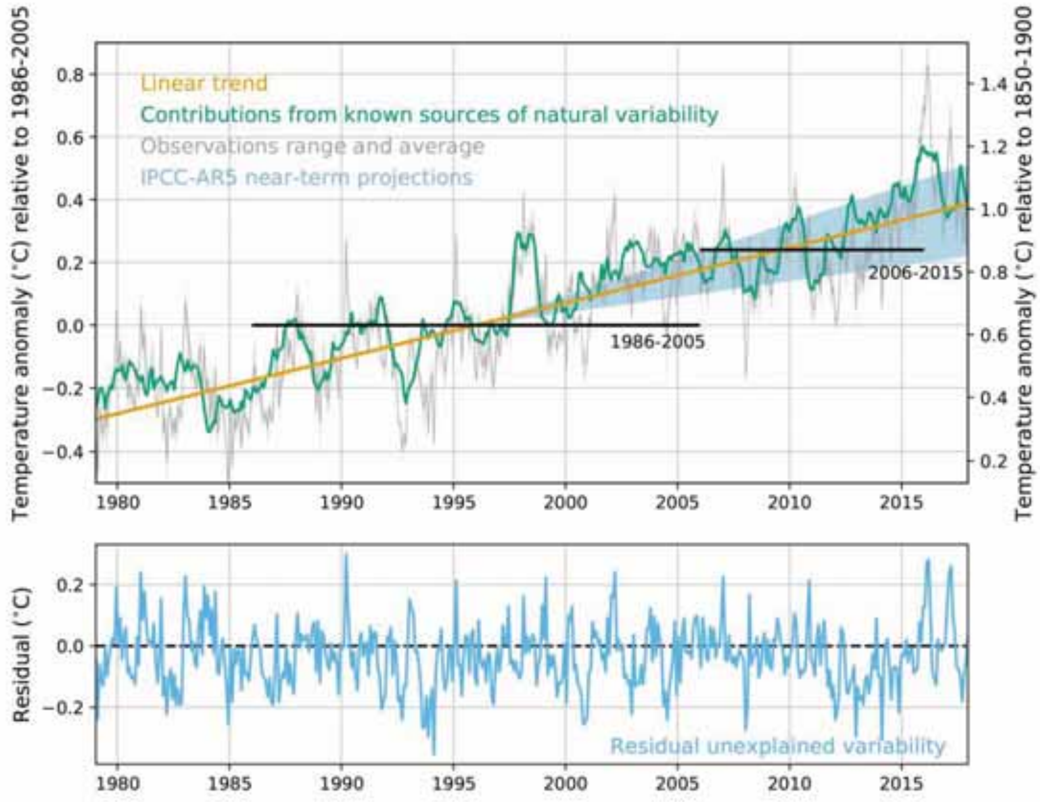
To provide a methodologically independent check on the attribution of human-induced warming since the 19th century (quantitative attribution results quoted in AR5 being primarily focussed on the period 1951-2010), Technical Annex 1.A Figure 6 shows a recalculation of the results of Ribes and Terray (2013), 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.

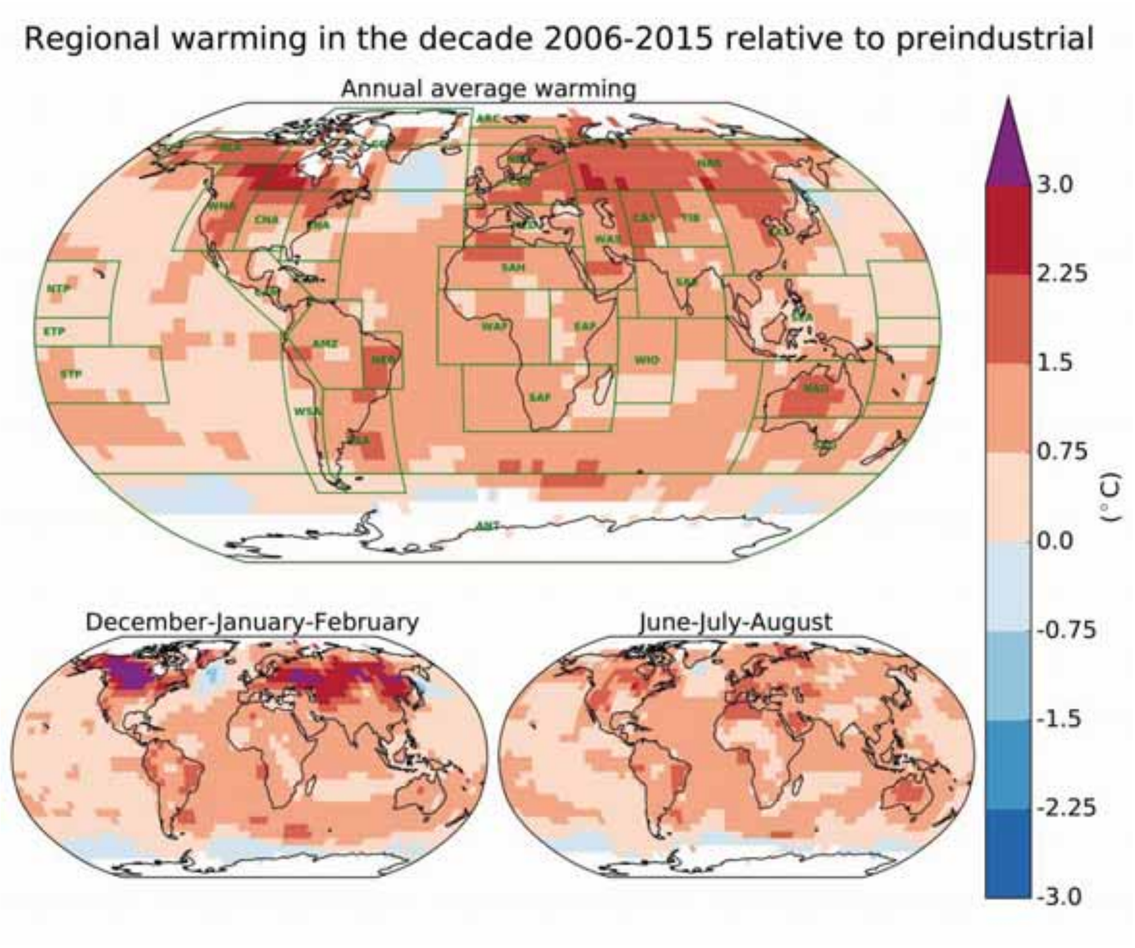


Technical Annex 1.A, Figure 7: Warming and warming rate 1979-2017. The solid grey line shows the average of the four observational datasets used in this assessment report with the observational range shown by grey shading. The yellow line shows the linear trend through the observational data, corrected 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.

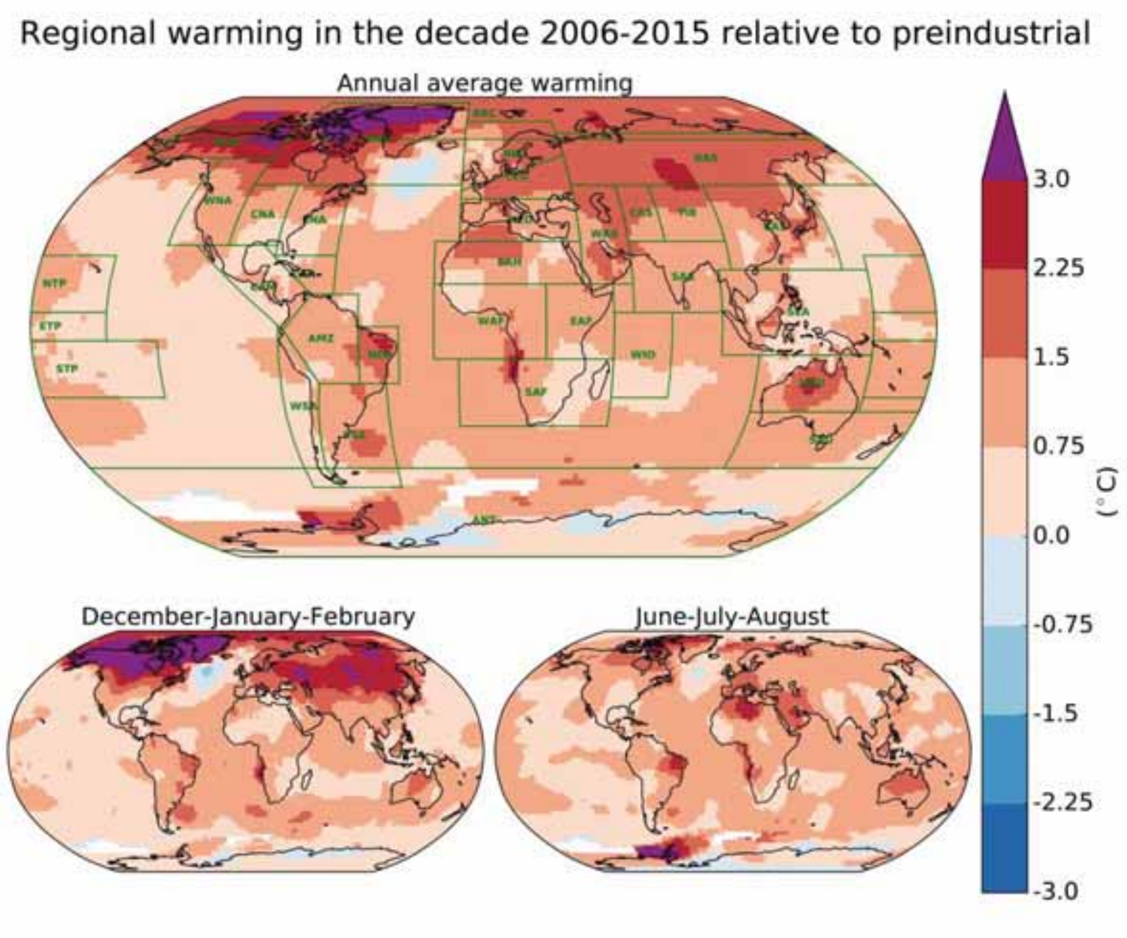
Annex 1.A.3: supporting material for Figure 1.3

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.

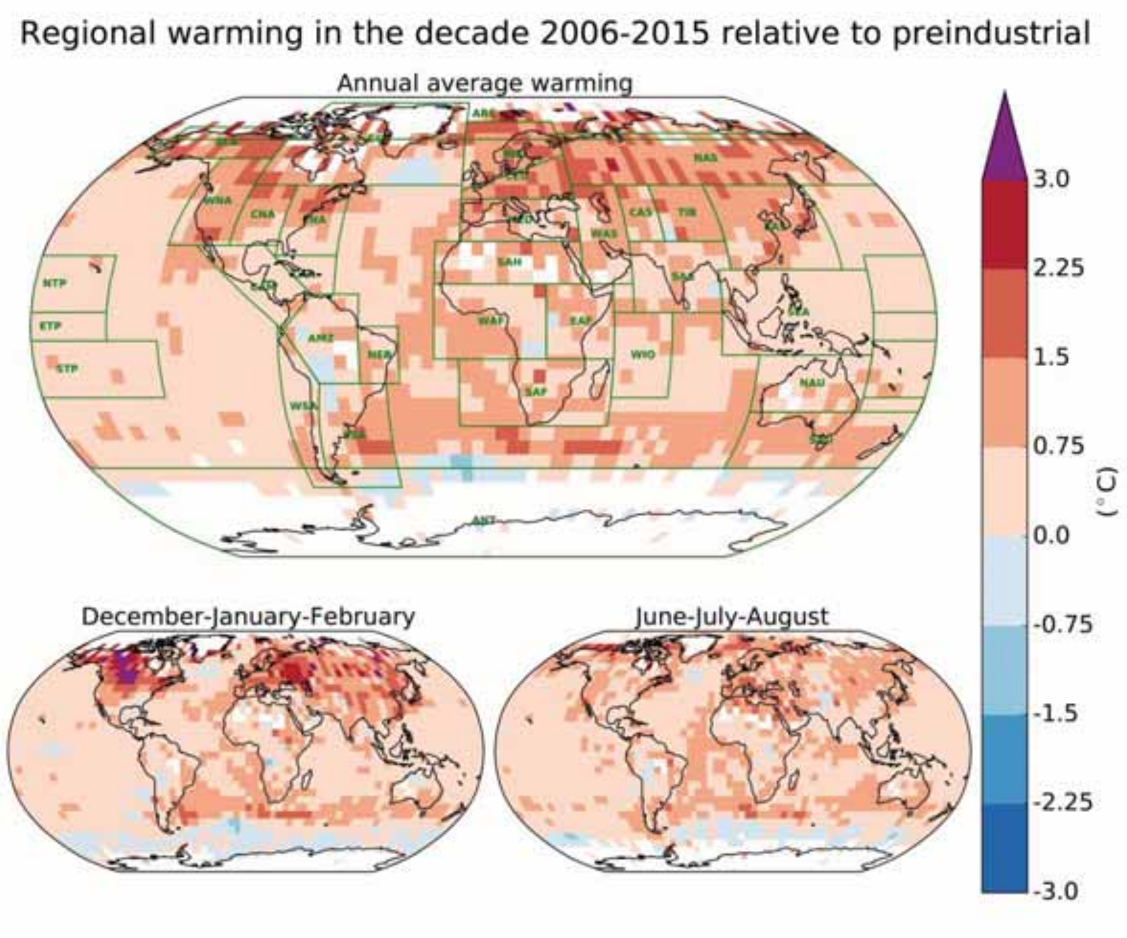
Supplementary maps are included below for the NOAA, GISTEMP and HadCRUT4 observational data. The regression of local temperature anomalies onto the global mean externally-forced warming, allows warming to be expressed relative to 1850-1900 despite many local series in these datasets beginning after 1900, 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, $T_{2017} = 1°\mathrm{C}$, 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).

