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Defining the Anthropocene

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Time is divided by geologists according to marked shifts in Earth's state. Recent global environmental changes suggest that Earth may have entered a new human–dominated geological epoch, the Anthropocene. Here we review the historical genesis of the idea and assess anthropogenic signatures in the geological record against the formal requirements for the recognition of a new epoch. The evidence suggests that of the various proposed dates two do appear to conform to the criteria to mark the beginning of the Anthropocene: 1610 and 1964. The formal establishment of an Anthropocene Epoch would mark a fundamental change in the relationship between humans and the Earth system.

Human activity has been a geologically recent, yet profound, influence on the global environment. The magnitude, variety and longevity of human-induced changes, including land surface transformation and changing the composition of the atmosphere, has led to the suggestion that we should refer to the present, not as within the Holocene Epoch (as it is currently formally referred to), but instead as within the Anthropocene Epoch[1–4] (Fig. 1). Academic and popular usage of the term has rapidly escalated[5,6] following two influential papers published just over a decade ago[1,2]. Three scientific journals focusing on the topic have launched: *The Anthropocene*, *The Anthropocene Review* and *Elementa*. The case for a new epoch appears reasonable: what matters when dividing geological-scale time is global-scale changes to Earth's status, driven by causes as varied as meteor strikes, the movement of continents and sustained volcanic eruptions. Human activity is now global and is the dominant cause of most contemporary environmental change. The impacts of human activity will probably be observable in the geological stratigraphic record for millions of years into the future[7], which suggests that a new epoch has begun[4].

Nevertheless, some question the types of evidence[8,9], because to define a geological time unit, formal criteria must be met[10,11]. Global-scale changes must be recorded in geological stratigraphic material, such as rock, glacier ice or marine sediments (see Box 1). At present, there is no formal agreement on when the Anthropocene began, with proposed dates ranging from before the end of the last glaciation to the 1960s. Such different meanings may lead to misunderstandings and confusion across several disciplines. Furthermore, unlike other geological time unit designations, definitions will probably have effects beyond geology. For example, defining an early start date may, in political terms, 'normalize' global environmental change. Meanwhile, agreeing a later start date related to the Industrial Revolution may, for example, be used to assign historical responsibility for carbon dioxide emissions to particular countries or regions during the industrial era. More broadly, the formal definition of the Anthropocene makes scientists arbiters, to an extent, of the human–environment relationship, itself an act with consequences beyond geology. Hence, there is more interest in the Anthropocene than other epoch definitions. Nevertheless, evidence will define whether the geological community formally ratifies a human-activity-induced geological time unit.

We therefore review human geology in four parts. First, we summarize the geologically important human-induced environmental impacts. Second, we review the history of naming the epoch that modern human societies live within, to provide insights into contemporary Anthropocene-related debates. Third, we assess environmental changes caused by human activity that may have left global geological markers consistent with the formal criteria that define geological epochs. Fourth, we highlight the

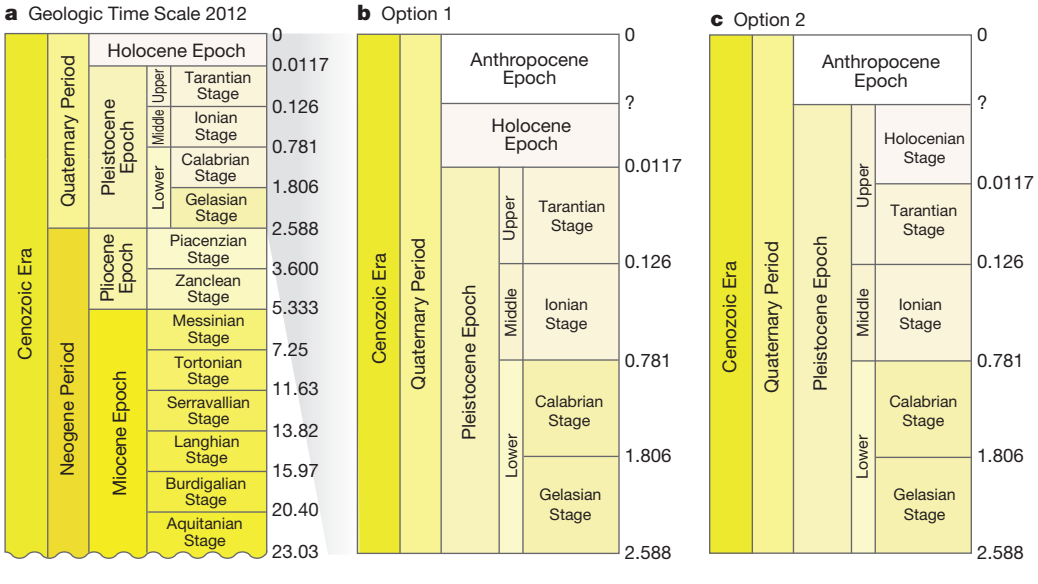

Figure 1 | Comparison of the current Geologic Time Scale[10] (GTS2012), with two alternatives. **a**, GTS2012, with boundaries marked in millions of years (ref. 10). **b**, **c**, The alternatives include a defined Anthropocene Epoch following either the Holocene (**b**) or directly following the Pleistocene (**c**). Defining the Anthropocene as an epoch requires a decision as to whether the Holocene is as distinct as the Anthropocene and Pleistocene; retaining it or not distinguishes between **b** and **c**. The question mark represents the current debate over the start of the Anthropocene, assuming it is formally accepted as an epoch (see Box 1, Fig. 2). Colour coding is used according to the Commission for the Geological Map of the World[10], except for the Anthropocene.

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BOX 1

Dividing geological time

Geological time is divided into a hierarchical series of ever-finer units (Fig. 1a). The present, according to *The Geologic Time Scale 2012*[10], is in the Holocene Epoch (Greek for 'entirely recent'; started 11,650 yr BP), within the Quaternary Period (started 2.588 million years ago), within the Cenozoic Era ('recent life'; started 66 million years ago) of the Phanerozoic Eon ('revealed life'; started 541 million years ago). Divisions represent differences in the functioning of Earth as a system and the concomitant changes in the resident life-forms. Larger differences result in classifications at higher unit-levels.

Formally, geological time units are defined by their lower boundary, that is, their beginning. Boundaries are demarcated using a GSSP, or if good candidate GSSPs do not exist, by an agreed date, termed a GSSA[10]. For a GSSP, a 'stratotype section' refers to a portion of material that develops over time (rock, sediment, glacier ice), and 'point' refers to the location of the marker within the stratotype. Each 'golden spike' is a single physical manifestation of a change recorded in a stratigraphic section, often reflecting a global-change phenomenon. GSSP markers are then complemented by a series of correlated changes, also recorded stratigraphically, termed auxiliary stratotypes, indicating widespread changes to the Earth system occurring at that time[10]. An exemplary GSSP is the Cretaceous–Paleogene period-level boundary, and the start of the Cenozoic Era, when non-avian dinosaurs declined to extinction and mammals radically increased in variety and abundance. The GSSP boundary marker is the peak in iridium—a residual of bolide impact with Earth—in rock dated at 66 million years ago, located at El Kef, Tunisia[10].

The widespread appearance of new species can also be used as GSSP boundary markers; for example, the Ordovician–Silurian period-level boundary, 443.8 million years ago, is marked by the appearance of a distinct planktonic graptolite, *Akidograptus ascensus* (a now-extinct hemichordate)[10]. From an Anthropocene perspective this example shows that the GSSP primary marker chosen as a boundary indicator may be of limited importance compared to the other events taking place that collectively show major changes to Earth at that time[67].

Formally, a GSSP must have (1) a principal correlation event (the marker), (2) other secondary markers (auxiliary stratotypes), (3) demonstrated regional and global correlation, (4) complete continuous sedimentation with adequate thickness above and below the marker, (5) an exact location—latitude, longitude and height/depth—because a GSSP can be located at only one place on Earth, (6) be accessible, and (7) have provisions for GSSP conservation and protection[10].

Alternatively, following a survey of the stratigraphic evidence, a GSSA date may be agreed by committee to mark a time unit boundary. GSSAs are typical in the Precambrian (>541 million years ago) because well-defined geological markers and clear events are less obvious further back in time[10]. Regardless of the marker type, formally ratifying a new Anthropocene Epoch into the GTS would first require a positive recommendation from the Anthropocene Working Group of the Subcommission of Quaternary Stratigraphy, followed by a supermajority vote of the International Commission on Stratigraphy, and finally ratification by the International Union of Geological Sciences[10] (see ref. 11 for full details).

advantages and disadvantages of the few global markers that may indicate a date to define the beginning of the Anthropocene. By consolidating research from disparate fields and the emerging Anthropocene-specific literature we aim to constrain the number of possible Anthropocene start dates, highlight areas requiring further research, and assist in moving towards an evidence-based decision on the possible ratification of a new Anthropocene Epoch.

The geological importance of human actions

Human activity profoundly affects the environment, from Earth's major biogeochemical cycles to the evolution of life. For example, the early-twentieth-century invention of the Haber–Bosch process, which allows the conversion of atmospheric nitrogen to ammonia for use as fertilizer, has altered the global nitrogen cycle so fundamentally that the nearest suggested geological comparison refers to events about 2.5 billion years ago[12]. Human actions have released 555 petagrams of carbon (where 1 Pg = 10^{15} g = 1 billion metric tons) to the atmosphere since 1750, increasing atmospheric CO_2 to a level not seen for at least 800,000 years, and possibly several million years[13,14], thereby delaying Earth's next glaciation event[15]. The released carbon has increased ocean water acidity at a rate probably not exceeded in the last 300 million years[16].

Human action also affects non-human life. Global net primary productivity appears to be relatively constant[17]; however, the appropriation of 25–38% of net primary productivity for human use[17,18] reduces the amount available for millions of other species on Earth. This land-use conversion to produce food, fuel, fibre and fodder, combined with targeted hunting and harvesting, has resulted in species extinctions some 100 to 1,000 times higher than background rates[19], and probably constitutes the beginning of the sixth mass extinction in Earth's history[19]. Species removals are non-random, with greater losses of large-bodied species from both the land and the oceans. Organisms have been transported around the world, including crops, domesticated animals and pathogens on land. Similarly, boats have transferred organisms among once-disconnected oceans. Such movement has led to a small number of extraordinarily common species, new hybrid species[20], and a global homogenization of Earth's biota. Ostensibly, this change is unique since Pangaea separated about 200 million years ago[21], but such trans-oceanic exchanges probably have no geological analogue.

Furthermore, human actions may well constitute Earth's most important evolutionary pressure[22,23]. The development of diverse products, including antibiotics[22], pesticides[22,24], and novel genetically engineered organisms[24], alongside the movement of species to new habitats[25], intense harvesting[23] and the selective pressure of higher air temperatures resulting from greenhouse gas emissions, are all likely to alter evolutionary outcomes[22–25]. Considered collectively, there is no geological analogue[22]. Furthermore, given that the lifespan of a species is typically 1–10 million years, the rates of anthropogenic environmental change in the near future may exceed the rates of change encountered by many species in their evolutionary history. Human activity has clearly altered the land surface, oceans and atmosphere, and re-ordered life on Earth.