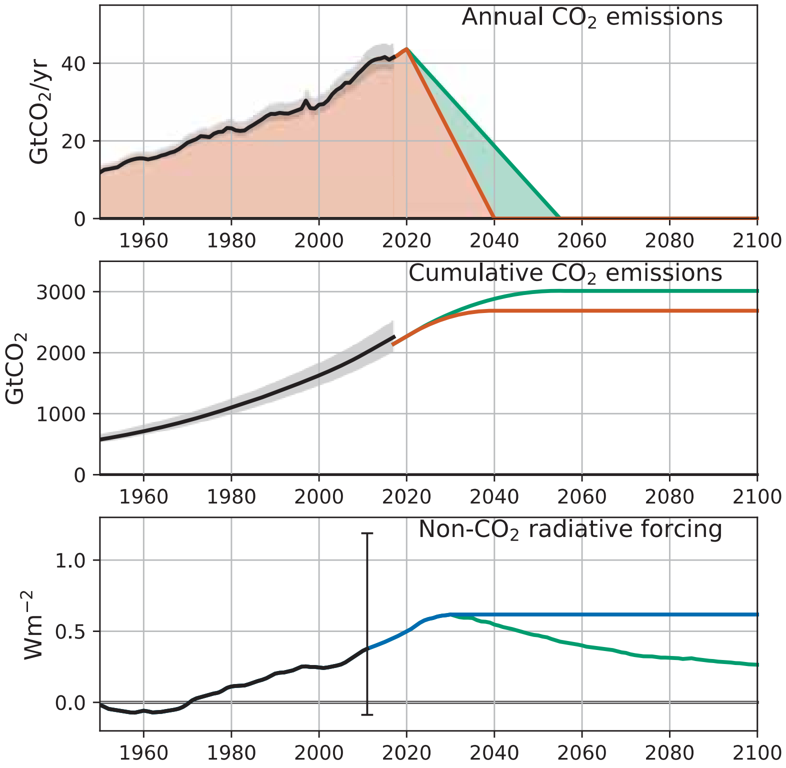
4. Zero GHG emissions, constant aerosol forcing (pink): FAIR spun up with anthropogenic forcing to 2020. All GHG emissions set abruptly to zero in 2021, with aerosol emissions held fixed at their 2020 levels.

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).



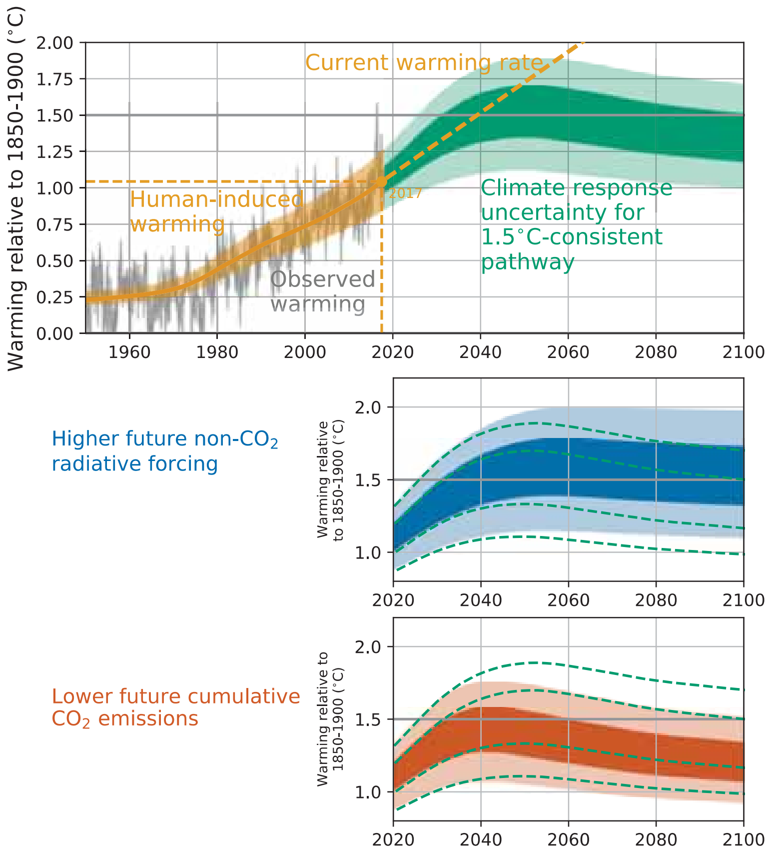
Technical Annex 1.A, Figure 11: Time-series of (top) annual CO_2 emissions, (middle) cumulative CO_2 emissions, and (bottom) non-CO_2 radiative forcing corresponding to observation-based estimates over the historical period and idealised 1.5°C-consistent pathways.

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.

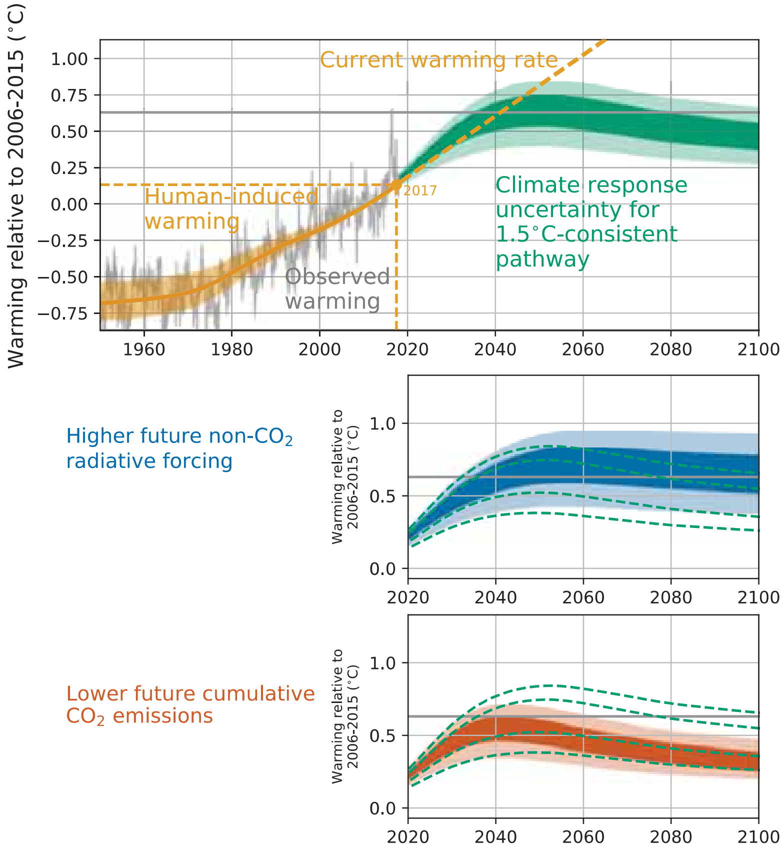
All 1.5°C-consistent scenarios that are also consistent with current emissions and radiative forcing trends show increasing non-CO_2 radiative forcing over the coming decade, as emissions of cooling aerosol precursors are reduced, but there is greater variation between scenarios in non-CO_2 radiative 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.

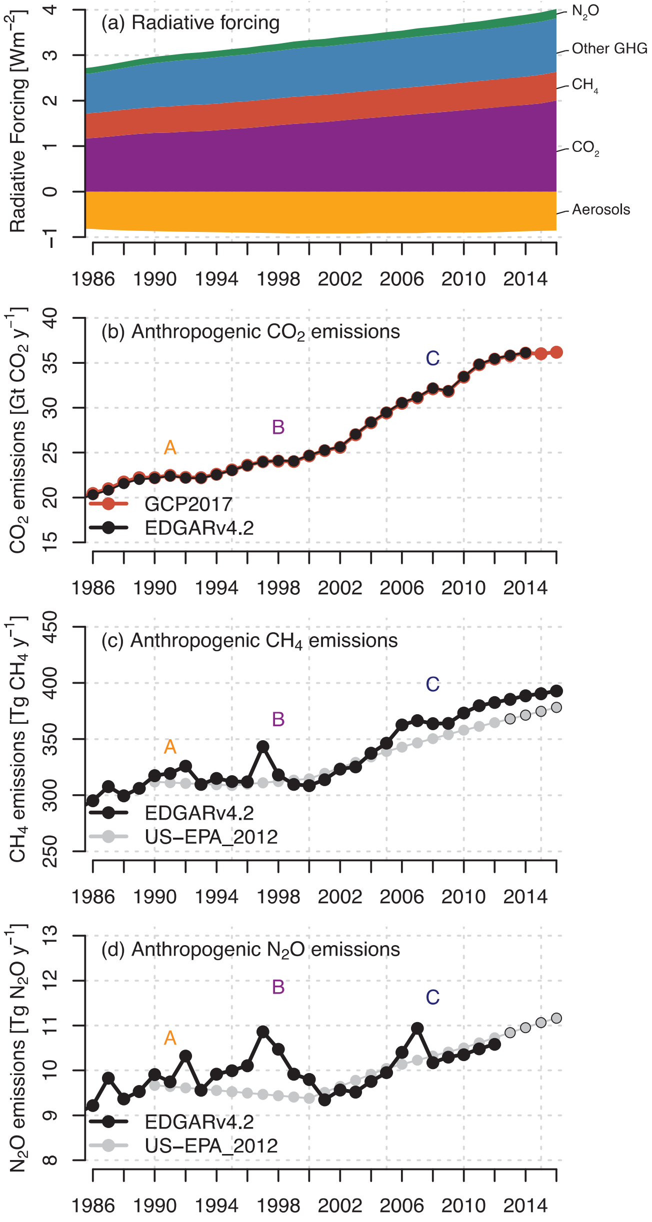
Most studies partition anthropogenic climate forcers into two groups by their lifetime. CO_2 and other long–lived greenhouse gases such as nitrous oxide, sulphur hexafluoride and some halogenated gases contribute to forcing over decades and centuries. Other halogenated gases, ozone precursors and aerosols 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).

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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).

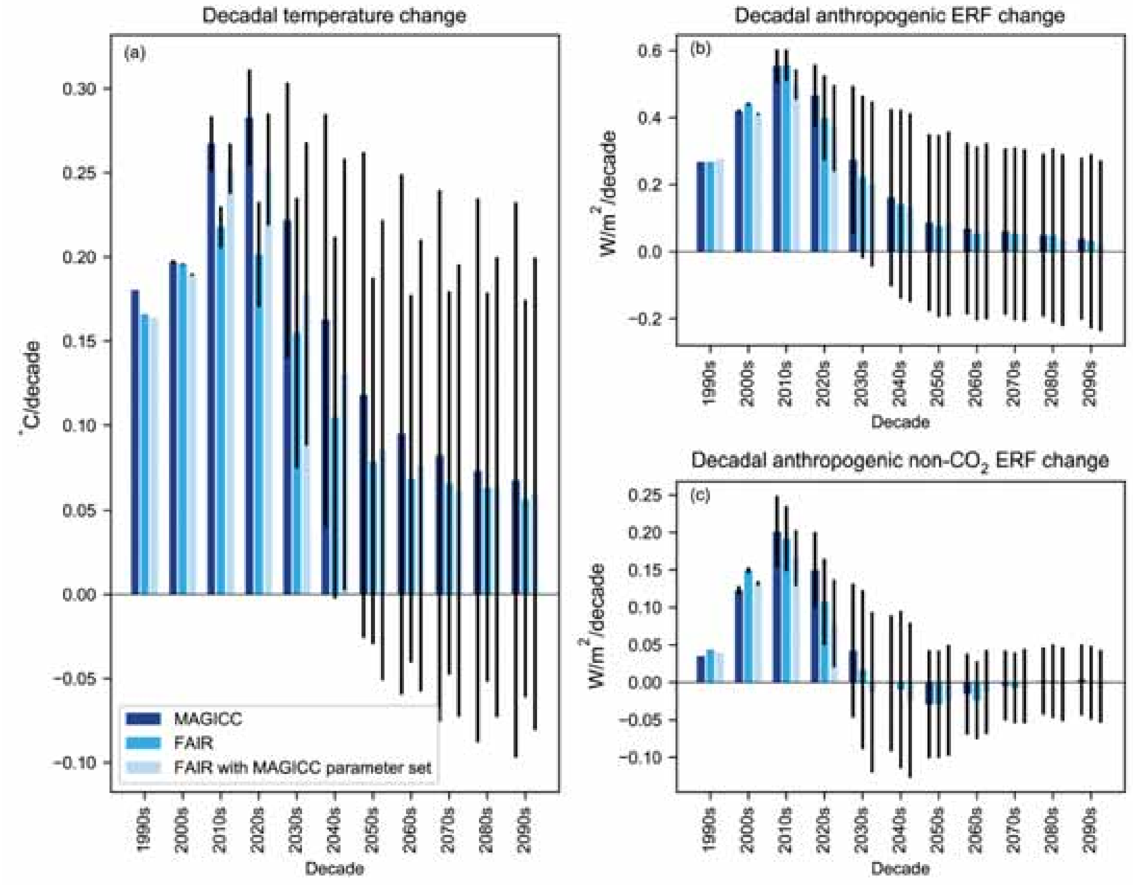

Figure 2.A.1: Warming rates per decade for MAGICC (dark blue), FAIR (sky blue) and FAIR matching the MAGICC parameter set (light blue) for the scenario dataset used in this report. Bars represent the mean of regression slopes taken over each decade (years 0 to 9) for scenario median temperature changes, over all scenarios. The black bars show the standard deviation over the set of scenarios.