Historical human geology

Human-related geological time units have a long history[26]. In 1778 Buffon published an early attempt to describe Earth's history, allocating a human epoch to be Earth's seventh and final epoch, paralleling the seven-day creation story[27]. By the nineteenth century, divine intervention was receding from consideration as a geological force. In 1854 the Welsh geologist and professor of theology, Thomas Jenkyn, appears to have first published the idea of an explicitly evidence-based human geological time unit in a series of widely disseminated geology lessons[28–30]. He describes the then present day as "the human epoch" based on the likely future fossil record[28]. In his final lecture he wrote, "All the recent rocks, called in our last lesson Post-Pleistocene, might have been called Anthropozoic, that is, human-life rocks."[29]. Similarly, the Reverend Haughton's 1865 Manual of Geology describes the Anthropozoic as the "epoch in which we live"[31], as did the Italian priest and geologist Antonio Stoppani a decade later[32]. Meanwhile in the USA, the geology professor James Dwight Dana's then-popular 1863 Manual of Geology[33] extensively refers to the "Age of Mind and Era of Man" as the youngest geological time, as did many of his US contemporaries[34].

In 1830 Charles Lyell had proposed that contemporary time be termed the Recent epoch[35] on the basis of three considerations: the end of the last glaciation, the then-believed coincident emergence of humans, and the

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rise of civilizations[26,35]. In the 1860s, the French geologist Paul Gervais made Lyell's term international, coining the term Holocene, derived from the Greek for 'entirely recent'. Thus, most nineteenth-century geological textbooks feature humans as part of the definition of the most recent geological time units. Critically, there was little discussion about any of these terms—Recent, Holocene or Anthropozoic—probably because each represented the same conceptual model and broad agreement that humans were part of the definition of the contemporary geological epoch. However, the wider written records of these often deeply religious men show that a separate human epoch was likely to have been more strongly influenced by theological concerns—in particular, separating *Homo sapiens* from other animals and retaining humans at the apex of life on Earth—than by the appraisal of stratigraphic evidence.

In the twentieth century, geologists in the West increasingly used the term Holocene for the current epoch, and Quaternary for the period. Meanwhile, in 1922 the Russian geologist Aleksei Pavlov described the present day as part of an "Anthropogenic system (period) or Anthropocene"[36]. The Ukrainian geochemist Vladimir Vernadsky then brought to widespread attention the idea that the biosphere, combined with human cognition, had created the Noösphere (from the Greek for mind), with humans becoming a geological force[37]. The term Noösphere was not well used, but non-Western scientists often used anthropogenic geological time units. The Russian term was anglicized as both Anthropogene and Anthropocene[36], sometimes creating confusion. The East–West differences in usage may have been due to differing political ideologies: an orthodox Marxist view of the inevitability of global collective human agency transforming the world politically and economically requires only a modest conceptual leap to collective human agency as a driver of environmental transformation. Again there was little broad interest in the various terms. The Holocene became the official term within the Geologic Time Scale (GTS; Fig. 1)[10,38], with its implication that the current interglacial differs from the previous Pleistocene interglacials owing to the influence of humans. It has therefore been argued that an Anthropocene Epoch is not required, given that some human influence is already contained within the definition of the Holocene Epoch[9]. Alternatively, defining the Anthropocene would deprive the Holocene Epoch of its ostensibly unique feature—humans—suggesting that the Holocene as an epoch may not be required.

The views of nineteenth- and twentieth-century scientists illustrate the influence of the dominant contemporary concerns on geological debates. Today's scientists may also not be immune to such influences. For example, a key concern for scientists and others is the central role of technology in modern society and its environmental impacts. Crutzen and Stoermer[1] originally proposed that the start of the Anthropocene should be coincident with the beginning of the Industrial Revolution and James Watt's 1784 refinement of the steam engine. Others followed, including stratigraphers, suggesting that 1800 should be the beginning of the Anthropocene[39,40], despite a lack of corresponding global geological markers, and the presence of well-known stratigraphic evidence suggestive of different dates, such as the radionuclide fallout from mid-twentieth-century nuclear weapons tests. Care is needed to ensure that the dominant culture of today's scientists does not subconsciously influence the assessment of stratigraphic evidence.

A human golden spike

Defining the beginning of the Anthropocene as a formal geologic unit of time requires the location of a global marker of an event in stratigraphic material, such as rock, sediment, or glacier ice, known as a Global Stratotype Section and Point (GSSP), plus other auxiliary stratigraphic markers indicating changes to the Earth system. Alternatively, after a survey of the stratigraphic evidence, a date can be agreed by committee, known as a Global Standard Stratigraphic Age (GSSA). GSSPs, known as 'golden spikes', are the preferred boundary markers[10] (see Box 1).

Generally, geologists have used temporally distant changes in multiple stratigraphic records to delimit major changes in the Earth system and thereby geological time units, for example, the appearance of new species as fossils within rocks, coupled with other temporally coincident changes. Perhaps the most useful GSSP example when considering a possible Anthropocene GSSP is that marking the beginning of the most recent epoch, the Holocene[38], because some similar choices and difficulties were faced. These include: not relying on solid aggregate mineral deposits ('rock') for the boundary; an event horizon largely lacking fossils (although fossils are used to recognize Holocene deposits); the need for very precise GSSP dating of events in the recent past; and how to formalize a time unit that extends to the present and thereby implicitly includes a view of the future.

Depending on the parameter considered, the current interglacial took decades to millennia to unfold, as global climate, atmospheric chemistry and the distribution of plant and animal species all altered. From these changes a single dated level within a single stratigraphic record was required to be chosen as a GSSP primary marker (Box 1; Fig. 2). Thus, formally, the Holocene is marked by an abrupt shift in deuterium (^{2}H) excess values at a depth of 1,492.25 m in the NorthGRIP Greenland ice core, dated 11,650 ± 99 yr BP (before present, where 'present' is defined to be 1950)[38]. This corresponds to the first signs of predominantly Northern Hemisphere climatic warming at the end of the Younger Dryas/ Greenland Stadial 1 cold period[38] (Fig. 2). Five further auxiliary stratotypes (four lakes and one marine sediment) showing clear correlated changes across the boundary complement the GSSP, consistent with the occurrence of global changes to the Earth system[38]. The requirements for a formal definition of the start of the Anthropocene are similar: a clear, datable marker documenting a global change that is recognizable in the stratigraphic record, coupled with auxiliary stratotypes documenting long-term changes to the Earth system.

Defining the Anthropocene presents a further challenge. Changes to the Earth system are not instantaneous. However, even spatially heterogeneous and diachronous (producing similar stratigraphic material varying in age) changes appear near-instantaneous when viewed millions of years after the event, especially as time-lags often fall within the error range of the dating techniques. In contrast, Anthropocene deposits are commonly dated on decadal or annual scales, so that all changes will appear diachronous, to some extent, from today's perspective (but not from far in the future)[11,41]. Judgement will be required to assess whether the time-lags following events and their significant global impacts are too long to be of use when defining any Anthropocene GSSP.

Several approaches have been put forward to define when the Anthropocene began, including those focusing on the impact of fire[42], pre-industrial farming[43–45], sociometabolism[46], and industrial technologies[1,39,40,41,47], but the relative merits of the evidence for various starting dates have not been systematically assessed against the requirements of a golden spike. Below, we review the major events in human history and pre-history and their impact on stratigraphic records. We focus on continuous stratigraphic material that may yield markers consistent with a GSSP (lake and marine sediments, glacier ice) and on the types of chemical, climatic and biological changes used to denote other epoch boundaries further in the past. We proceed chronologically forward in time, presenting the reason why each event was originally proposed, evaluate the existence of stratigraphic markers, and assess whether the event provides a potential GSSP. The hypotheses and evidence are summarized in Table 1. Following the evidence review we briefly consider the relative merits of the differing events that probably fulfil the GSSP criteria, and assess related GSSA dates.

Pleistocene human impacts

The first major impacts of early humans on their environment was probably the use of fire. Fossil charcoal captures these events from the Early Pleistocene Epoch[42,48]. However, fires are inherently local events, so they do not provide a global GSSP. The next suggested candidate is the Megafauna Extinction between 50,000 and 10,000 years ago, given that other epoch boundaries have been defined on the basis of extinctions or on the resultant newly emerging species[10]. Overall, during the Megafauna Extinction about half of all large-bodied mammals worldwide, equivalent to 4% of all mammal species, were lost[49]. The losses were not evenly distributed: Africa lost 18%, Eurasia lost 36%, North

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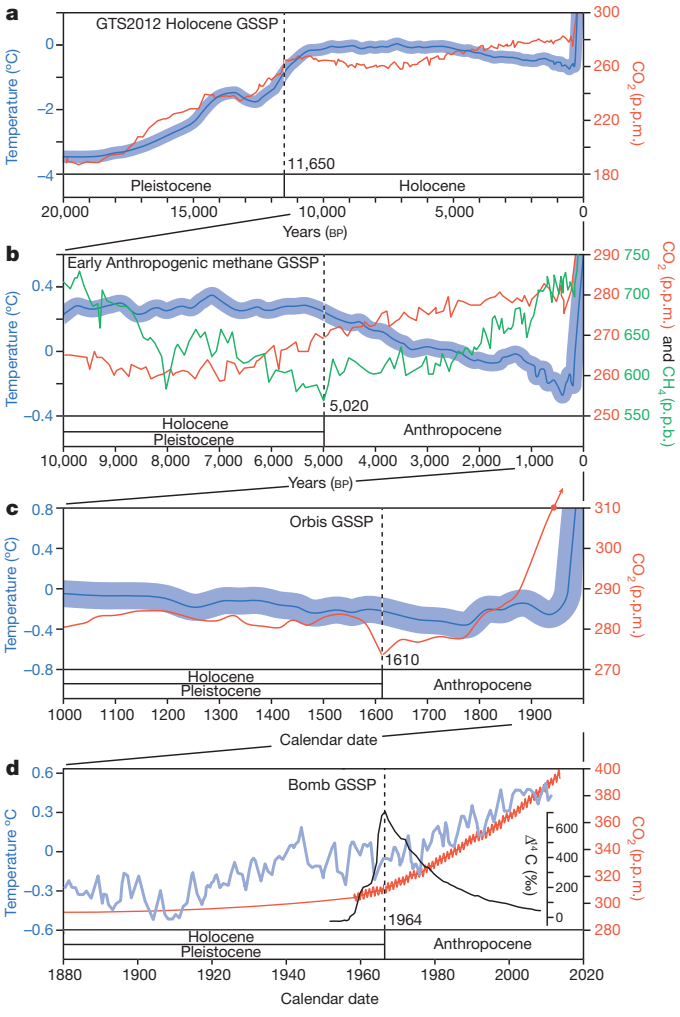

Figure 2 | Defining the beginning of the Anthropocene. **a**, Current GTS2012 GSSP boundary between the Pleistocene and Holocene[38] (dashed line), with global temperature anomalies (relative to the early Holocene average over the period 11,500 BP to 6,500 BP)[112] (blue), and atmospheric carbon dioxide composite[113] on the AICC2012 timescale[114] (red). **b**, Early Anthropogenic Hypothesis GSSP suggested boundary (dashed line), which posits that early extensive farming impacts caused global environmental changes, defined here by the inflection and lowest level of atmospheric methane (in parts per billion, p.p.b.) from the GRIP ice core[59] (green), with global temperature anomalies (relative to the average over the period 1961 to 1990)[115] (blue), and atmospheric carbon dioxide[113] (red). **c**, Orbis GSSP suggested boundary (dashed line), representing the collision of the Old and New World peoples and homogenization of once distinct biotas, and defined by the pronounced dip in atmospheric carbon dioxide (dashed line) from the Law Dome ice core[75,76] (blue), with global temperature data anomalies (relative to the average over the period 1961 to 1990)[115] (red). **d**, Bomb GSSP suggested boundary (dashed line), characterized by the peak in atmospheric radiocarbon from annual tree-rings (black)[103] (the $\Delta^{14}C$ value is the relative difference between the absolute international standard (base year 1950) and sample activity corrected for the time of collection and $\delta^{13}C$), with atmospheric carbon dioxide from Mauna Loa, Hawaii, post-1958[116], and ice core records pre-1958[75,76] (red), and global temperature anomalies (relative to the average over the period 1961 to 1990)[116] (blue).