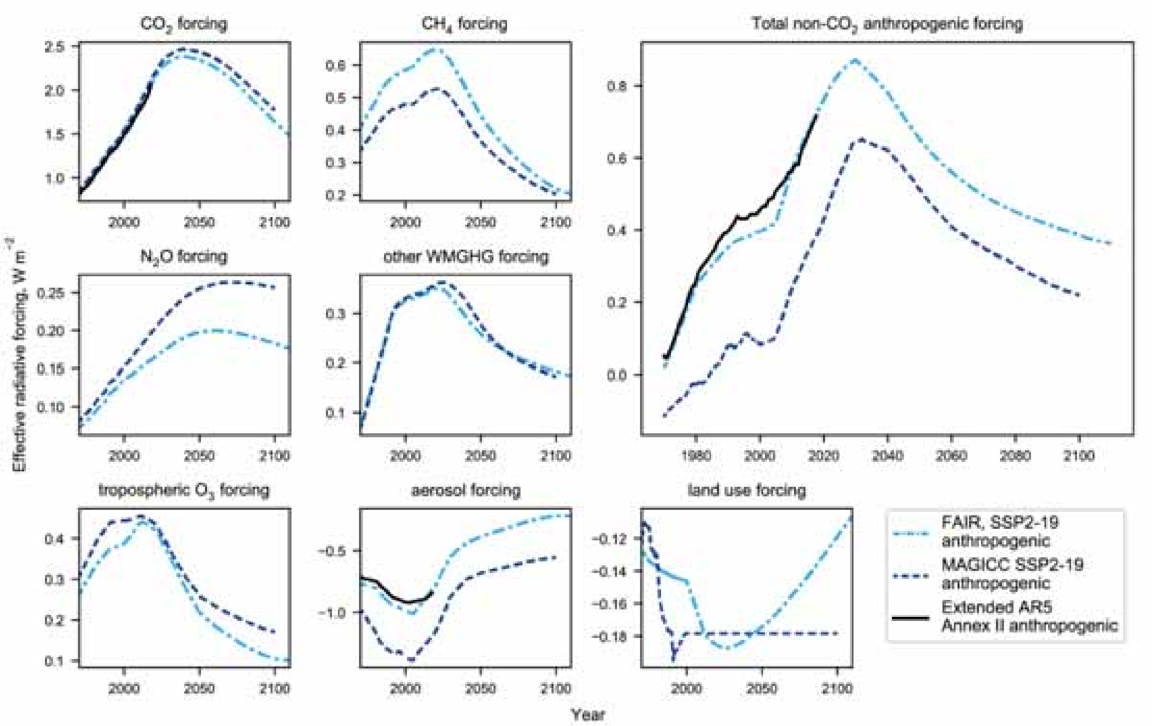

Figure 2.A.2: Time series of MAGICC (dark blue dashed) and FAIR (sky blue dash-dotted) effective radiative forcing for an example emission scenario for the main forcing agents where the models exhibit differences. AR5 data is from Myhre et al. (2013), extended from 2011 until the end of 2017 with greenhouse 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.

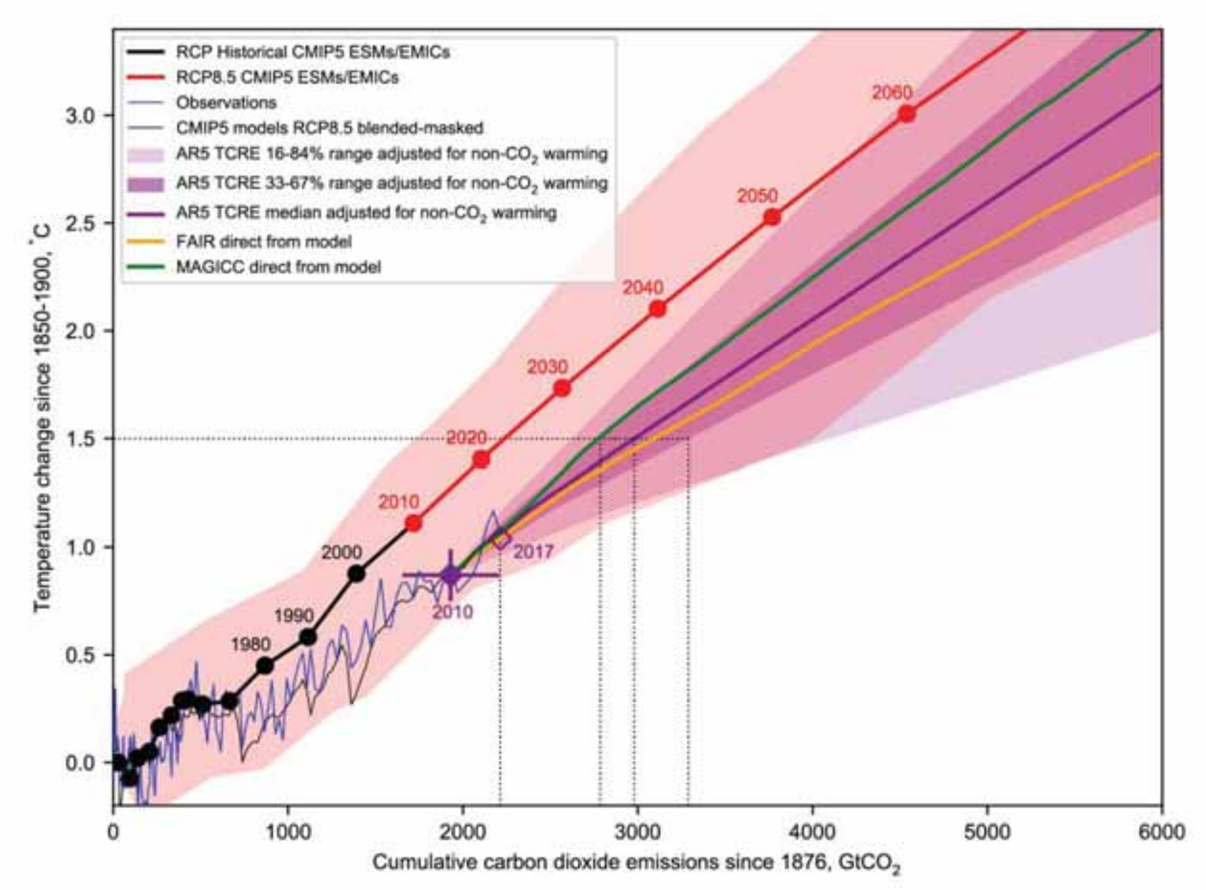

Figure 2.A.3: This figure follows Figure 2.3 of the main report with two extra lines on each showing FAIR (orange) and MAGICC (green) results separately. These additional lines show the full model response averaged across all scenarios and geophysical parameters.

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 ($\Delta T_{\mathrm{peak}} - RNCTC$).

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 21^{st} 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.

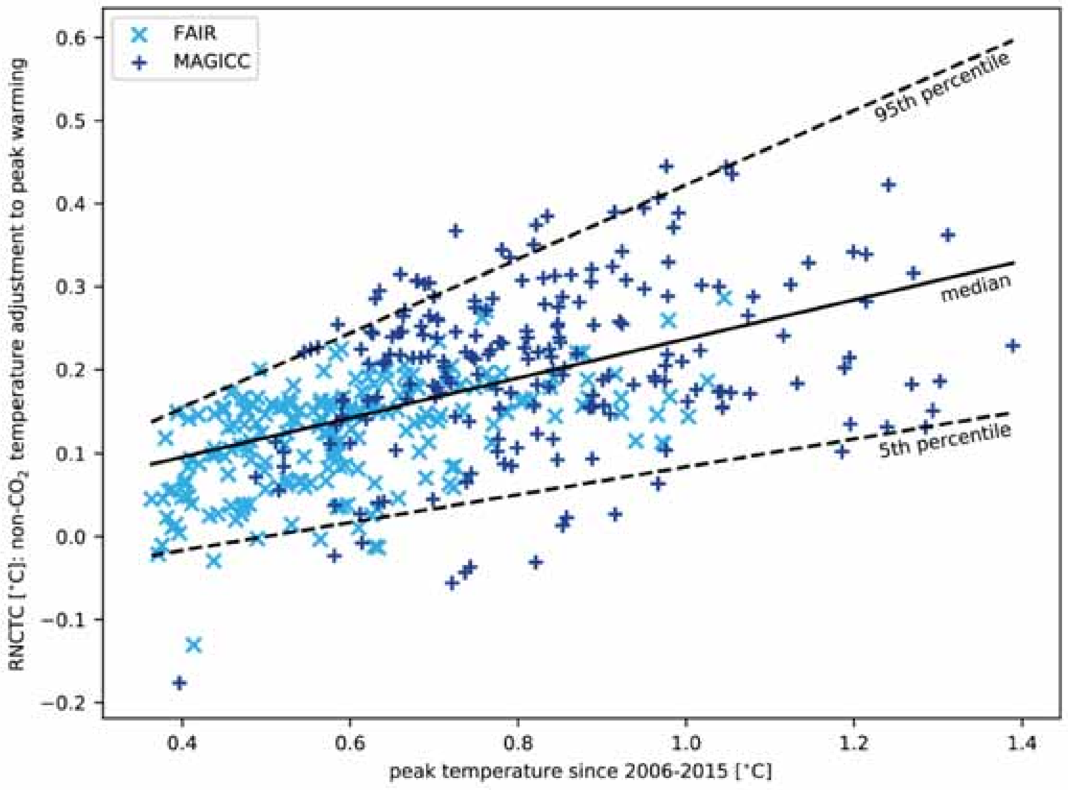

Figure 2.A.4: Relationship of RNCTC with peak temperature in the FAIR and MAGICC models. The black line is the linear regression relationship between peak temperature and RNCTC. The dashed lines show the quantile regressions at the 5th and 95th percentile.

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 ($GtCO_2$)	**Normal distribution**			**Log-normal distribution**		
	TCRE 0.35 °C per 1000$GtCO_2$	TCRE 0.45 °C per 1000$GtCO_2$	TCRE 0.55 °C per 1000$GtCO_2$	TCRE 0.30 °C per 1000$GtCO_2$	TCRE 0.38 °C per 1000$GtCO_2$	TCRE 0.50 °C per 1000$GtCO_2$
Additional warming from 2005-2015 °C	TCRE 33%	TCRE 50%	TCRE 67%	TCRE 33%	TCRE 50%	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 ($GtCO_2$)		**MAGICC**				**FAIR**		
Additional warming from 2006-2015 °C	**MAGICC RNCTC** °C	TCRE 33%	TCRE 50%	TCRE 67%	**FAIR RNCTC** °C	TCRE 33%	TCRE 50%	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 ($\mathrm{AGWP}_H(\mathrm{CO_2})$) over time horizon H, taken to be 100 years:

$$\Delta T_{\text{peak}} \approx \mathrm{TCRE} \times \left(G_{\mathrm{CO2}} + \Delta F_{\text{non-CO2}} \times \left(H/\mathrm{AGWP}_H(\mathrm{CO_2})\right)\right) \qquad (1)$$

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.

		FAIR		
Remaining budgets ($GtCO_2$) Additional warming from 2006-2015 °C	**FAIR RNCFC** (Wm^{-2})	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 ($GtCO_2$)	**Log-normal minus normal TCRE distribution**		
Additional warming from 2006-2015 °C	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

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
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

	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
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																					

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
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

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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

Table of Contents

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.

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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

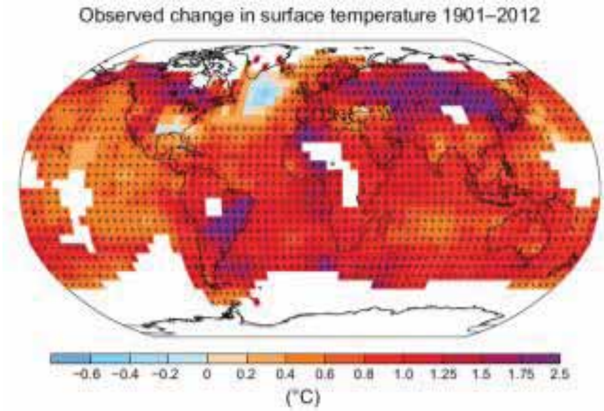


Figure S3.1: Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset. Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records 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).

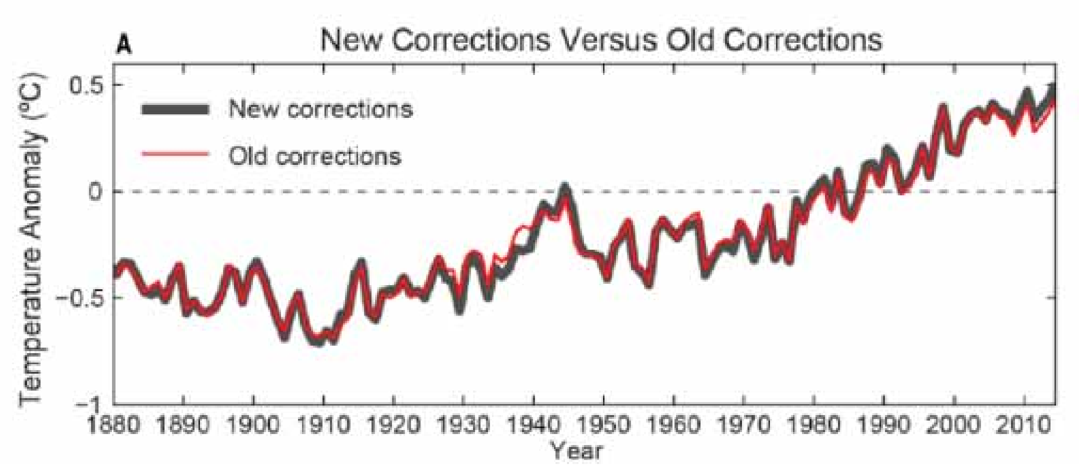
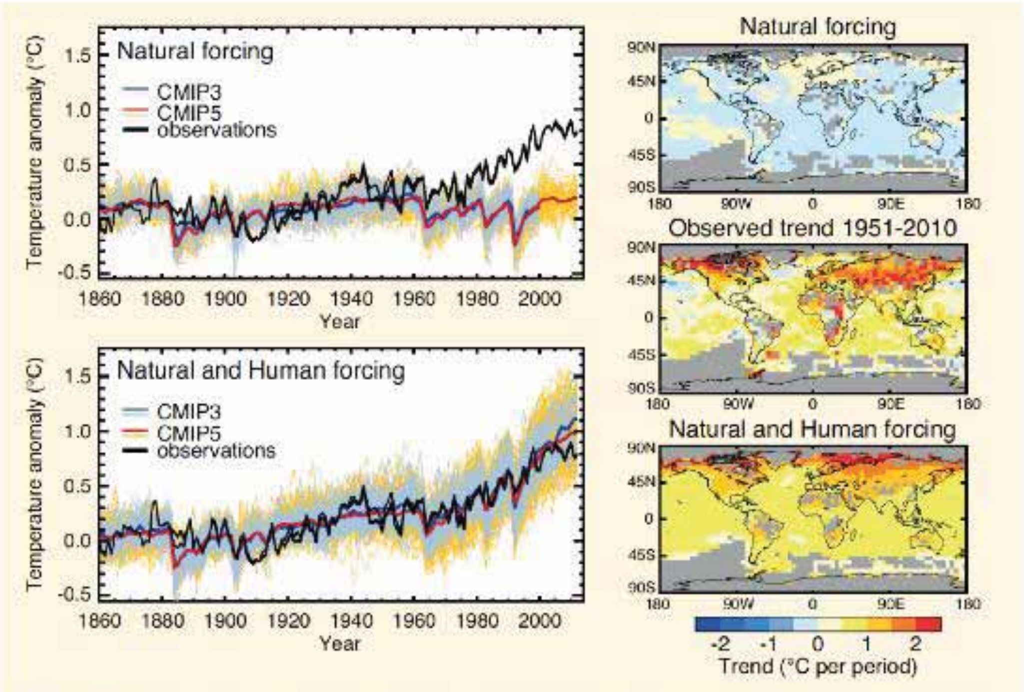


Figure S3.2: Global temperature warming using older and newer corrections (Karl et al. 2015)



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).

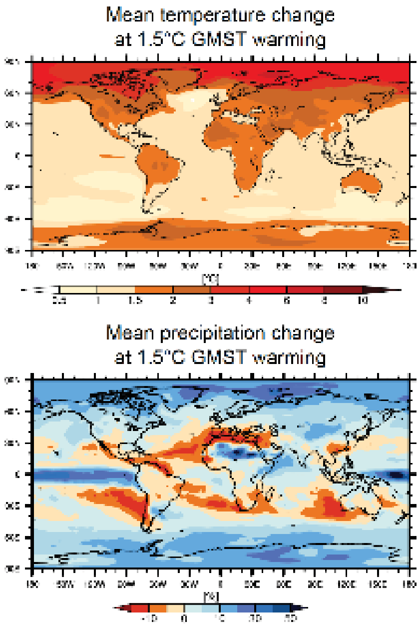


Figure S3.4: Same as left-hand plots of Figure 3.3, but based on the Representative Concentration Pathway (RCP)2.6 scenarios

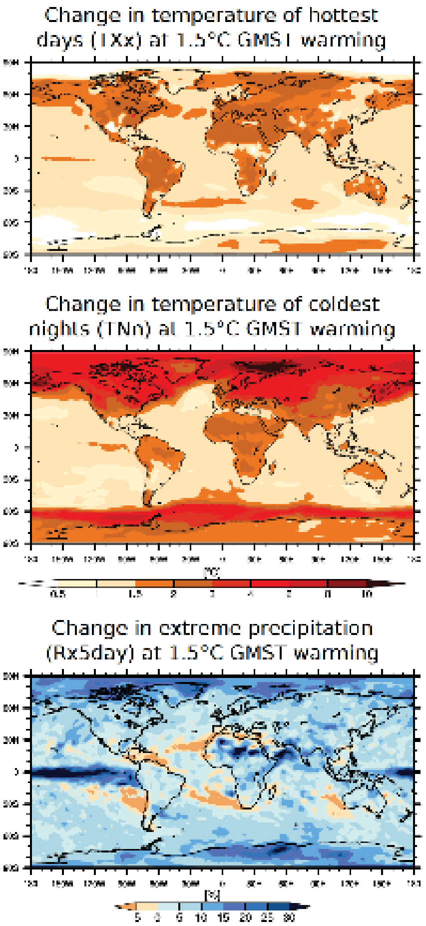


Figure S3.5: Same as left-hand plot of Figure 3.4, but based on the Representative Concentration Pathway (RCP)2.6 scenarios

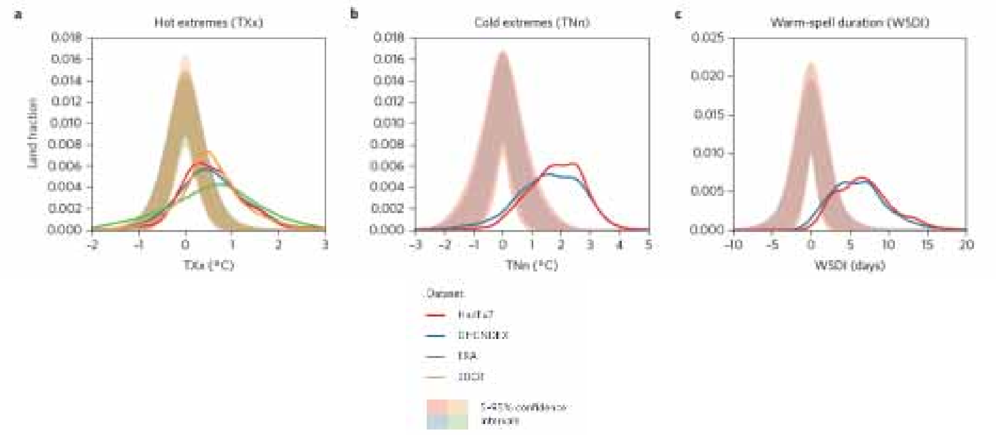


Figure S3.6 : Difference in extreme temperature event indices for 0.5°C warming over the observational record. Probability density functions show the globally aggregated land fraction that experienced a certain change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. For 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)

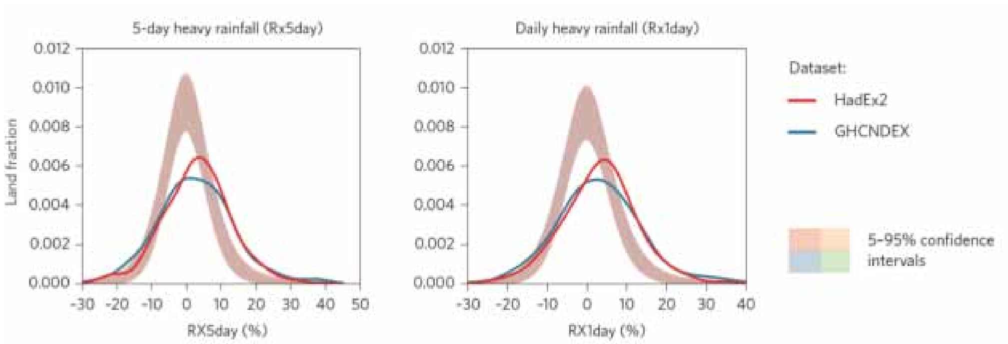


Figure S3.7 : Differences in extreme precipitation event indices for 0.5°C warming over the observational record. Probability density functions show the globally aggregated land fraction that experienced a certain change between the 1991–2010 and 1960–1979 periods for the HadEX2 and GHCNDEX datasets. Light-coloured envelopes illustrate the changes expected by internal variability alone, estimated by statistically resampling individual years. From Schleussner et al. (2017)

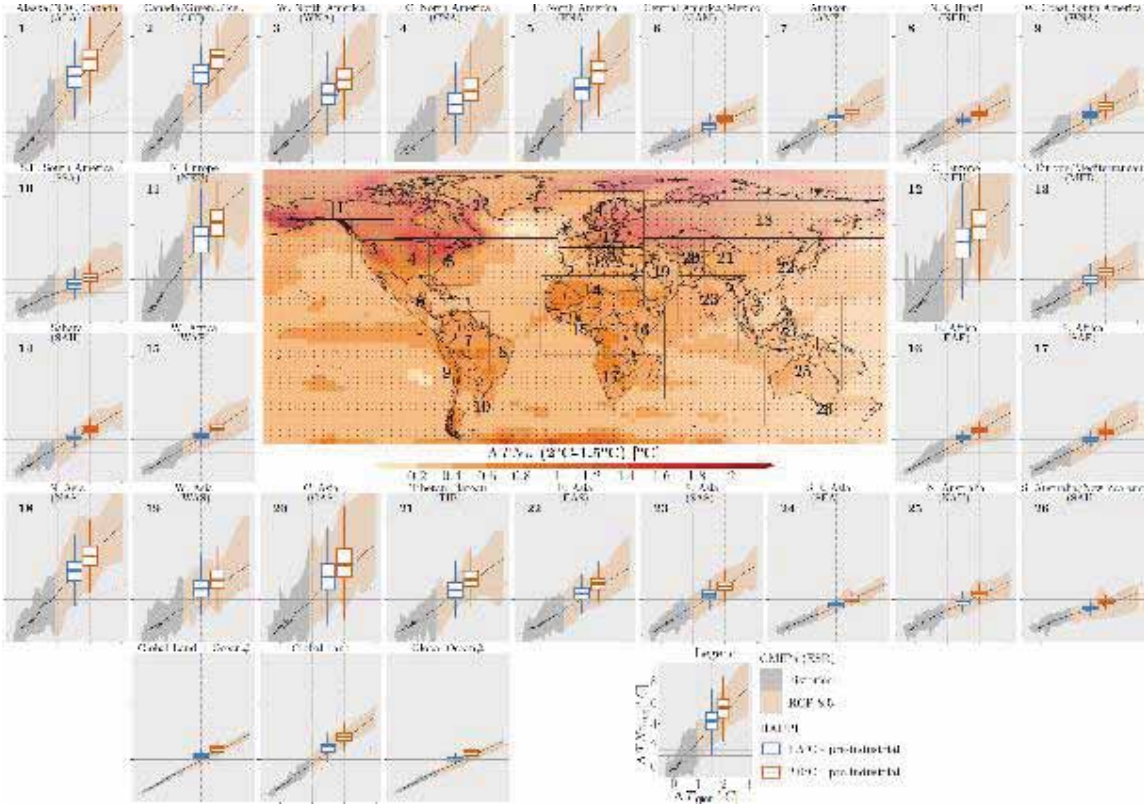


Figure S3.8 : Same analysis as Figure 3.5, but for the annual minimum night-time temperature (TNn). For more details on computation, see description of computation of Figure 3.5 in the present Annex, as well as Wartenburger et al. (2017), Seneviratne et al. (2016) and Seneviratne et al. (2018).

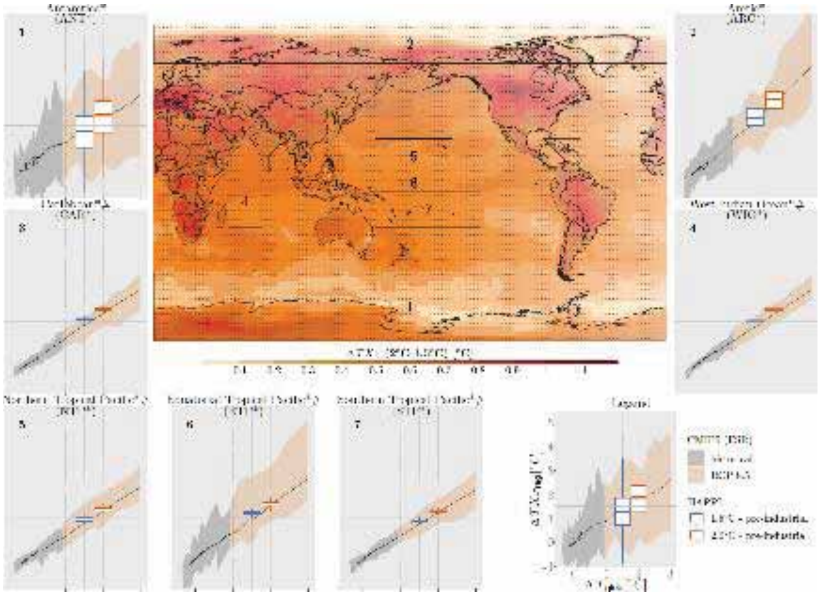


Figure S3.9: Same analysis as Figure 3.5 (projected changes in annual maximum daytime temperature (TXx) as function of global temperature warming) for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). 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.