America lost 72%, South America lost 83%, and Australia lost 88% of their large-bodied mammalian genera[50,51]. So the Megafauna Extinction was actually a series of events on differing continents at differing times and therefore lacks the required precision for an Anthropocene GSSP marker.

Origins and impacts of farming

The development of agriculture causes long-lasting anthropogenic environmental impacts as it replaces natural vegetation, and thereby increases species extinction rates, and alters biogeochemical cycles. Agriculture had multiple independent origins: first occurring about 11,000 years ago in southwest Asia, South America and north China; between 6,000–7,000 years ago in Yangtze China and Central America; and 4,000–5,000 years ago in the savanna regions of Africa, India, southeast Asia, and North America[52]. Thus, the increasing presence of fossil pollen from domesticated plants in sediment is too local and lacking in global synchrony to form a GSSP marker. Critically, for the Holocene GSSP, auxiliary markers within stratigraphic material did not include any human-derived markers[38], illustrating the lack of anthropogenic impacts at that time. Long-lasting cultural evidence related to agriculture is similarly constrained. Although ceramics are datable and preserved in stratigraphic records (for example, the mineral mullite[41]), they appeared in Africa before agriculture, while early southwest Asian farming cultures did not produce ceramics. Similarly, anthropogenically formed soils, derived from intensive farmland management, have also been suggested as a marker of the Anthropocene[53]. Although these soils are widespread, like vegetation clearance, they are highly diachronous over about 2,000 yr, thus excluding their use as a GSSP marker[54].

A series of Neolithic revolutions resulted in the majority of *Homo sapiens* becoming agriculturalists to some extent by around 8,000 yr BP, rising to a maximum of about 99% by about 500 yr BP[46]. The Early Anthropogenic Hypothesis posits that the current interglacial was similar to the previous seven interglacial periods until around 8,000 yr BP[43,55]. By comparison with the closest astronomical analogue of the current interglacial (795,000–780,000 yr BP)[55], atmospheric CO_2 should have continued to decline after 8,000 yr BP, eventually reaching about 240 parts per million (p.p.m.), and the onset of glaciation should have begun[43,55]. However, by 6,000–8,000 yr BP, farmers' conversion of high-carbon storage vegetation (forest, woodland, woody savanna) to crops and grazing lands, plus associated fire impacts, may have increased atmospheric CO_2 levels, and postponed this new glaciation[43] (Fig. 2). Thus, the lowest level of CO_2 within an ice core record could, in principle, provide a golden spike, but the CO_2 record lacks a distinct inflection point at this time (Fig. 2). Furthermore, the evidence that human activity was responsible for the gradual increase in CO_2 after 6,000 yr BP is extensively debated[43,56–58].

Methane provides a clearer inflection point, which may provide a possible GSSP at 5,020 yr BP, the date of the lowest methane value recorded in the GRIP ice core[59] (Fig. 2). Archaeological evidence suggests that the inflection is caused by rice cultivation in Asia and the expansion of populations of domesticated ruminants. Comparisons of changes in atmospheric methane from the current and past interglacials[43], and some methane $\delta^{13}C$ value evidence[60], also suggest a human cause. However, a model study suggests that orbital forcing altering methane emissions from tropical wetlands may be responsible[61]. Auxiliary markers could include stone axes and fossilized domesticated crop pollen and ruminant remains, but these do not provide temporally well-correlated markers that collectively document globally synchronous changes to the Earth system.

Collision of the Old and New Worlds

The arrival of Europeans in the Caribbean in 1492, and subsequent annexing of the Americas, led to the largest human population replacement in the past 13,000 years[62], the first global trade networks linking Europe, China, Africa and the Americas[63,64], and the resultant mixing of previously separate biotas, known as the Colombian Exchange[63,64]. One biological result of the exchange was the globalization of human foodstuffs. The New World crops maize/corn, potatoes and the tropical staple manioc/cassava were subsequently grown across Europe, Asia and Africa. Meanwhile, Old World crops such as sugarcane and wheat were planted in the New World. The cross-continental movement of dozens of other food species (such as the common bean, to the New World), domesticated animals (such as the horse, cow, goat and pig, all to the Americas) and human commensals (the black rat, to the Americas), plus accidental transfers (many species of earth worms, to North America; American mink to Europe) contributed to a swift, ongoing, radical reorganization of life on Earth without geological precedent.

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Table 1 | Potential start dates for a formal Anthropocene Epoch

Event	Date	Geographical extent	Primary stratigraphic marker	Potential GSSP date*	Potential auxiliary stratotypes
Megafauna extinction	50,000–10,000 yr BP	Near-global	Fossil megafauna	None, diachronous over ~40,000 yr	Charcoal in lacustrine deposits
Origin of farming	~11,000 yr BP	Southwest Asia, becoming global	Fossil pollen or phytoliths	None, diachronous over ~5,000 yr	Fossil crop pollen, phytoliths, charcoal
Extensive farming	~8,000 yr BP to present	Eurasian event, global impact	CO_2 inflection in glacier ice	None, inflection too diffuse	Fossil crop pollen, phytoliths, charcoal, ceramic minerals
Rice production	6,500 yr BP to present	Southeast Asian event, global impact	CH_4 inflection in glacier ice	5,020 yr BP CH_4 minima	Stone axes, fossil domesticated ruminant remains
Anthropogenic soils	~3,000–500 yr BP	Local event, local impact, but widespread	Dark high organic matter soil	None, diachronous, not well preserved	Fossil crop pollen
New–Old World collision	1492–1800	Eurasian–Americas event, global impact	Low point of CO_2 in glacier ice	1610 CO_2 minima	Fossil pollen, phytoliths, charcoal, CH_4, speleothem $\delta^{18}O$, tephra†
Industrial Revolution	1760 to present	Northwest Europe event, local impact, becoming global	Fly ash from coal burning	~1900 (ref. 94); diachronous over ~200 yr	^{14}N:^{15}N ratio and diatom composition in lake sediments
Nuclear weapon detonation	1945 to present	Local events, global impact	Radionuclides (^{14}C) in tree-rings	1964 ^{14}C peak§	^{240}Pu: ^{239}Pu ratio, compounds from cement, plastic, lead and other metals
Persistent industrial chemicals	~1950 to present	Local events, global impact	For example, SF_6 peak in glacier ice	Peaks often very recent so difficult to accurately date§	Compounds from cement, plastic, lead and other metals

For compliance with a Global Stratotype Section and Point (GSSP) definition, a clearly dated global marker is required, backed by correlated auxiliary markers that collectively indicate global and other widespread and long-term changes to the Earth system. BP, before present, where present is defined as calendar date 1950.
* Requires a specific date for a GSSP primary marker. †From Huaynaputina eruption in 1600 (refs 78, 79).
§ Peak, rather than earliest date of detection selected, because earliest dates reflect available detection technology, are more likely influenced by natural background geochemical levels[101], and will be more affected by the future decay of the signal, than peak values.

In terms of stratigraphy, the appearance of New World plant species in Old World sediments—and vice versa—may provide a common marker of the Anthropocene across many deposits because pollen is often well preserved in marine and lake sediments. For example, pollen of New World native *Zea mays* (maize/corn), which preserves very well[41], first appears in a European marine sediment core in 1600[65]. The European Pollen Database lists a further 70 lake and marine sediment cores containing *Zea mays* after this date. Phytoliths can similarly record such range expansions[66]. Specifically, the transcontinental range extension of at least one Old World species into the New World (banana, as phytoliths in Central and tropical South America sediments) and a second species from the New World expanding into the Old World (maize/corn, as pollen preserved in sediments in Eurasia and Africa) together constitute a unique signature in the stratigraphic record. This transcontinental range expansion—stratigraphically marking before and after an event—is comparable to the use of the appearance of new species as boundary markers in other epoch transitions[49,67].

Besides permanently and dramatically altering the diet of almost all of humanity, the arrival of Europeans in the Americas also led to a large decline in human numbers. Regional population estimates sum to a total of 54 million people in the Americas in 1492[68], with recent population modelling estimates of 61 million people[58]. Numbers rapidly declined to a minimum of about 6 million people by 1650 via exposure to diseases carried by Europeans, plus war, enslavement and famine[58,63,68,69]. The accompanying near-cessation of farming and reduction in fire use resulted in the regeneration of over 50 million hectares of forest, woody savanna and grassland with a carbon uptake by vegetation and soils estimated at 5–40 Pg within around 100 years[58,70–72]. The approximate magnitude and timing of carbon sequestration suggest that this event significantly contributed to the observed decline in atmospheric CO_2 of 7–10 p.p.m. (1 p.p.m. CO_2 = 2.1 Pg of carbon) between 1570 and 1620 documented in two high-resolution Antarctic ice core records[73–76] (Fig. 2 and Box 2). This dip in atmospheric CO_2 is the most prominent feature, in terms of both rate of change and magnitude, in pre-industrial atmospheric CO_2 records over the past 2,000 years[75] (Fig. 2).

On the basis of the movement of species, atmospheric CO_2 decline and the resulting climate-related changes within various stratigraphic records, we propose that the 7–10 p.p.m. dip in atmospheric CO_2 to a low point of 271.8 p.p.m. at 285.2 m depth of the Law Dome ice core[75], dated 1610 (±15 yr; refs 75, 76), is an appropriate GSSP marker (Fig. 2). Auxiliary stratotypes could include: the first occurrence of a cross-ocean range extension in the fossil record (*Zea mays*, in 1600[65]) plus a range of deposits showing distinct changes at that time, including tephra[77,78] and other signatures from the 1600 Huaynaputina eruption detected at both poles and in the tropics[77–79]; charcoal reductions in deposits in the Americas[71] and globally[80]; decreases in atmospheric methane, enrichment of methane $\delta^{13}C$, and decreases in carbon monoxide in Antarctic ice cores[60,81–84]; pollen in lacustrine sediments showing vegetation regeneration[85]; proxies indicating anomalous Arctic sea-ice extent[86]; changing $\delta^{18}O$ derived from speleothems from caves in China and Peru[14] and other studies noting changes coincident with 1600 and the coolest part of the Little Ice Age (1594–1677; ref. 87), a relatively synchronous global event noted in geologic deposits worldwide[87].