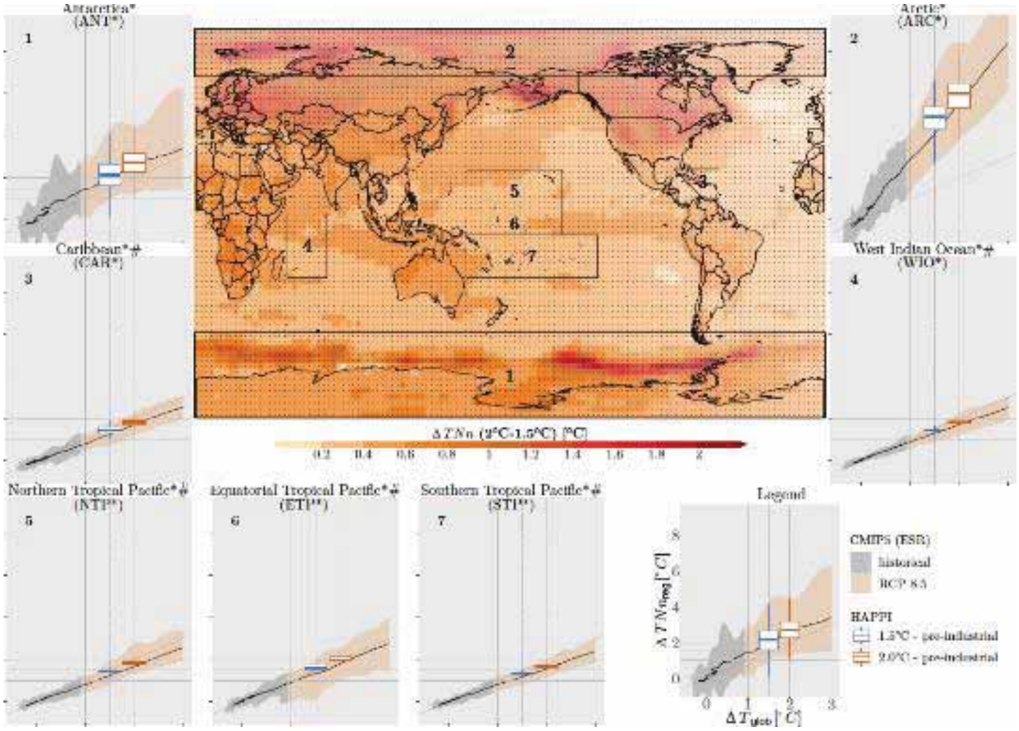


Figure S3.10: Same analysis as Figure S3.8 (projected changes in annual minimum nightime temperature (TNn) as function of global temperature warming) for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

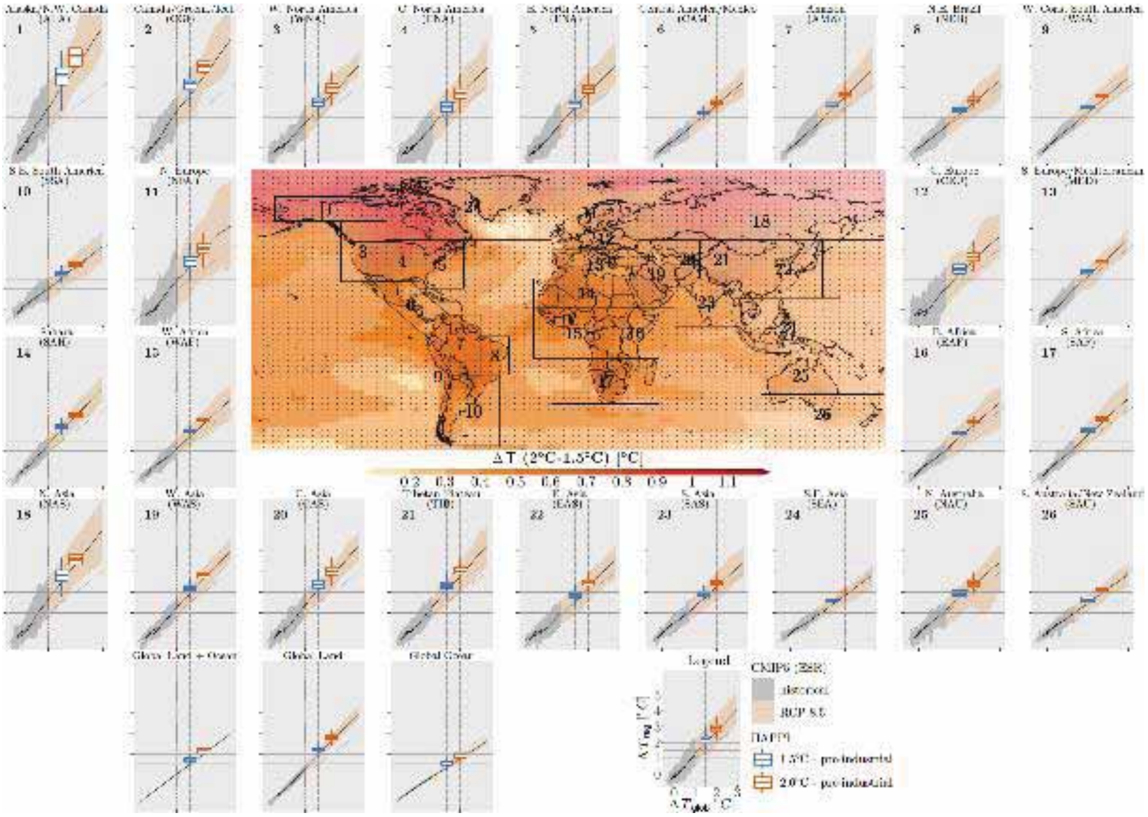


Figure S3.11: Same analysis as Figure 3.5, but for the mean surface temperature (Tmean).

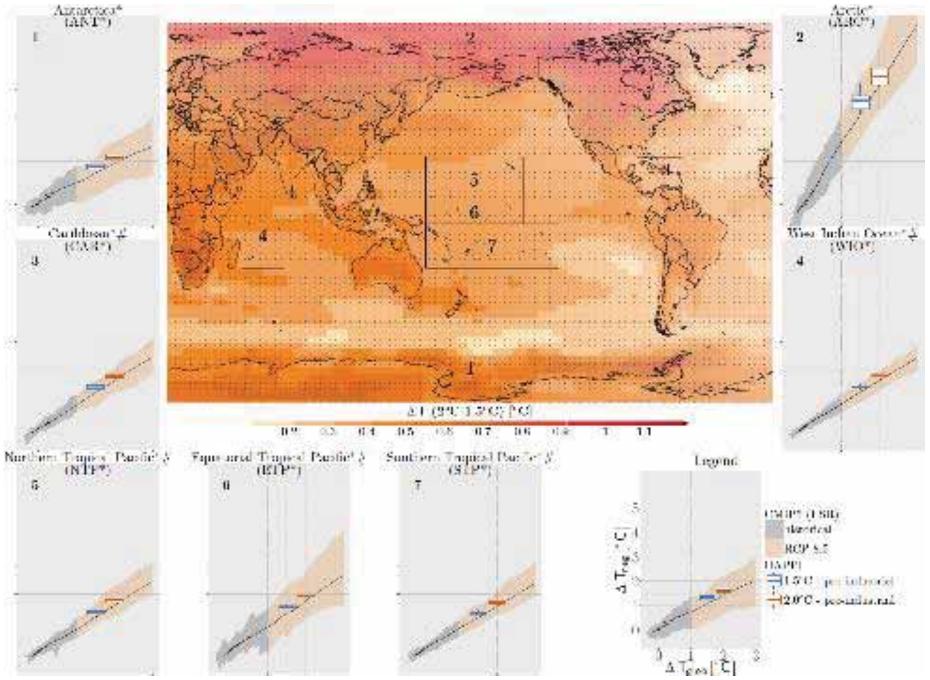


Figure S3.12: Same analysis as Figure 3.11 (projected in the changes in the mean surface temperature (Tmean) as function of the mean global temperature) for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

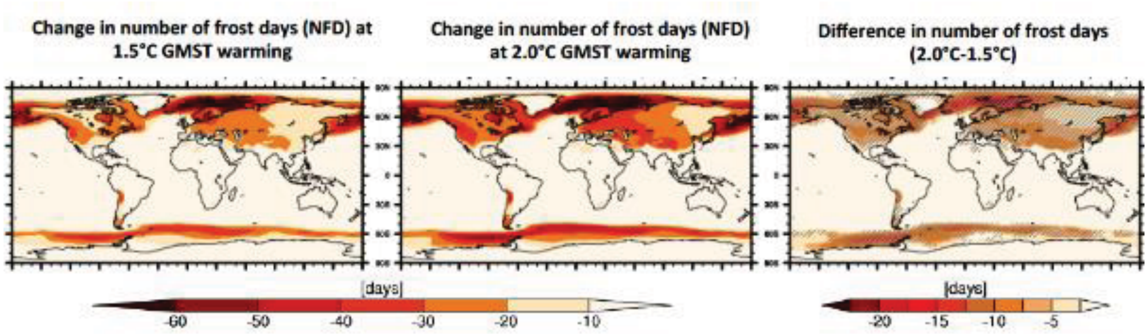


Figure S3.13: Projected changes in number of hot days (10% warmest days, top) and in number of frost days (days with T<0°C, bottom) at 1.5°C (left) and 2°C (right) GMST warming, and their difference (right; hatching highlights areas in which 2/3 of the models agree on the sign of change). Adapted from Wartenburger et al. (2017).

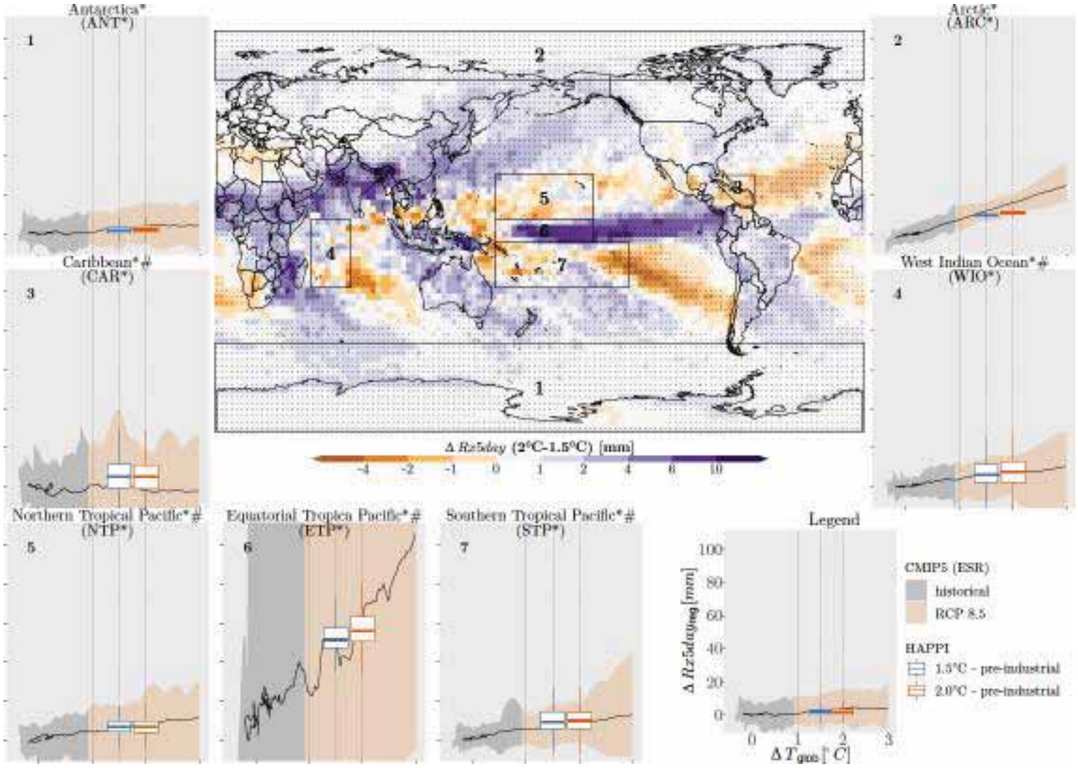


Figure S3.14: Same analysis as Figure 3.9 for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

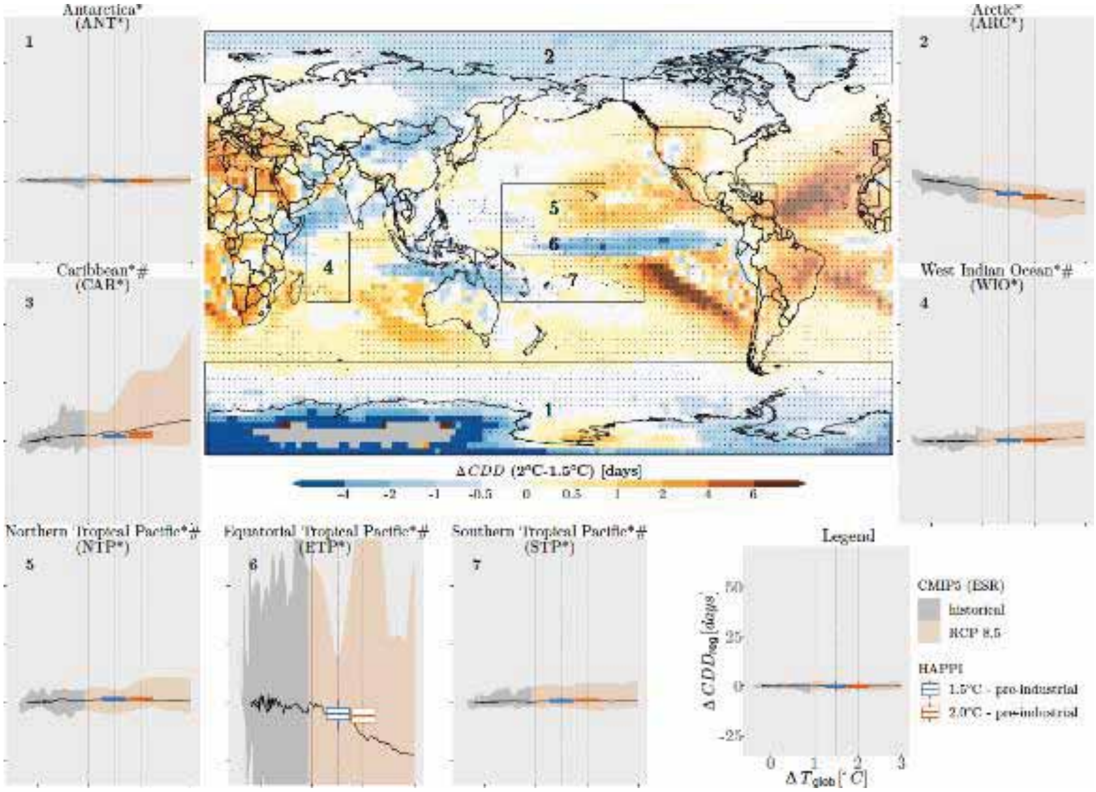


Figure S3.15: Same analysis as Figure 3.12 for additional regions displayed with asterisks in Figure 3.2 (island regions, polar regions). Asterisks (*) indicate non-SREX reference regions (http://www.ipcc-data.org/guidelines/pages/ar5_regions.html). Pound sign (#) indicates island regions; for these regions, the ocean area was not masked out in the analyses.

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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).

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S3-4-4_Supplementary information to Section 3.4.4

Update of Expert assessment by Gattuso et al. (2015).

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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^{o}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

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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

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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. albopictus* 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.		

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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)		

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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)

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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.

<table>
<tr><th>Entry for indicator-option combination</th><th colspan="2">Guidance for conducting the feasibility assessment of mitigation and adaptation options</th></tr>
<tr><td>NA (not applicable)</td><td colspan="2">The indicator is not relevant to the option</td></tr>
<tr><td>NE (no evidence)</td><td colspan="2">• 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</td></tr>
<tr><td>LE (limited evidence)</td><td colspan="2">• 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</td></tr>
<tr><td>A</td><td rowspan="3">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</td><td>A = The indicator could block the feasibility of this option</td></tr>
<tr><td>B</td><td>B = The indicator does not have a positive, nor a negative effect on the feasibility of the option</td></tr>
<tr><td>C</td><td>C = The indicator does not pose any barrier to the feasibility of this option</td></tr>
</table>

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	$AVG = (1 \ast \#A + 2 \ast \#B + 3 \ast \#C)/\#effective\ indicators$

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**
▨	$\#indicators = \#NA$
☐	$\#NE\&LE > 0.5 \ast \#effective\ indicators$
░	$AVG \leq 1.5$ $\#NE\&LE \leq 0.5 \ast \#effective\ indicators$
▒	$1.5 < AVG \leq 2.5$ $\#NE\&LE \leq 0.5 \ast \#effective\ indicators$
▓	$AVG > 2.5$ $\#NE\&LE \leq 0.5 \ast \#effective\ indicators$

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)

		🟫						🟫	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/ecologic al	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	
Geophysic	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.

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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^{o}C from both y-axes as in SPM-2
SPM2	3	131	Figure 3-20 - Remove text '0.87^{o}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^{O}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

Global Warming of 1.5 °C an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty

Headline Statements

A. Understanding Global Warming of 1.5°C4

A1. Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C. Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (*high confidence*).

A.2. Warming from anthropogenic emissions from the pre-industrial period to the present will persist for centuries to millennia and will continue to cause further long-term changes in the climate system, such as sea level rise, with associated impacts (*high confidence*), but these emissions alone are unlikely to cause global warming of 1.5°C (*medium confidence*).

A3. Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present, but lower than at 2°C (*high confidence*). These risks depend on the magnitude and rate of warming, geographic location, levels of development and vulnerability, and on the choices and implementation of adaptation and mitigation options (*high confidence*).

B. Projected Climate Change, Potential Impacts and Associated Risks

B1. Climate models project robust7 differences in regional climate characteristics between present-day and global warming of 1.5°C, and between 1.5°C and 2°C. These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*).

B2. By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depends on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*).

B3. On land, impacts on biodiversity and ecosystems, including species loss and extinction, are projected to be lower at 1.5°C of global warming compared to 2°C. Limiting global warming to 1.5°C compared to 2°C is projected to lower the impacts on terrestrial, freshwater, and coastal ecosystems and to retain more of their services to humans (*high confidence*).

B4. Limiting global warming to 1.5°C compared to 2ºC is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5°C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans, as illustrated by recent changes to Arctic sea ice and warm water coral reef ecosystems (*high confidence*).

B5. Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C.

B6. Most adaptation needs will be lower for global warming of 1.5°C compared to 2°C (*high confidence*). There are a wide range of adaptation options that can reduce the risks of climate change (*high confidence*). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, with associated losses (*medium confidence*). The number and availability of adaptation options vary by sector (*medium confidence*).

C. Emission Pathways and System Transitions Consistent with 1.5°C Global Warming

C1. In model pathways with no or limited overshoot of 1.5°C, global net anthropogenic CO2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2°C, CO2 emissions are projected to decline by about 20% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2075 (2065–2080 interquartile range). Non-CO2 emissions in pathways that limit global warming to 1.5°C show deep reductions that are similar to those in pathways limiting warming to 2°C (*high confidence*).

C2. Pathways limiting global warming to 1.5°C with no or limited overshoot would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems (*high confidence*). These systems transitions are unprecedented in terms of scale, but not necessarily in terms of speed, and imply deep emissions reductions in all sectors, a wide portfolio of mitigation options and a significant upscaling of investments in those options (*medium confidence*).

C3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 GtCO2 over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (*high confidence*). CDR deployment of several hundreds of GtCO2 is subject to multiple feasibility and sustainability constraints (*high confidence*). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred GtCO2 without reliance on bioenergy with carbon capture and storage (BECCS) (*high confidence*).

D. Strengthening the Global Response in the Context of Sustainable Development and Efforts to Eradicate Poverty

D1. Estimates of the global emissions outcome of current nationally stated mitigation ambitions as submitted under the Paris Agreement would lead to global greenhouse gas emissions in 2030 of 52–58 GtCO2eq yr-1 (*medium confidence*). Pathways reflecting these ambitions would not limit global warming to 1.5°C, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (*high confidence*). Avoiding overshoot and reliance on future largescale deployment of carbon dioxide removal (CDR) can only be achieved if global CO2 emissions start to decline well before 2030 (*high confidence*).

D2. The avoided climate change impacts on sustainable development, eradication of poverty and reducing inequalities would be greater if global warming were limited to 1.5°C rather than 2°C, if mitigation and adaptation synergies are maximized while trade-offs are minimized (*high confidence*).

D3. Adaptation options specific to national contexts, if carefully selected together with enabling conditions, will have benefits for sustainable development and poverty reduction with global warming of 1.5°C, although trade-offs are possible (*high confidence*).

D4. Mitigation options consistent with 1.5°C pathways are associated with multiple synergies and trade-offs across the Sustainable Development Goals (SDGs). While the total number of possible synergies exceeds the number of trade-offs, their net effect will depend on the pace and magnitude of changes, the composition of the mitigation portfolio and the management of the transition (*high confidence*).

D5. Limiting the risks from global warming of 1.5°C in the context of sustainable development and poverty eradication implies system transitions that can be enabled by an increase of adaptation and mitigation investments, policy instruments, the acceleration of technological innovation and behaviour changes (*high confidence*).

D6. Sustainable development supports, and often enables, the fundamental societal and systems transitions and transformations that help limit global warming to 1.5°C. Such changes facilitate the pursuit of climate-resilient development pathways that achieve ambitious mitigation and adaptation in conjunction with poverty eradication and efforts to reduce inequalities (*high confidence*).

D7. Strengthening the capacities for climate action of national and sub-national authorities, civil society, the private sector, indigenous peoples and local communities can support the implementation of ambitious actions implied by limiting global warming to 1.5°C (*high confidence*). International cooperation can provide an enabling environment for this to be achieved in all countries and for all people, in the context of sustainable development. International cooperation is a critical enabler for developing countries and vulnerable regions (*high confidence*).

INTERGOVERNMENTAL PANEL ON climate change

2018/24/PR

IPCC PRESS RELEASE

8 October 2018

Summary for Policymakers of IPCC Special Report on Global Warming of 1.5ºC approved by governments

INCHEON, Republic of Korea, 8 Oct - Limiting global warming to 1.5ºC would require rapid, far-reaching and unprecedented changes in all aspects of society, the IPCC said in a new assessment. With clear benefits to people and natural ecosystems, limiting global warming to 1.5ºC compared to 2ºC could go hand in hand with ensuring a more sustainable and equitable society, the Intergovernmental Panel on Climate Change (IPCC) said on Monday.

The Special Report on Global Warming of 1.5ºC was approved by the IPCC on Saturday in Incheon, Republic of Korea. It will be a key scientific input into the Katowice Climate Change Conference in Poland in December, when governments review the Paris Agreement to tackle climate change.

“With more than 6,000 scientific references cited and the dedicated contribution of thousands of expert and government reviewers worldwide, this important report testifies to the breadth and policy relevance of the IPCC,” said Hoesung Lee, Chair of the IPCC.

Ninety-one authors and review editors from 40 countries prepared the IPCC report in response to an invitation from the United Nations Framework Convention on Climate Change (UNFCCC) when it adopted the Paris Agreement in 2015.

The report’s full name is *Global Warming of 1.5°C, an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.

“One of the key messages that comes out very strongly from this report is that we are already seeing the consequences of 1°C of global warming through more extreme weather, rising sea levels and diminishing Arctic sea ice, among other changes,” said Panmao Zhai, Co-Chair of IPCC Working Group I.

The report highlights a number of climate change impacts that could be avoided by limiting global warming to 1.5ºC compared to 2ºC, or more. For instance, by 2100, global sea level rise would be 10 cm lower with global warming of 1.5°C compared with 2°C. The likelihood of an Arctic Ocean free of sea ice in summer would be once per century with global warming of 1.5°C, compared with at least once per decade with 2°C. Coral reefs would decline by 70-90 percent with global warming of 1.5°C, whereas virtually all (> 99 percent) would be lost with 2ºC.

“Every extra bit of warming matters, especially since warming of 1.5ºC or higher increases the risk associated with long-lasting or irreversible changes, such as the loss of some ecosystems,” said Hans-Otto Pörtner, Co-Chair of IPCC Working Group II.

Limiting global warming would also give people and ecosystems more room to adapt and remain below relevant risk thresholds, added Pörtner. The report also examines pathways available to limit warming to 1.5ºC, what it would take to achieve them and what the consequences could be.

“The good news is that some of the kinds of actions that would be needed to limit global warming to 1.5ºC are already underway around the world, but they would need to accelerate,” said Valerie Masson-Delmotte, Co-Chair of Working Group I.

The report finds that limiting global warming to 1.5°C would require “rapid and far-reaching” transitions in land, energy, industry, buildings, transport, and cities. Global net human-caused emissions of carbon dioxide (CO_2) would need to fall by about 45 percent from 2010 levels by 2030, reaching ‘net zero’ around 2050. This means that any remaining emissions would need to be balanced by removing CO_2 from the air.

“Limiting warming to 1.5ºC is possible within the laws of chemistry and physics but doing so would require unprecedented changes,” said Jim Skea, Co-Chair of IPCC Working Group III.

Allowing the global temperature to temporarily exceed or ‘overshoot’ 1.5ºC would mean a greater reliance on techniques that remove CO_2 from the air to return global temperature to below 1.5ºC by 2100. The effectiveness of such techniques are unproven at large scale and some may carry significant risks for sustainable development, the report notes.

“Limiting global warming to 1.5°C compared with 2°C would reduce challenging impacts on ecosystems, human health and well-being, making it easier to achieve the United Nations Sustainable Development Goals,” said Priyardarshi Shukla, Co-Chair of IPCC Working Group III.

The decisions we make today are critical in ensuring a safe and sustainable world for everyone, both now and in the future, said Debra Roberts, Co-Chair of IPCC Working Group II.

“This report gives policymakers and practitioners the information they need to make decisions that tackle climate change while considering local context and people’s needs. The next few years are probably the most important in our history,” she said.

The IPCC is the leading world body for assessing the science related to climate change, its impacts and potential future risks, and possible response options.

The report was prepared under the scientific leadership of all three IPCC working groups. Working Group I assesses the physical science basis of climate change; Working Group II addresses impacts, adaptation and vulnerability; and Working Group III deals with the mitigation of climate change.

The Paris Agreement adopted by 195 nations at the 21st Conference of the Parties to the UNFCCC in December 2015 included the aim of strengthening 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.”

As part of the decision to adopt the Paris Agreement, the IPCC was invited to produce, in 2018, a Special Report on global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. The IPCC accepted the invitation, adding that the Special Report would 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.

Global Warming of 1.5ºC is the first in a series of Special Reports to be produced in the IPCC’s Sixth Assessment Cycle. Next year the IPCC will release the *Special Report on the Ocean and Cryosphere in a Changing Climate*, and *Climate Change and Land*, which looks at how climate change affects land use.

The Summary for Policymakers (SPM) presents the key findings of the Special Report, based on the assessment of the available scientific, technical and socio-economic literature relevant to global warming of 1.5°C.

The Summary for Policymakers of the Special Report on *Global Warming of 1.5ºC* (SR15) is available at http://www.ipcc.ch/report/sr15/ or www.ipcc.ch.

Key statistics of the Special Report on Global Warming of 1.5ºC

91 authors from 44 citizenships and 40 countries of residence
- 14 Coordinating Lead Authors (CLAs)
- 60 Lead authors (LAs)
- 17 Review Editors (REs)

133 Contributing authors (CAs)
Over 6,000 cited references
A total of 42,001 expert and government review comments
(First Order Draft 12,895; Second Order Draft 25,476; Final Government Draft: 3,630)

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Notes for editors

The Special Report on *Global Warming of 1.5 ºC* , known as SR15, is being prepared in response to an invitation from the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change in December 2015, when they reached the Paris Agreement, and will inform the Talanoa Dialogue at the 24th Conference of the Parties (COP24). The Talanoa Dialogue will take stock of the collective efforts of Parties in relation to progress towards the long-term goal of the Paris Agreement, and to inform the preparation of nationally determined contributions. Details of the report, including the approved outline, can be found on the report page. The report was prepared under the joint scientific leadership of all three IPCC Working Groups, with support from the Working Group I Technical Support Unit.

What is the IPCC?

The Intergovernmental Panel on Climate Change (IPCC) is the UN body for assessing the science related to climate change. It was established by the United Nations Environment Programme (UN Environment) and the World Meteorological Organization (WMO) in 1988 to provide policymakers with regular scientific assessments concerning climate change, its implications and potential future risks, as well as to put forward adaptation and mitigation strategies. It has 195 member states.

IPCC assessments provide governments, at all levels, with scientific information that they can use to develop climate policies. IPCC assessments are a key input into the international negotiations to tackle climate change. IPCC reports are drafted and reviewed in several stages, thus guaranteeing objectivity and transparency.

The IPCC assesses the thousands of scientific papers published each year to tell policymakers what we know and don't know about the risks related to climate change. The IPCC identifies where there is agreement in the scientific community, where there are differences of opinion, and where further research is needed. It does not conduct its own research.

To produce its reports, the IPCC mobilizes hundreds of scientists. These scientists and officials are drawn from diverse backgrounds. Only a dozen permanent staff work in the IPCC's Secretariat.

The IPCC has three working groups: Working Group I, dealing with the physical science basis of climate change; Working Group II, dealing with impacts, adaptation and vulnerability; and Working Group III, dealing with the mitigation of climate change. It also has a Task Force on National Greenhouse Gas Inventories that develops methodologies for measuring emissions and removals.