The impacts of the meeting of Old and New World human populations—including the geologically unprecedented homogenization of Earth's biota[63,64]—may serve to mark the beginning of the Anthropocene. Although it represents a major event in world history[62–64,88], the collision of the Old and New Worlds has not been proposed previously, to our knowledge, as a possible GSSP. We suggest naming the dip in atmospheric CO_2 the 'Orbis spike' and the suite of changes marking 1610 as the beginning of the Anthropocene the 'Orbis hypothesis', from the Latin for world, because post-1492 humans on the two hemispheres were connected, trade became global, and some prominent social scientists refer to this time as the beginning of the modern 'world-system'[89].

Industrialization

The beginning of the Industrial Revolution has often been suggested as the beginning of the Anthropocene, because accelerating fossil fuel use and coupled rapid societal changes herald something important and unique in human history[1–4,39]. Yet humans have long been engaging in industrial-type production, such as metal utilization from around 8,000 yr BP onwards, with attendant pollution[90]. Elevated mercury records are documented at around 3,400 yr BP in the Peruvian Andes[91], while the impacts of Roman Empire copper smelting are detectable in a Greenland ice core at around 2,000 yr BP[92]. This metal pollution, like other examples predating the Industrial Revolution, is too local and diachronous to provide a golden spike.

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BOX 2

Origins of the 1610 decrease in atmospheric CO_2

Is the CO_2 decline real?

Two independent high-resolution Antarctic ice core records from the Law Dome and the Western Antarctic Ice Sheet show a reduction in atmospheric CO_2 of 7–10 p.p.m. between 1570 and 1620[73–75] (Fig. 2). A smaller CO_2 decrease is also observed in less highly resolved Antarctic cores[117,118]. The decline exceeds the measurement error of the cores, 1–2 p.p.m., and experiments suggest that it does not result from *in situ* changes within the ice core[119].

Did human activity cause the decline?

The arrival of Europeans in the Americas led to a catastrophic decline in human numbers, with about 50 million deaths between 1492 and 1650, according to several independent sources[58,63,68,69]. Contemporary field observations of soil[120] and vegetation[121] carbon dynamics following agriculture abandonment suggest that about 65 million hectares (that is, 50 million people × 1.3 hectares per person) would sequester 7–14 Pg of carbon over 100 years (that is, 100–200 Mg of carbon per hectare total uptake, above- and below-ground). Reduction in fire use for land management would additionally increase carbon uptake outside farmed areas. Studies using a variety of methods report broadly consistent estimates[58,70–72] of carbon uptake by vegetation of 5–40 Pg (2.1 Pg of carbon = 1 p.p.m. atmospheric CO_2 over shorter timescales, lessening over time[127]). Given that maximum human mortality rates were not reached for some decades after 1492[62,63], and maximum carbon uptake would take place 20–50 yr after farming abandonment, peak carbon sequestration would occur approximately between 1550 and 1650.

Some model studies spanning thousands of years find a net land surface carbon uptake spanning 1500–1650 across the Americas[58], while others do not[122]. However, in general, evidence from such studies weakly constrain the problem because Holocene carbon cycle modelling is designed to investigate changes associated with long-acting slow processes (carbon uptake by peat or coral reefs) and feedback mechanisms (oceanic outgassing, oceanic uptake and CO_2 fertilization of vegetation), and probably poorly represent the short period of the CO_2 dip (for example, ref. 57). For example, a study calculating a net zero impact of the cessation of farming in the Americas[122] included a large soil carbon flux to the atmosphere, which contradicts field evidence[120,123], and had the effect of offsetting the uptake from growing trees[122]. Carbon cycle models with robust representations of land-use change and subsequent vegetation regeneration following the Americas population catastrophe will be required to improve estimates of carbon uptake compared with carbon accounting studies.

The approximate magnitude and timing of carbon sequestration make the population decline in the Americas the most likely cause of the observed decline in atmospheric CO_2. Atmospheric[74,124,125] and tropical marine $\delta^{13}C$ analyses[126] also support uptake of CO_2 by vegetation rather than oceanic uptake. The 1600 Huaynaputina eruption in Peru[78,79] probably exacerbated the CO_2 minima, and a lagged oceanic outgassing in response to the land carbon uptake probably contributed to the fast rebound of atmospheric CO_2 after 1610[127]. In addition, multi-proxy reconstructions of temperature indicate that, after accounting for both solar and volcanic radiative forcing, additional terrestrial carbon uptake is required to explain temperature declines over the 1550–1650 period[107]. This is consistent with uptake by vegetation following the population crash in the Americas[107].

Definitions of the Industrial Revolution give an onset date anywhere between 1760 and 1880, beginning as an event local to northwest Europe[88]. Given the initial slow spread of coal use, ice core records show little impact on global atmospheric CO_2 concentration until the nineteenth century, and then they show a relatively smooth increase rather than an abrupt change, precluding this as a GSSP marker (Fig. 2). Similarly, other associated changes, including methane and nitrate[15], products of fossil fuel burning (including spherical carbonaceous particles[93] and magnetic fly ash[94]) plus resultant changes in lake sediments[95,96] alter slowly as the use of fossil fuels increased over many decades. Lead, which was once routinely added to vehicle fuels, has been proposed as a possible marker, because leaded fuel was almost globally used and is now banned[97]. However, peak lead isotope ratio values from this source in sediments and other deposits vary from 1940 to after 1980, limiting the utility of this marker. The Industrial Revolution thus provides a number of markers spreading from northwest Europe to North America and expanding worldwide since about 1800, although none provides a clear global GSSP primary marker.

The Great Acceleration

Since the 1950s the influence of human activity on the Earth system has increased markedly. This 'Great Acceleration' is marked by a major expansion in human population, large changes in natural processes[3,12,98], and the development of novel materials from minerals to plastics to persistent organic pollutants and inorganic compounds[41,47,97]. Among these many changes the global fallout from nuclear bomb tests has been proposed as a global event horizon marker[41,47]. The first detonation was in 1945, with a peak in atmospheric testing from the late 1950s to early 1960s, followed by a rapid decline following the Partial Test Ban Treaty in 1963 and later agreements, such that only low test levels continue to the present day (Fig. 2). A resulting distinct peak in radioactivity is recorded in high-resolution ice cores, lake and salt marsh sediments, corals, speleothems and tree-rings from the early 1950s onwards, declining in the late 1960s[15,99]. The clearest signal is from atmospheric ^{14}C, seen in direct air measurements and captured by tree-rings and glacier ice, which reaches a maximum in the mid- to high-latitude Northern Hemisphere at 1963–64 and a year later in the tropics[100]. Although ^{14}C has a relatively short half-life (5,730 years), elevated levels will persist long enough to be useable for several generations of geologists in the future.

While recognizing that many apparently novel industrially produced chemicals are occasionally produced in small quantities naturally[101], chemical signatures from long-lived well-mixed gases in glacier ice or sediments may also meet GSSP criteria. Potential long-lived gases are the halogenated gases, such as SF_6, C_2F_6, CF_4 (with half-lives of 3,000 yr, 10,000 yr and 50,000 yr, respectively). Most were first manufactured industrially in the 1950s, and many are measurable in firn air[102], and with large enough samples could be measured in ice cores[15]. But although they are measurable, distinct peaks are very recent and sometimes absent because major declines in industrial production are occurring after the negotiation and ratification of the 1989 Montreal and 2005 Kyoto protocols.

Of the various possible mid- to late-twentieth-century markers of the Great Acceleration, the global ^{14}C peak provides an unambiguously global change in a number of stratigraphic deposits. We suggest that an unequivocally annual record is the optimal choice to reflect the ^{14}C peak, thereby giving a dating accuracy of one year. We propose that the GSSP marker should be the ^{14}C peak, at 1964, within dated annual rings of a pine tree (*Pinus sylvestris*) from King Castle, Niepołomice, 25 km east of Kraków, Poland[103] (Fig. 2). Secondary correlated markers would include plutonium isotope ratios ($^{240}Pu/^{239}Pu$) in sediments indicating bomb testing[104], (fast-decaying) 137-Caesium[97], alongside the presence of peaks in very long-lived iodine isotopes (^{129}I, with half-life 15.7 million years) found in marine sediments[105] and soils[106].

While radionuclide fallout did not have major biological or other widespread physical repercussions, other auxiliary stratotypes may include the numerous other human-driven changes resulting in mid- to late-twentieth-century changes in geological deposits, including fossil pollen of novel genetically modified crops; declines in $\delta^{15}N$ in Northern Hemisphere

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lakes[96] and ice cores[15]; the emergence of SF_6 and CF_4 from background levels[15]; lead isotopes in ice cores[15]; microplastics in marine sediments[97]; diatom assemblages in lakes in response to eutrophication[41]; and benthic foraminifera changes in marine sediments[41].

Dating the Anthropocene

We conclude that most proposed Anthropocene start dates, including the earliest detectable human impacts[42], earliest widespread impacts[45], and historic events such as the Industrial Revolution[1–3,39,40], can probably be rejected because they are not derived from a globally synchronous marker. Our review highlights that only those environmental changes associated with well-mixed atmospheric gases provide clearly global synchronous geological markers on an annual or decadal scale, as is required to define a GSSP for the Anthropocene. The earliest potential GSSP primary marker we identify is the inflection of atmospheric methane at 5,020 yr BP (Fig. 2; Table 1), but correlated auxiliary stratotypes are lacking. Thus, the CH_4 inflection is unlikely to be a strong candidate for the beginning of the Anthropocene. We find that only two other events—the Orbis spike dip in CO_2 with a minimum at 1610, and the bomb spike 1964 peak in ^{14}C—appear to fulfil the criteria for a GSSP to define the inception of the Anthropocene (Fig. 2; Table 1). While both GSSP dates have a number of correlated auxiliary stratotypes there are advantages and disadvantages associated with each.