IPCC Assessment Reports consist of contributions from each of the three working groups and a Synthesis Report. Special Reports undertake an assessment of cross-disciplinary issues that span more than one working group and are shorter and more focused than the main assessments.

Sixth Assessment Cycle

At its 41st Session in February 2015, the IPCC decided to produce a Sixth Assessment Report (AR6). At its 42nd Session in October 2015 it elected a new Bureau that would oversee the work on this report and Special Reports to be produced in the assessment cycle. At its 43rd Session in April 2016, it decided to produce three Special Reports, a Methodology Report and AR6.

The Methodology Report to refine the 2006 IPCC Guidelines for National Greenhouse Gas Inventories will be delivered in 2019. Besides *Global Warming of 1.5ºC*, the IPCC will finalize two further special reports in 2019: *the Special Report on the Ocean and Cryosphere in a Changing Climate* and *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. The AR6 Synthesis Report will be finalized in the first half of 2022, following the three working group contributions to AR6 in 2021.

For more information, including links to the IPCC reports, go to: www.ipcc.ch

SR1.5°C FAQs

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[1]. 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[2] 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.

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.

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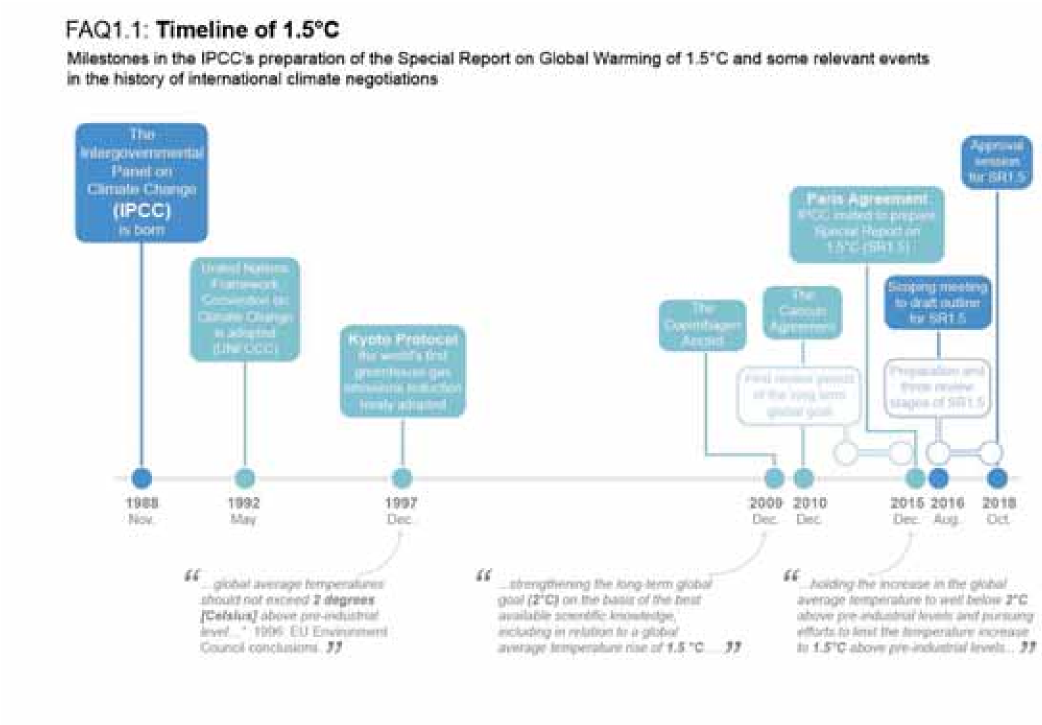
[1] Paris Agreement FCCC/CP/2015/10/Add.1 https://unfccc.int/documents/9097

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



Caption: 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.

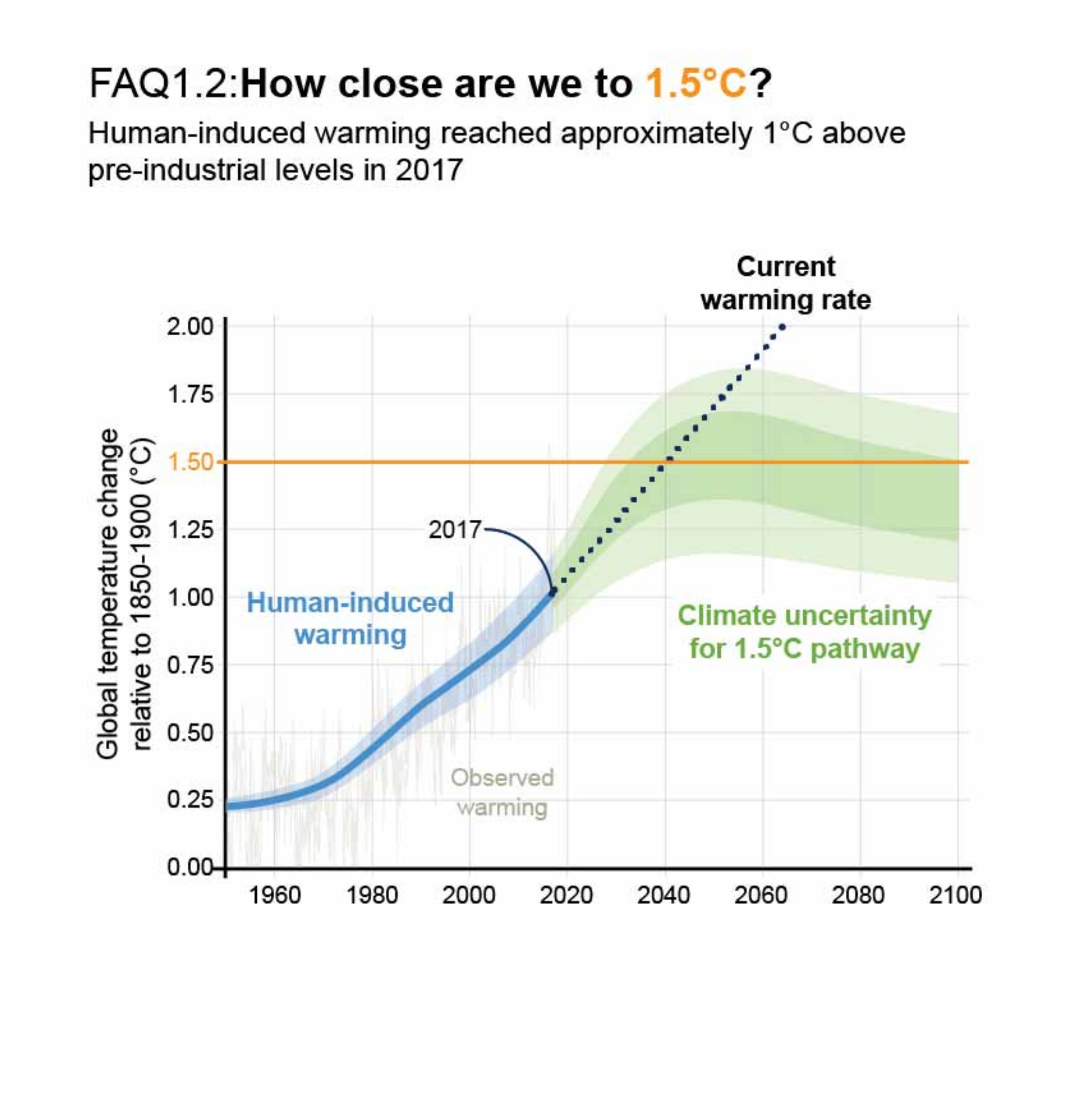
The choice of pre-industrial reference period, along with the method used to calculate global average temperature, can alter scientists' estimates of historical warming by a couple of tenths of a degree Celsius. Such differences become important in the context of a global temperature limit just half 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.



Caption: 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.

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.*

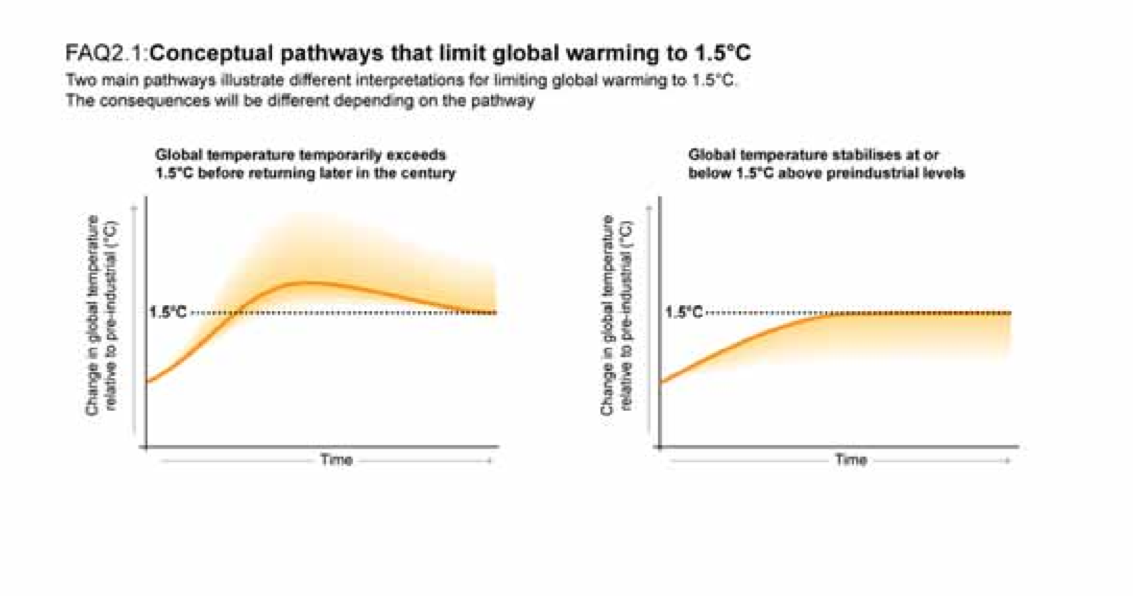
Scientists use computer models to simulate the emissions of greenhouse gases that would be consistent with different levels of warming. The different possibilities are often referred to as 'greenhouse gas emission pathways'. There is no single, definitive pathway to limiting warming to 1.5°C.

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: **Conceptual pathways that limit global warming to 1.5°C**

Two main pathways illustrate different interpretations for limiting global warming to 1.5°C.
The consequences will be different depending on the pathway

Global temperature temporarily exceeds 1.5°C before returning later in the century

Global temperature stabilises at or below 1.5°C above preindustrial levels

Caption: 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?

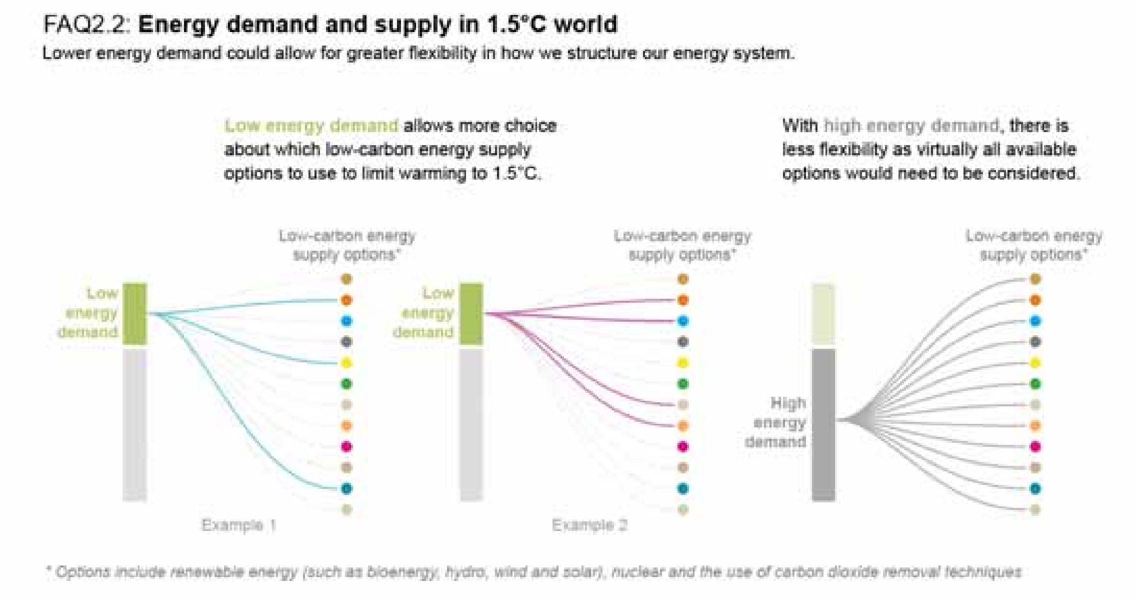
***Summary**: Limiting global warming to 1.5°C above pre-industrial levels would require major reductions in greenhouse gas emissions in all sectors. But different sectors are not independent of each other and making changes in one can have implications for another. For example, if we as a society use 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.



Caption: 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.

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.