The main advantage to the 1610 Orbis spike is the geological and historical importance of the event. In common with other epoch boundaries[10] this boundary would document changes in climate[87,107], chemistry[75] and palaeontological[65,85] signals. Critically, the transoceanic movement of species is an unambiguously permanent change to the Earth system[40], and such a boundary would mark Earth's last globally synchronous cool period[87] before the long-term global warmth of the Anthropocene Epoch. Historically, the Industrial Revolution has often been considered as the most important event in relation to the inception of the Anthropocene[1,2,39,40], but we have not identified a clear global Industrial Revolution GSSP. However, in the view of many historians, industrialization and extensive fossil fuel use were only made possible by the annexing of the Americas[88]. Before the Industrial Revolution both northwest Europe and southern China were similar in terms of life expectancy and material consumption patterns, including modest coal use, and both regions faced productive boundaries based on the available land area[88]. Thus, the agricultural commodities from the vast new lands of the Americas allowed Europe to transcend its ecological limits and sustain economic growth. In turn, this freed labour, allowing Europe to industrialize. That is, the Americas made industrialization possible owing to the unprecedented inflow of new cheap resources (and profitable new markets for manufactured goods). This 'Great Divergence' of Europe from the rest of the world required access to and exploitation of new lands plus a rich source of easily exploitable energy: coal[88]. Thus, dating the Anthropocene to start about 150 years before the beginning of the Industrial Revolution is consistent with a contemporary understanding of the likely material causes of the Industrial Revolution. The main disadvantage to the Orbis hypothesis is that a number of deposits may not show large changes around 1600, particularly in terms of biological material from the transport of species to new continents or oceans, because there are time-lags before species newly appear in geological deposits.

The key advantage of selecting 1964 as the base of a new Anthropocene Epoch is the sheer variety of human impacts recorded during the Great Acceleration: almost all stratigraphic records today, and over recent decades, have some marker of human activity. The latter part of the twentieth century is unambiguously a time of major anthropogenic global environmental impacts[108]. One disadvantage is that although nuclear explosions have the capacity to fundamentally transform many aspects of Earth's functioning, so far they have not done so, making the radionuclide spike a good GSSP marker but not an Earth-changing event. A further possible limitation in selecting such a recent date is that some deposits, notably some marine sediments, do not accumulate and stabilize over time spans as short as the past 50 years, making clear datable changes and correlation among some stratotypes sometimes difficult to discern[40].

Choosing between the 1610 Orbis and 1964 bomb spikes is challenging. As an alternative, a GSSA date, based on stratigraphic evidence, could be agreed upon by committee as the inception of the Anthropocene. However, any chosen date would be potentially open to challenge as arbitrary. For example, the Industrial Revolution is certainly a pivotal moment in human history, yet it is unclear how one could choose, based on the available geological evidence, an early Industrial Revolution GSSA date, say 1800, over a later date, perhaps 1850 or 1900. Similarly, the Great Acceleration is diachronous[108], and GSSA suggested dates could be 1945, 1950 or 1954 (ref. 109). Given such difficulties, given that GSSP markers are preferred[10], and given that candidate GSSP markers exist, a GSSA date seems unnecessary. Of the GSSP possibilities we tend to prefer 1610, because the transoceanic movement of species is a clear and permanent geological change to the Earth system. This date also fits more closely with Crutzen and Stoermer's original proposal[1] of an important historical juncture—the Industrial Revolution—as the beginning of the Anthropocene, which has been enduringly popular and useful, suggesting 1610 may be similarly so.

We hope that identifying a limited number of possible events and GSSP markers may assist in focusing research efforts to select a robust GSSP alongside a series of auxiliary stratotypes. Such research might include compiling data sets of the first appearance of non-native species in lake and marine sediments to better document the transoceanic spread of species and improve the evidence on which the 1610 proposal is based. The reliable detection of ^{129}I in high-resolution glacier ice and expanding the number of locations at which novel minerals, compounds and other recent human signals are investigated[41,47] would advance the 1964 GSSP proposal.

Ratification of an Anthropocene Epoch would require a further decision to be made, that is, whether to retain the Holocene Epoch (Fig. 1). All Anthropocene GSSP choices would leave a complete Holocene Epoch at least three orders of magnitude shorter than any other epoch[10] and similar to previous Pleistocene interglacials[55], which are not epoch-level events. Furthermore, the existence of a Holocene Epoch is due, in part, to the view—originating from nineteenth-century geologists—that the presence or influence of humans distinguished the Holocene from the Pleistocene[9,26,27,35,38]. An Anthropocene Epoch, combined with today's evidence that *Homo sapiens* is a Pleistocene species, removes key justifications for retaining the Holocene as an epoch-level designation. We therefore suggest that if the Anthropocene is accepted as an epoch it should directly follow the Pleistocene (Fig. 1c), as suggested independently elsewhere[110]. If the Holocene ceases to be an epoch but refers instead to the final stage of the Pleistocene Epoch, we suggest that the term Holocenian Stage is used, to maintain consistency with current terminology. While an alternative informal geological term, the Flandrian stage, denotes the current interglacial as part of the Pleistocene, its use has strongly declined over recent decades[10], and would not be as recognizable as the Holocenian Stage. Re-classifying any pre-Anthropocene Epoch interglacial time unit as the Holocenian Stage will create the usual tension[10] between resistance to altering past GTS agreements and the maintenance of GTS internal consistency.

The wider importance

The choice of either 1610 or 1964 as the beginning of the Anthropocene would probably affect the perception of human actions on the environment. The Orbis spike implies that colonialism, global trade and coal brought about the Anthropocene. Broadly, this highlights social concerns, particularly the unequal power relationships between different groups of people, economic growth, the impacts of globalized trade, and our current reliance on fossil fuels. The onward effects of the arrival of Europeans in the Americas also highlights a long-term and large-scale example of human actions unleashing processes that are difficult to predict or manage. Choosing the bomb spike tells a story of an elite-driven technological development that threatens planet-wide destruction. The

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long-term advancement of technology deployed to kill people, from spears to nuclear weapons, highlights the more general problem of 'progress traps'[111]. Conversely, the 1963 Partial Test Ban Treaty and later agreements highlight the ability of people to collectively successfully manage a major global threat to humans and the environment. The event or date chosen as the inception of the Anthropocene will affect the stories people construct about the ongoing development of human societies.

Past scientific discoveries have tended to shift perceptions away from a view of humanity as occupying the centre of the Universe. In 1543 Copernicus's observation of the Earth revolving around the Sun demonstrated that this is not the case. The implications of Darwin's 1859 discoveries then established that *Homo sapiens* is simply part of the tree of life with no special origin. Adopting the Anthropocene may reverse this trend by asserting that humans are not passive observers of Earth's functioning. To a large extent the future of the only place where life is known to exist is being determined by the actions of humans. Yet, the power that humans wield is unlike any other force of nature, because it is reflexive and therefore can be used, withdrawn or modified. More widespread recognition that human actions are driving far-reaching changes to the life-supporting infrastructure of Earth may well have increasing philosophical, social, economic and political implications over the coming decades.

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to S.L.L. (s.l.lewis@ucl.ac.uk).

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NEW ZEALAND

Report on the in-depth review of the national communication of New Zealand

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GE.96-

Under Articles 4 and 12 of the Convention. Parties are requested to prepare national communications on their implementation of the Convention. Guidelines for the preparation of national communications and the

process for the review were agreed on by the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change, by its decisions 9/2 and 10/1, and 3/CP.1 (see FCCC/CP/1995/7/Add.1) In accordance with these decisions, a compilation and synthesis of the 15 national communications from Annex I Parties was prepared (A/AC.237/81).

When reviewing the implementation of the Convention of the Parties, the subsidiary bodies and the Conference of the Parties will have this report available to them in English as well as the summary of the report in the six official languages of the United Nations. (These bodies will also have before them the executive summary of the first national communication of New Zealand and country-specific information drawn from a compilation and synthesis report covering all countries that have submitted national communications.)

Summary[(1)]

1. The in-depth review was carried out during the period June to November 1995 and included a visit by the team from 3 to 7 July 1995. The team included experts from

Sri Lanka, Slovakia and the United Kingdom of Great Britain and Northern Ireland. It concluded that the New Zealand communication generally followed the format and requirements of the guidelines, but additional information obtained during the review helped improve the transparency.

2. New Zealand has adopted a net approach to carbon dioxide (CO_2), adding emissions by sources and uptakes by sinks (planted forests). Its target is to stabilize net emissions at 1990 levels by 2000. This is to be achieved with a 20 per cent contribution from reductions of CO_2 emissions relative to a rising baseline, and an 80 per cent contribution from sink enhancement. The team noted that the proportion of the various gases in emissions and the situation with regard to carbon sinks in forests are very different from those of other Annex I Parties, owing to natural circumstances and economic structure. Based on the most recent global warming potentials (GWPs), methane (CH_4) emissions, basically from agriculture, represent 57 per cent of the gross greenhouse gas (GHG) emissions in New Zealand's inventory for 1990, CO_2 33 per cent and nitrous oxide (N_2O) less than 10 per cent.

3. CO_2 emissions per capita (8 tons) are relatively low compared with the average in countries of the Organisation for Economic Co-operation and Development (OECD) (approximately 12 tons). Energy prices are generally low through a combination of low-cost indigenous energy sources and nil or low taxation levels on liquid, including transport, fuels. Although total taxation on gasoline makes up almost 50 per cent of the final price, gasoline prices, in particular, are low compared with most OECD countries. This may be relevant to the rising level of transport sector emissions, which constitute the largest component of the CO_2 inventory.

4. New Zealand, with 3.5 million inhabitants, has a small economy very dependent on import and export. It has a diverse energy base and relatively high utilization of renewable energy sources, and is self-sufficient in energy except for liquid fuels. The manufacturing industry benefits from that energy base, and is also based to a large extent on the products of agriculture, fisheries, and forestry. New Zealand has been through a major restructuring of the economy which has had and is expected to continue to have consequences for emissions. Important aspects are abolition of subsidies in all sectors including agriculture, deregulation, privatization, enhanced competition and streamlining of the public sector. Deregulation and restructuring in the electricity sector are expected to be particularly important, although the

implications for emissions are not yet clear. As an example, if mitigation was not a condition of the resource consent, adding a 400 MW gas-fired power station could increase national emissions by 5 per cent. The growth rate of gross domestic product (GDP) is now at a record high (6 per cent in 1994) by historical standards, following a period of low growth.

5. There is considerable sequestration of carbon in planted forest, which now covers 5 per cent of the country's area (1.4 million ha). New Zealand sees enhancement of carbon sinks in forests as an important, but nevertheless transitional, way of mitigating climate change, as sequestration of carbon at the present level could take place over a maximum of 50-100 years. These forests are monocultures and particularly well monitored, although estimates of carbon content and annual increment have been significantly revised since the communication was submitted. The high level of present sequestration is due to the fact that the age-class of trees is young and to increased planting on land previously used for sheep and beef farming, stimulated by the economic reforms.

6. The team noted in particular the uncertainties associated with indigenous forest carbon storage levels (in both directions) together with the main influences in any changes in carbon stored. These are pest-induced (notably possums, goats and deer) deforestation (an emission) and regeneration (an absorption). Indigenous forests are largely protected, and at present cover 23 per cent (6.2 million ha) of the country's area and have 3-4 times higher carbon stock per hectare and possibly 10-15 times as high total storage as the planted forest. The Government is seeking to combat the severe threat to parts of the indigenous forest estate, for a range of policy reasons. Any loss of forest or regeneration will have implications for total future carbon balances. No projections are given for natural forests because of the lack of data in this area.

7. CO_2 emissions are projected to grow by 14-17 per cent from 1990 to 2000 with 2-3 per cent growth in GDP if the CO_2 programmes are on track, while sequestration in planted forest is expected to return to approximately 1990 levels by 2000. The revision of the planted forest inventory for 1990 reflects a higher sequestration in the base year, and revised projections based on an improved model with the same assumptions show an absorption of 18.6 Mt CO_2 in 2000 compared to 17.7 Mt in 1990, or a considerably slower acceleration of sequestration than was originally reported (25.5 as against 16.7 Mt CO_2). New Zealand now expects that carbon sequestration will equal CO_2 emissions perhaps by 2010, and that a return to 1990 levels could be achieved sometime after 2000. If the CO_2 programme is not seen as being on track by 1997, the Government has announced its intention to introduce a low level carbon charge by the end of that year.

8. Methane (CH_4) emissions are expected to remain the dominant GHG in New Zealand. They follow development in the agricultural sector and have been slightly declining through the 1990s. Emissions from ruminants could increase from around 1998, but current modelling suggests that CH_4 emissions will be below 1990 levels in 2000. Emissions of N_2O and perfluorocarbons (PFCs) are not expected to increase.

9. Since the communication was submitted, voluntary agreements have been signed between the Government and major companies in the energy and industry sectors. An energy saver fund of $NZ 18 million over five years has been set up for residential sector energy efficiency projects, and New Zealand has acquired more experience with its energy efficiency programmes, where the central coordinating body was set up in 1992. The Government has also used the Resource Management Act to intervene in a major project in the electricity sector. In August 1995, the Government set up a new working group on CO_2 policy to analyse the appropriateness of such a case-by-case approach, the impacts of the high economic growth, development of carbon sinks and reservoirs and the efficiency of a carbon charge in comparison with other economic instruments, such as tradable permits, as the next part of the policy response.

10. New Zealand is contributing more than twice its assessed share to the replenishment of the Global Environment Facility (GEF) for 1994-1996. It did not contribute to the pilot phase. The contribution is in addition to its official development assistance (ODA), which in 1993 was 0.25 per cent of GDP according to the OECD Development Assistance Committee statistics. Activities relevant to the UNFCCC are concentrated in the Asia and South Pacific region. The team also noted that substantial technology transfer occurs through overseas activities of New Zealand private companies.

11. New Zealand recognizes that, given its location, it has special responsibilities for monitoring climate change. The scientific community has made a relatively comprehensive assessment of the impacts of climate change on New Zealand and this work continues. Some of New Zealand ecosystems and economic sectors are vulnerable to climate change. Under the Resource Management Act, guidance is given to local communities on adaptation to sealevel rise. A need for a more comprehensive strategy on adaptation is recognized. New Zealand has established regular consultations with non-governmental organizations, some of which participate in the public sector/private sector working group on carbon dioxide policy.

I. INTRODUCTION AND NATIONAL CIRCUMSTANCES

12. New Zealand ratified the Convention on 16 September 1993. The national communication was received by the UNFCCC secretariat on 21 September 1994. The

in-depth review of the national communication was carried out during the period June to November 1995, including a country visit from 3 to 7 July 1995. The team comprised

Mr. Janaka Ratnasiri (Sri Lanka), Mr. Ivan Mojik (Slovakia), Mr. John Moss (United Kingdom of Great Britain and Northern Ireland) and Mr. Peer Stiansen (UNFCCC secretariat, Coordinator).

13. New Zealand has a small, open economy with its industry based on natural resources, agriculture and forestry. It is heavily dependent on trade with distant markets. Population in 1990 was 3.5 million, population density is relatively low and growth is approximately 0.7 per cent annually, which is near the OECD average. New Zealand is self-sufficient in energy except for liquid fuels, and has considerable indigenous resources of natural gas, coal and renewables, most notably hydropower. It has a low rate of CO_2 emissions per capita (8 tons) compared to the OECD average (12 tons), largely thanks to the fact that electric power is approximately 70-75 per cent hydro in origin and 7 per cent geothermal. Contrary to the average trend in OECD countries, energy intensity (energy supply/GDP) in New Zealand grew over the two decades up to 1993 but has fallen in the last two years, mainly because of the expansion of energy-intensive industry. Still, energy use per capita was below the OECD average in 1990. The availability of low-cost indigenous energy sources, particularly hydro, and nil or low rates of taxation, even on liquid and transport fuels, mean energy prices are low compared with the OECD average. It was noted however that total taxation on gasoline makes up almost 50 per cent of the final price, and that although direct taxation on diesel is low, all diesel vehicles are subject to road user charges, which are related directly to weight and distance travelled. Further expansion of electricity supply is likely to be based upon fossil fuels, although a limited contribution from renewables, principally hydro and geothermal and possibly wind, landfill methane and biomass, is expected. There are already small power stations using landfill methane as fuel.

14. New Zealand has a substantial amount of stored carbon in the forests compared to its gross emissions. Most of this is in the indigenous forest, which covers 23 per cent of the land with high amounts of carbon per hectare. The current net sink in planted forests, which covers only 5 per cent of the area, is also considerable. Planted forests are a crop, and the rotation period is relatively low (25-30 years).

15. In its response to climate change, New Zealand takes all greenhouse gases and sectors into account, and it is an advocate for considering emissions and enhancement of sinks (of CO_2) together, what is referred to as the net approach. Pursuant to this, and recognizing the differences in growth rates of gross emissions and sequestration in managed forests, New Zealand has set a target of reducing net CO_2 emissions to 1990 levels in 2000. This is further refined to mean that a 20 per cent reduction in the growth in gross emissions should be achieved compared to a "business as usual" scenario, with 80 per cent of the growth in gross emissions being covered by the enhancement of sinks. Inside this approach, the "gross" emissions could be allowed to show substantial growth combined with an increasing sequestration of carbon in the forests. The target is further specified for various levels of economic growth. There will be a review in 1997 to decide whether

New Zealand is on track to meet this goal.

16. The rights of the Maori people in respect to land and natural resources are described in the Treaty of Waitangi which was signed in 1840. Maori consultation is required in connection with many activities related to climate change, including utilization of energy and forest resources and efforts to assess and mitigate emissions and their impacts. Accordingly, the Government has taken care to develop all aspects of the climate change programme in accordance with the treaty.

17. New Zealand has been through a major restructuring of the economy and the system of government, during the past decade. Subsidies have largely been eliminated in all sectors. This is the case even in the agricultural sector, which is the most important source of emissions. Developments in agriculture also influence sequestration in forests. The Government's role is limited to policy formation and the creation of a level playing-field for the market to operate. The scale of government has been dramatically reduced, following elimination of interventionist policies. Most remaining executive and operational functions are now performed by independent agencies and non-government bodies. It has pursued a strategy of deregulation and to some extent privatization. Following this process, New Zealand has experienced high economic growth (6 per cent in 1994) after years in recession, but GDP per capita is still lower than the OECD average.

18. New Zealand has simplified, modernized and consolidated the environmental legislation in the Resource Management Act of 1991, which replaced numerous pieces of earlier legislation, integrating land, air and water issues for the first time. The Act is the major legislative instrument governing the integration of climate change concerns in activities in the energy, industry, agriculture and forestry sectors. Similar modernization has also taken place in other sectors, notably the energy sector, leading to changes in domestic energy (electricity and gas) markets.

19. New Zealand's response to climate change is organized through an interdepartmental effort coordinated by the Ministry of the Environment, which started its Climate Change Programme in 1988 with an assessment of impacts. There is widespread division of responsibilities for the development of policies and measures and for technical information. For example, basic inventory data are supplied from sector authorities. The Officials Committee on Energy Policy, which brings together representatives of the most relevant ministries, also plays an important role in decisions affecting GHG emissions.

20. Following the government reforms, the Ministry of the Environment's role is to provide environmental policy advice, with limited operational responsibilities. The Department of Conservation is responsible for management of the "protected estate", which includes the natural forest, while the Ministry of Commerce provides energy policy advice and has led the way in developing voluntary agreements with industry. There is also a parliamentary Commissioner for the Environment who acts as an independent "ombudsman".

II. INVENTORIES OF ANTHROPOGENIC EMISSIONS AND REMOVALS

21. The communication contains inventories for CO_2, CH_4, N_2O, PFCs, hydrofluorocarbons (HFCs) and the precursor nitrogen oxides (NO_x) for the calendar year 1990. Work is now under way to produce inventories also for the other precursors carbon monoxide (CO) and non-methane volatile organic compound (NMVOC). These have traditionally not been monitored since acidification and local air pollution problems are considered to be minor in New Zealand, given its location and natural conditions. Estimates have been carried out for the actual stock of carbon in vegetation and soils, but only for the subset "managed forest" has the contribution as sources and/or sinks been estimated. Responsibilities for producing inventories are divided among several ministries; inventories for energy-related emissions, for example, are established by

the Ministry of Commerce. Based on the Intergovernmental Panel on Climate Change (IPCC) global warming potentials (GWPs) from 1994, methane represented 57 per cent of total gross GHG emissions, CO_2 33 per cent and nitrous oxide less than 10 per cent.

22. A subsectoral demand approach was used for the "all energy" sector, except for gas flaring and own use by gas producers. New Zealand also used country-specific emission factors for each sector. The communication itself did not include the IPCC standard data tables and it required additional information to be fully transparent. Ample supporting data were given to the team during the visit, though not always in the IPCC format, documenting activity levels, conversion factors, and areas of uncertainty and further work. New Zealand has so far given priority to the major emission sources, and none of these were omitted. All these are included in the annual *Energy Greenhouse Gas Emissions Report* prepared by the Ministry of Commerce. However, emissions from the minor sources waste water and agricultural waste burning were not estimated.

23. The 1990 data were revised and updated after the submission, but the new figures are close to those reported. New Zealand is trying to reduce the remaining uncertainties and further revisions may be expected, especially for emissions of gases other than CO_2. A comparison of CO_2 emissions from fuel combustion estimated using IPCC methodology and its own, which was based on the IPCC but further developed, was provided and no significant difference was found. For the CO_2 emissions, uncertainties are estimated at around 5 per cent; for the other gases it is considerably higher, but similar to uncertainties in other countries.

24. The principal source of CO_2 is transport (34 per cent). Process emissions of CO_2 from industry are relatively high (10 per cent) compared to other countries, reflecting the high proportion of heavy industry in New Zealand. The chief source of methane is enteric fermentation in ruminants and animal wastes, which accounts for around 77 per cent, while the waste sector is estimated to account for 21 per cent, with one third of that coming from landfills. The N_2O estimates of 9.3-45.3 Gg in total are based on calculated emissions from combustion activities and a limited number of actual measurements from agricultural soils. These actual measurements have been extrapolated to cover the whole country, hence the range given (1-37 Gg) which reflects the uncertainties regarding emissions from soils. As agricultural practices involve only small amounts of artificial fertilizers, these emissions are relatively low compared to other countries.

25. New Zealand provided the team with information on inventories for energy-related emissions for the period 1990-1993. These show a 6-7 per cent increase in CO_2 emissions, mainly explained by a growing transport sector, but it should also be noted that the hydro power shortage in 1992 led to a peak, since the shortfall was partly compensated by higher thermal production. This illustrates the fluctuations in emissions that the mainly

renewables-based electricity system creates.