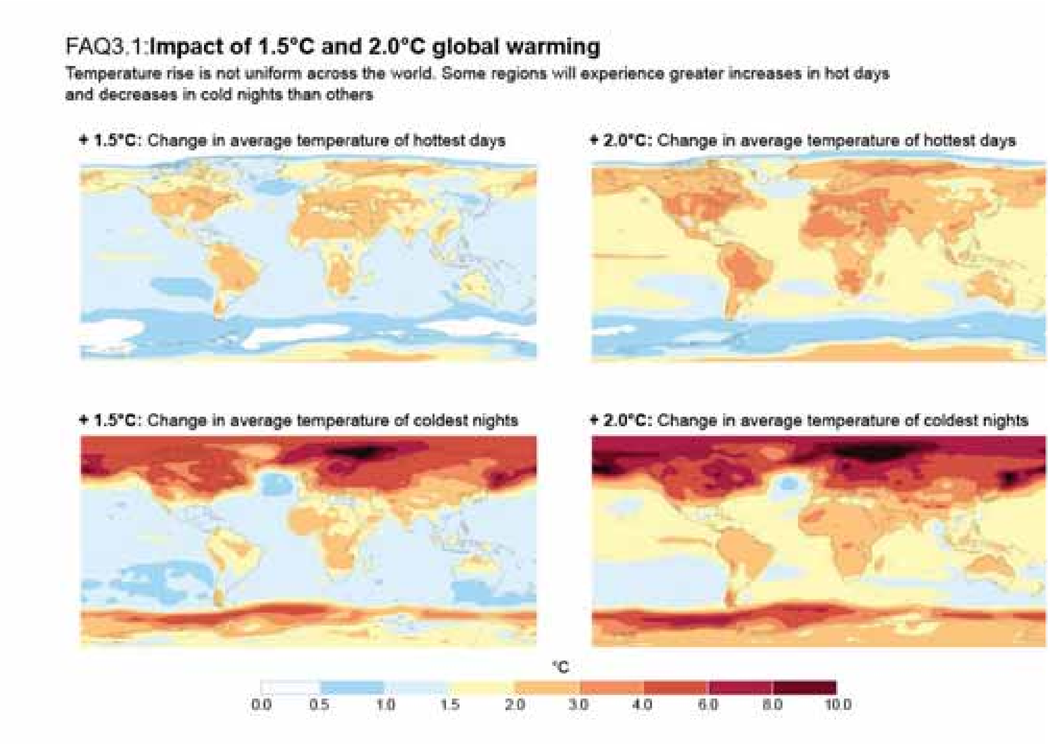
Extra warming on top of the ~1°C we have seen so far would amplify the risks and associated impacts, with implications for the world and its inhabitants. This would be the case even if the total warming is held at 1.5°C, just half a degree above where we are now, and would be further amplified at 2°C 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.



Caption: 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.

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.

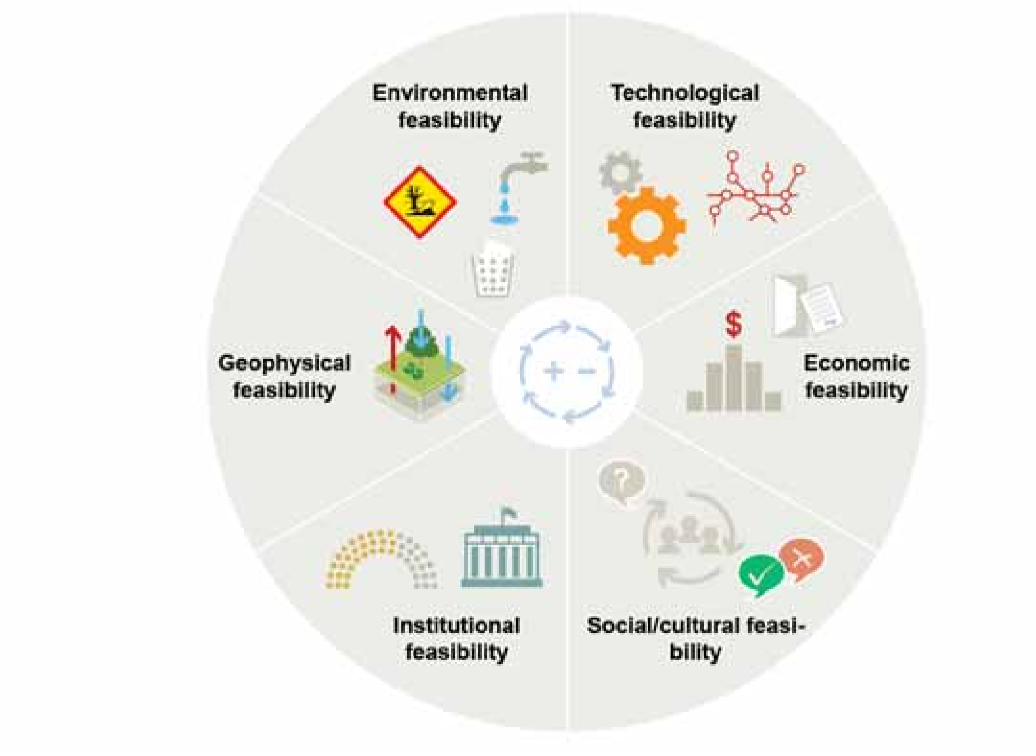
Different types of transitions carry with them different associated costs and requirements for institutional or governmental support. Some are also easier to scale up than others, and some need more government support than others. Transitions between, and within, these systems are connected and none 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.



Caption: 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.*

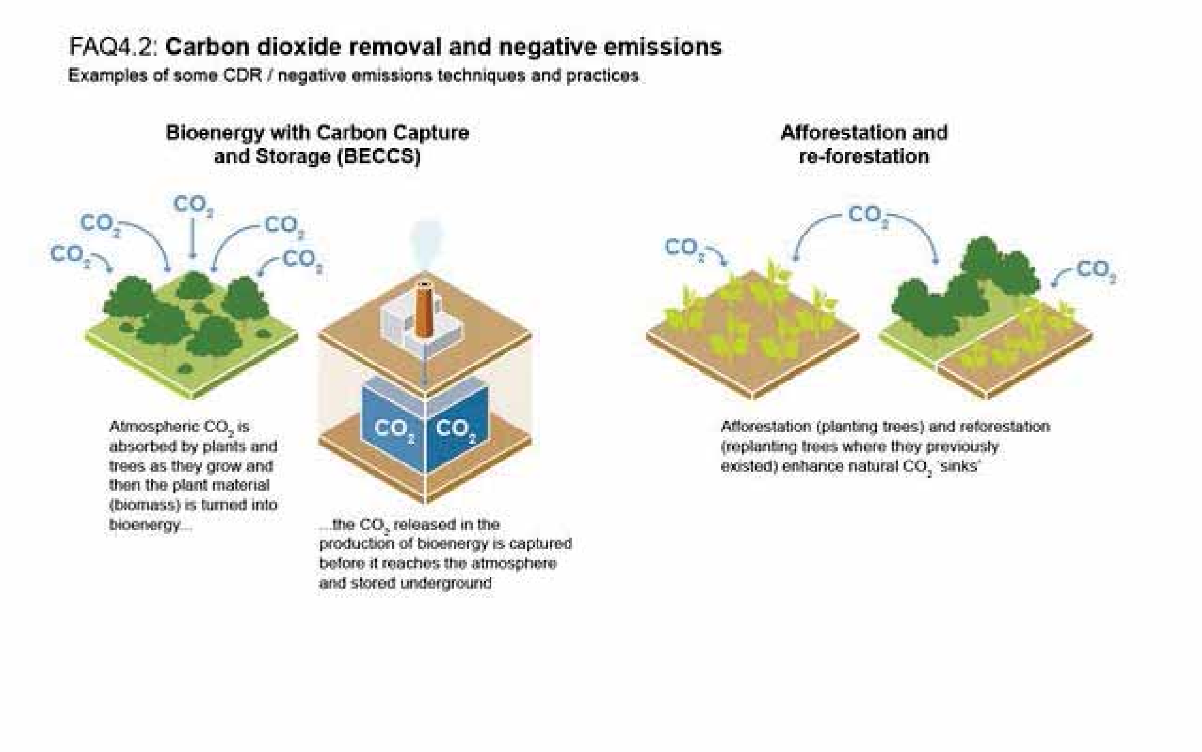
Limiting warming to 1.5°C above preindustrial levels would require unprecedented rates of transformation in many areas, including in the energy and industrial sectors, for example. Conceptually, it is possible that techniques to draw CO_2 out of the atmosphere (known as Carbon Dioxide Removal, or CDR) 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.



Caption: Carbon Dioxide Removal (CDR) refers to the process of removing CO_2 from the atmosphere. There are 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.

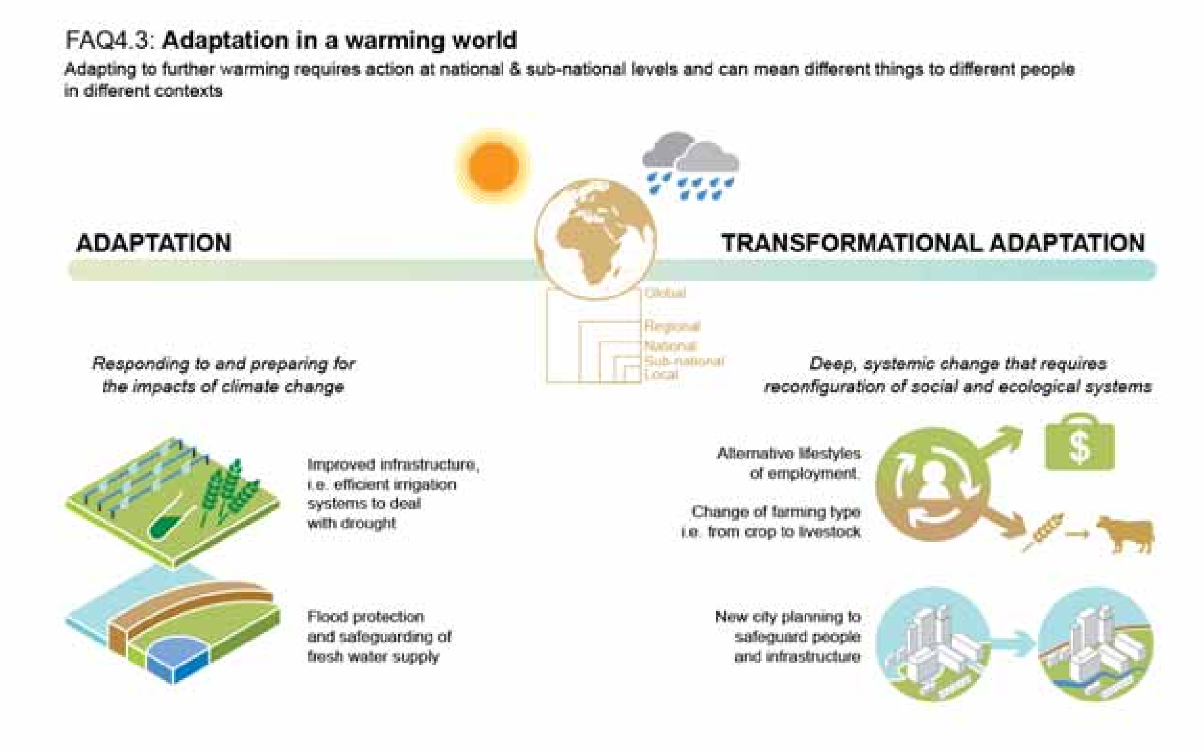
The world is already experiencing the impacts from 1°C of global warming above preindustrial levels and there are many examples of adaptation to impacts associated with this warming. Examples of adaptation efforts taking place around the world include investing in flood defences such as building sea 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.



Caption: 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.

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)

Caption: 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.

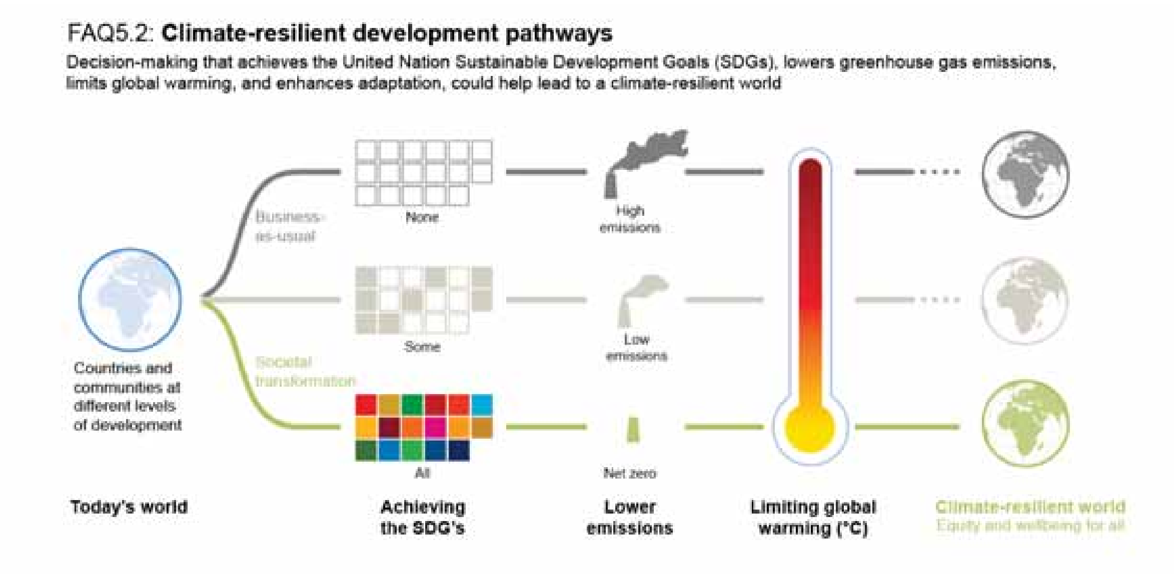
The Paris Agreement states that it "will be implemented to reflect equity… in the light of different national circumstances" and calls for "rapid reductions" of greenhouse gases to be achieved "on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty". Similarly, 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.



Caption: 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.

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Date of Draft: June 2018

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TS1: Framing and Context

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}

TS2: Mitigation pathways compatible with 1.5°C in the context of sustainable development

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

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

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}.

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}

TS3: Impacts of 1.5ºC global warming on natural and human systems

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 *(high confidence).* Temperature means and extremes are higher at 2°C as compared to 1.5°C global warming in most land regions, and display in some regions 2-3 times greater increases when compared to 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}.

Substantial changes in regional climate occur between 1.5°C and 2°C (*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 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*) {3.3.3, 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, and 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 1.6ºC and 2.6ºC 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}

TS4: Strengthening and implementing the global response

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[2] 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}

TS5: Sustainable Development, Poverty Eradication and Reducing Inequalities

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

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[2] FOOTNOTE: Annual capital revenues are the paid interests plus the increase of the asset value.

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}.

Chapter 1: Framing and Context

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Date of Draft: 4/06/18

Notes: TSU compiled version. Copy editing not done.

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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