26. The team notes that the indigenous forests represent a massive carbon reservoir. They cover 23 per cent of the land and are largely protected in national parks, only 2 to 3 per cent being managed for wood production. The communication did not provide an estimate of the size of this reservoir, and there are great uncertainties as to whether it is a net sink or source. Additional information was given on the indigenous forest situation, including information on carbon released through logging, which is now limited in quantity and is expected to be eliminated within a few years. According to the material provided indigenous forests have 3-4 times higher actual storage per hectare (above ground) than planted forest (1836 Mt C for forest in total, of which 125 Mt C was planted forest in 1992), and the amount of carbon stored there at present could be 10-15 times higher than in the planted forest. Given the high stock of carbon in this reservoir, the uncertainty about the development of this sector constitutes a major uncertainty in compiling a comprehensive inventory for New Zealand.

27. The existing planted forest covers 5 per cent of the land (1.4 million ha in 1994), 90 per cent of which is a monoculture of *Pinus radiata* normally harvested after 25-30 years. This is a considerable net sink due to a relatively young age class of trees, and conversion of shrub, abandoned land and pastureland to forest. The carbon storage in these forests is monitored through 20 000 sample plots annually. The team was provided with documentation on measurement methods but noted that, although New Zealand's monitoring and modelling of this sector is among the most sophisticated in the world, estimates of storage and sink capacity have been substantially revised since the country visit. The new figures, building on better estimates of planting in the 1990s and of the age structure, give an estimate of 17.7 Mt CO_2 in 1990 (the year ending 31 March 1991), or 1.0 Mt more than was reported in the national communication. The development of soil carbon is discussed in an annex to the communication and work is going on to improve the understanding of the situation.

28. Emissions from international marine and aviation transport (bunker fuels) are reported separately. These correspond to 9 per cent of national emissions, which is high in an international context and is due to New Zealand's location and trade patterns.

III. POLICIES AND MEASURES

29. In May 1993, the Government announced its intention to develop a comprehensive strategy on climate change covering sources and sinks of all greenhouse gases. It also announced its domestic CO_2 target described in chapter I. There are no specified targets for other gases.

30. Greenhouse gases are considered contaminants under the Resource Management Act, which applies to all sectors, including energy, industry, agriculture and forestry. It requires "sustainable management" of natural and physical resources, and provides the basis for local and regional governments' responses to climate change through control of emissions by a

system of consents and planning measures. In the view of the team, continued application of the provisions of the Act can be an important option in the fulfillment of New Zealand's strategies.

31. The team noted that the Act encourages local authorities to:

- urge consent applicants to use best practicable means to limit emissions

- base decisions on emission reductions on a "no regrets" approach

- consider greenhouse gas emissions and sinks in preparing regional policies and plans.

32. In the event that the package of measures relating to CO_2, including the new voluntary agreements, fails to achieve the desired result by 1997, the Government has announced its intention to introduce a low-level carbon charge. The design of this tax has not been decided, but it is expected that it could cover all sources of CO_2 emissions. The team noted that the full effects of introducing a tax or most other measures by late 1997 are unlikely to be achieved before the turn of the century. However, announcing the tax in this way will encourage decision makers to plan for such an event now, which could in itself reduce emissions.

33. Since the present marginal electricity capacity is based on fossil fuels, and further development of the electricity system is also expected largely to utilize these energy sources, there is a direct link between measures to improve energy efficiency and CO_2 savings, despite the high proportion of renewables in New

Zealand's energy system.

34. Acting in accordance with the Resource Management Act, the Ministry of the Environment has made submissions to several consent hearings with implications for greenhouse gas emissions. A recent example was the decision on the 400 MW Stratford/Taranaki gas-fired power plant, which alone and seen in isolation would increase national emissions by 5 per cent (emissions of a maximum of 1.5 Mt CO_2). The effect it would have through the system would lead to lower emission growth than seen in isolation, for example if it replaces coal use. The Minister, acting as consent authority and in response to the recommendations of a Board of Inquiry, decided that the CO_2 added by the plant to the total power sector emissions would have to be offset by mitigation actions such as energy efficiency improvements or enhancement of sinks. It is unclear how the Act will be applied in similar cases in the future, and whether decisions on consents will be left to regional councils.

35. New Zealand is in the process of implementing important reforms in the energy sector, aimed at facilitating the development of competitive gas and electricity markets. A stated objective is to improve the sector's efficiency in both production and use of energy for the overall benefit of the economy. Significant changes include:

- separate accounting of energy distribution and retailing functions;

- a requirement that energy companies disclose information about transmission and

energy costs and charges;

- removal of franchise areas for electricity gas retailers;

- removal of price controls on gas.

36. All these measures are aimed at promoting competition in electricity and gas markets and facilitating the entry of new firms. The team notes that the achievement of effective competition, taken with other measures, including the requirements of the Resource Management Act, could stimulate substantial efficiency improvements and the use of new renewable energy sources. At present, wind power is seen as particularly promising on a commercial basis. For example, consent was announced for the Wairarapa wind farm during the team's visit. The plant is expected to produce 3-3.5 MW at a cost close to prices already paid for electricity from other sources, and will be one of the first commercial wind power plants to be set up in New Zealand by a small independent producer. Consequently, this reform could prove to have considerable effects in a sector that is projected to have the highest annual growth (4.8 per cent) in emissions in the present decade.

37. The team noted that energy sector deregulation is still in an early phase, and that close monitoring is needed to ensure that a really competitive market is achieved, especially in areas where there are natural monopolies (for example in transmission) or dominant producers in the market. At the time of the team's visit the Electricity Corporation New Zealand produced 96 per cent of the electricity. The team thus notes the importance of the Government's efforts to encourage new players to enter into the market by, for example, ensuring them access to the grid on reasonable terms and limiting the influence of major existing companies. At the time of the team's visit, there were negotiations on splitting the Corporation into two entities which has since been accomplished, to improve the competitiveness of the market and to ease the entry of other producers. The introduction of a genuinely competitive market can be expected to stimulate greater efficiency at all points of the fuel cycle, eventually leading to prices reflecting long-run marginal costs, accompanied by energy savings, but without consumer prices necessarily rising in real terms. The position will need to be monitored, and the team noted that the changing regime in the electricity sector may require a revision of the

types of policies and measures to mitigate climate change that would be appropriate for this sector. The inclusion of electricity producers in the voluntary agreements can be seen in this perspective.

38. The New Zealand Government has taken several energy efficiency initiatives, which are coordinated by the Energy Efficiency and Conservation Authority (EECA). This independent body was established in 1992, and has a major role in developing and implementing New Zealand's energy efficiency strategy. It gives policy advice and carries out operational activities, and is actively seeking to benefit from the experience of similar institutions in other countries. After examining these activities, the team found them well described in the national communication. It noted as examples of potentially important initiatives the voluntary programmes "Energy Wise Companies", which had passed a preliminary milestone of 300 participating private sector entities by December 1995, and "Government Leadership" which involves public sector agencies and institutions. EECA has developed a proposal for minimum energy performance standards for a range of end-use applications, which is under consideration by the Government. EECA has also led the technical development of a proposal for revising and expanding the energy efficiency requirements in the New Zealand Building Code, which also requires Government consideration before it can be adopted. Pending the outcome, full effects are not expected until after the turn of the century. EECA is a relatively new body for which monitoring and evaluation of the programmes is crucial. At the time of the team's visit it was too early to provide empirical documentation of results from the various initiatives. The team noted that EECA will have the challenge of operating in an energy sector undergoing major reforms in the coming years. Finally, the team noted that the electricity shortage of 1992 seems to have led to greater awareness of how to save energy, particularly in the residential sector, which may have a lasting effect.

39. As part of the electricity reform, the Government in June 1995 announced the creation of a new, $NZ 18 million five-year transitional Energy Saver Fund. It will be targeted at the residential sector, since that sector uses 35 per cent of the total electricity supply and there are considerable potentials for cost-effective savings. Unlike the case in the energy, industry and commercial sectors, the incentives to improve energy efficiency are not seen as strong, and consequently there is a need to enhance them. This initiative is only in its embryonic phase, and was not reported in the communication.

40. In the industry and energy transformation sectors, which together accounted for approximately 55 per cent of CO_2 emissions in 1990, the Government has concluded a number of voluntary agreements to obtain CO_2 savings. At the time of the team's visit, the Government (Ministry of Commerce) was in the process of negotiating agreements with a broad range of business sector groups to reduce their CO_2 emissions. The process originally targeted 12 industries which accounted for over 50 per cent of industrial CO_2 emissions, but smaller industries have also opted to join. The first nine agreements were signed on

6 September 1995, a further six were signed on 17 October 1995 and others are under negotiation. Updated material on this was made available to the team. The commitments are not legally binding but must be seen in the light of the contingent introduction of a low-level carbon charge and the possibility of using other instruments derived from the Resource Management Act. The agreements vary in nature, reflecting differences in the industries' situations and options, but typically they specify an improvement in CO_2 emissions per unit of production by 2000. They are likely to be renegotiated if annual reporting shows a major diversion from original expectations. Voluntary agreements do not at present include gases other than CO_2 or possibilities for offsetting emissions, either domestically or abroad.

41. The volume of transport services (which accounted for 34 per cent of CO_2 emissions in 1990) has grown strongly, especially in the commercial sector, largely in response to an upturn of economic activity. Alternative transport fuels such as compressed natural gas and liquified petroleum gas have been available in New Zealand for some time, but their use is now in decline. The Government started drawing up strategies to limit emissions around 1992, and some studies on options could be finished shortly. As part of the restructuring of the economy, public transport has been deregulated in the 1980s and 1990s. In 1992 the central Government reduced direct involvement in public transport funding. To partially compensate for lost revenue, five regional councils were authorized to levy a regional petrol tax of up to two cents per litre, to

raise additional funds for public transit. Central Government has recently discontinued the regional petrol tax and returned to a central system of funding to maintain existing levels of public transit service. The team noted that strategy development has not yet led to the implementation of new measures that could be considered as having major impacts, although there has been a stronger enforcement of speed limits and the investigation of education schemes for drivers as part of the energy efficiency campaigns run by EECA. However, at the time of the team's visit, legislation was before the House of Representatives to reform the administration of road funding and develop a national land transport strategy.

42. New Zealand's planted forests, composed of non-native trees and occupying approximately 5 per cent of the land area (1.4 million ha in 1994), is a crop rather than a product of natural ecosystems. The rotation period is typically only 25-30 years. Reforms in taxation, removal of agricultural subsidies and world timber demand have led to increased forest planting. By 1994 the annual planting rate had reached almost 100,000 ha.

43. Indigenous forests occupy 23 per cent of the land area, or 6.2 million ha. They are mainly protected from all harvesting. Some 164,000 ha of Crown forest is potentially available for wood production although this is occurring in only a few areas. New legislation has been passed that requires indigenous forest harvesting to be on a sustainable basis. Under transitional arrangements specified levels of sustainable harvesting can continue until July 1996. The legislation does not apply to most Crown forest managed for wood production but a separate arrangement requires sustainability of these with a small single exception which expires in 2005. Some 20,000 ha of Maori land is also exempt from the legislation. Government is currently negotiating with the owners regarding its future inclusion. These forests are under stress which in some areas is severe, from introduced animals such as possums, goats and deer, so there is potentially a major carbon loss from this reservoir. The Government is actively trying to minimize the damage caused by animals through systematic programmes of poisoning, hunting etc. Given the large amount of carbon stored in these forests (approximately 1700 Mt C or 6200 Mt CO_2), the emissions that would result from a possible massive degradation could dominate the carbon budget of New Zealand. Consequently, the team recognized the measures to mitigate such a development as being of the utmost importance. The team also took note of the New Zealand Forest Accord by which industrial and environmental non-governmental organizations agree to protect indigenous forests from being converted to managed ones.

44. In August 1995, the Government set up a new working group on CO_2 policy. The group's task is to analyse the conflict between a case-by-case approach rooted in the Resource Management Act and the Government's more economy-wide approach, the impacts of higher-than-expected levels of economic growth, the need for further analysis relating to New Zealand's carbon sink and reservoirs, and whether a carbon charge is the most efficient economic instrument to use, should that be necessary, when progress under the current policy is revised in 1997. The group includes representatives from some non-governmental organizations, notably forest, electricity and environmental interests.

45. New Zealand is carrying out research into the feasibility of measures to limit CH_4 emissions from agriculture, for example, ways of modifying enteric ecology to reduce emissions from each ruminant. The emissions from this source, which is the main source of GHGs in New Zealand, are expected to be below 1990 levels by 2000 owing to structural change in the agricultural sector caused by the abolition of subsidies and the conditions on the world market. Further, waste management policies could reduce emissions from landfills.

46. New Zealand has not implemented specific policies to reduce emissions of N_2O, PFCs and HFCs. However, there is a dialogue with the relevant industry and the provisions of the Resource Management Act could be enforced, if this is seen as the right approach.

IV. PROJECTIONS AND EFFECTS OF POLICIES AND MEASURES

47. New Zealand provided projections for CO_2, CH_4, N_2O and PFCs. For the last mentioned, the communication merely stated that they are expected in 2000 to be below 1990 levels. The team was given projections of energy-related N_2O emissions, which show a slight growth. The methodologies for projecting energy-related emissions appear to be generally sound and well documented in the supplementary material. The team found that economic assumptions were in line with international sources at the time the projections were made. The oil price chosen was high compared to assumptions in other countries, while the GDP growth rate was relatively low compared to actual development. New Zealand has enjoyed much faster growth than expected, reaching a historical high of 6 per cent in 1994, but this rate is not expected to last.

48. Given the major uncertainties involved, New Zealand presented the projection data for CO_2 as intervals, on the basis of sensitivity analysis with different GDP assumptions. It is estimated that with 2-3 per cent growth in GDP till 2000 there could be an 18-22 per cent increase in CO_2 emissions in a "business as usual" scenario, mainly because of expansion in thermal power and transport. With measures, including a conditional carbon tax from 1997, the increase is estimated at 14-17 per cent with the same assumptions. The reduced figures are based on a rough assessment of effects, where the programmes in general are assumed to increase the rate of energy efficiency improvements by 0.5 per cent over and above the historic rate. Since 1990 GDP and actual CO_2 emissions have grown faster than the projections.

49. New Zealand has made a relatively thorough study of the supply options as a basis for the projections. The team noted that the projections documented in the supplementary material show a shift from the historic trend of growing energy intensity to a situation where GDP grows faster (3 per cent) than energy consumption (1.4 per cent). This development reflects the fact that the starting point and development of energy-intensive industry in New Zealand over the past decades has been different to that in other OECD countries, but it may now follow a more similar growth path. It is recognized that there is significant untapped

potential for improved energy efficiency; in the electricity sector the growth and penetration of unconventional renewables represents a significant uncertainty, especially after 2000. This is well illustrated in the documentation.

50. An additional uncertainty is the effect of the reforms in the electricity market. If the market becomes completely competitive, new capacity in this sector will in general be added to the system when the price at least covers the long-term marginal costs. Despite the shortage in 1992, the market is expected to have excess supply until after the turn of the century, with the result that expected prices are below long-term marginal costs. The team noted that there will be little economic incentive to add new capacity to the system, be it based on fossil fuels or renewables, until a balance is established. Further, the reforms may change behaviour in the sector, adding an additional uncertainty.

51. In the longer term, CO_2 emissions could grow significantly in the absence of further measures, owing to an increased energy demand. Major uncertainties are to what extent coal will be used for electricity generation, which could happen after the turn of the century, and whether or not new discoveries of natural gas will be made. Further, some of the existing energy-intensive industry (petrochemicals) will reach the end of its expected life by the end of the next decade with the prospect of reduced emissions if plants are closed down.

52. The team noted that methane emissions, stemming largely from ruminants (77 per cent of the total), are projected to follow the anticipated development in the agricultural sector. The implementation of the Uruguay Round is expected to be a driving force in this sector, offering greater opportunities for New Zealand production, and consequently increased emissions, from around 1998. The estimated 2000 figures

would still be lower than those for 1990, and the development of the sector could be influenced by the planting of forest. No reductions from measures based on ongoing research on ruminants are expected in the short term. Emissions from animal wastes and landfills are not expected to grow. The team was provided with background material on projections for emissions from landfills (7 per cent of total emissions) and for methane emissions from energy sources (3 per cent of total emissions), which show little or no growth in a "business as usual" scenario. Actual

energy-related emissions have declined compared to projections.

53. The team noted the considerable uncertainty as to how sequestration of carbon in planted forests will develop, depending on planting and cutting rates and the fact that they represent only a small sector in terms of land use but one which is changing rapidly. Consequently, it would like to underline the uncertainties in the projections. Given its outstanding, but still uncertain, inventory data seen from an international perspective, New Zealand has an excellent database for making projections in this sector. Without changes in management practices, carbon sequestration in these forests is expected to increase up to 2000 due to a relatively young age class of trees. The projections of this sequestration are highly dependent on the rate of planting of new areas, the fertility of these lands and the management practices. This is especially true for figures after 2000, but impacts could also be significant before then. With no new planting, sequestration could decrease after the turn of the century. However, there is sufficient plantable land (shrub, pasture and arable land at present makes up more than 50 per cent of the area) in New Zealand to maintain the present high rate of sequestration for 50 to 100 years. If planting is accelerated, sequestration could be increased in a shorter period than this.

54. The assumption of 100,000 ha for new area planted reflects higher planting rates than those seen before 1994, but the rationale is that the economic feasibility of planting has shifted drastically. The revision of the inventory for 1990 reflects a higher sequestration in the base year, and revised projections based on an improved model with the same assumptions show an absorption equivalent to 18.6 Mt CO_2 in 2000 compared to 17.7 Mt in 1990, or a considerably slower acceleration of sequestration then was presented in the communication (25.5 as against 16.7 Mt CO_2). Therefore New Zealand does not now expect to achieve its stabilization target until sometime after 2000.

55. New Zealand did not give projections for development of the carbon stock in the indigenous forest (23 per cent of the land area), which the team finds reasonable because of the lack of quantitative understanding of the present contribution and the huge uncertainties of future development. The development of this sector was the subject of considerable attention during the review. In addition to covering a much bigger area than the planted forest, the indigenous forest has much higher carbon storage per hectare. The range of development paths could go from a reasonable increase in the carbon stock due to natural regeneration of forest on abandoned marginal pasture land and reduced wood harvesting, to a major decrease if wild animal control is not maintained and successful. It can still be questioned whether the main causes for the present degradation - the introduction of animals which go a century and more back - can be regarded as anthropogenic in relation to the UNFCCC. Still the team wants to emphasize that the natural forest may become a major negative contributor to the overall carbon budget for New Zealand, unless effective animal control is maintained. There is a tension between a decline in storage due to wild animal impacts, and an increase due to natural forest expansion onto abandoned land. There is both a significant potential upside and downside risk for this carbon store. Efforts to control the degradation therefore appear crucial.

V. EXPECTED IMPACTS OF CLIMATE CHANGE

56. A broad assessment of possible impacts of climate change was made when New Zealand started to develop its climate change strategy in 1988. This assessment, published in 1990, is still valid and is based on

scenarios describing sealevel rise and changes in weather patterns. Types of possible impacts are presented in the communication, but are described as highly uncertain at this disaggregated level of geography. The team noted that New Zealand is a country that already has a variable climate, yet there are ecosystems and groups in society that are particularly vulnerable to a change in their conditions. The initial assessment has led to follow-up research and development projects in various areas.

VI. ADAPTATION MEASURES

57. The team noted that New Zealand has an established tradition of ready adaptation to strong variations in natural and economic conditions. The New Zealand Coastal Policy Statement prepared under the Resource Management Act has provisions for adaptation to sealevel rise to be implemented at the local level. The Government recognizes the need to look more closely at adaptation and possibly develop a national strategy.

VII. FINANCIAL ASSISTANCE AND TECHNOLOGY TRANSFER

58. New Zealand did not contribute to the pilot phase of GEF, but sought to integrate climate change concerns in its ODA. For the GEF replenishment for 1994-1996, New Zealand is paying its assessed share, plus a supplementary contribution of a similar size. This is in addition to ODA, which in 1994 was 0.24 per cent of GDP, according to Development Assistance Committee/OECD statistics.

59. New Zealand supports consideration by multilateral development agencies of the environmental, including climate change, implications of their funding policies. A unit in the Ministry of Foreign Affairs and Trade's Development Cooperation Division considers the environmental (including climate change) implications of New Zealand's ODA programme.

60. New Zealand institutions have a tradition of close cooperation with developing countries and regional organizations such as the South Pacific Regional Environment Programme (SPREP) in the Asia and South Pacific region, for example between the meteorological services and in coastal planning. These activities appear important for monitoring and capacity-building. Some of the cooperation is on a commercial basis, and the team noted that both the Government and the private sector recognized the central role of the latter in technology transfer. Substantial parts of industry have strong ownership and activity links to other countries, and technical know-how in such areas as forestry is spread through them. The team also took note of New Zealand's participation in the recently established Group of Temperate Southern Hemisphere Countries on Environment (Valdivia Group) which aims to facilitate information exchange and cooperation on international environment and related science issues.

61. New Zealand is positive towards the concept of joint implementation/activities implemented jointly (AIJ), but at the time of the team's visit it had not established any programmes to explore this area.

VIII. RESEARCH AND SYSTEMATIC OBSERVATION

62. New Zealand recognizes that, because of its location (southern hemisphere, mid latitude, mid-ocean) and since it has unique natural conditions regarding land, flora and

fauna, it has a special responsibility for monitoring and researching climate change. The team noted that New Zealand has collected unique data sets on climatic conditions in the region.

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63. The team noted that the Minister for the Environment is also the Minister of Research, Science and Technology. The response to climate change through public R and D efforts appears well organized, with an independent committee (the National Science Strategy Committee for Climate Change) formed in 1991 providing advice to the Minister of Research, Science and Technology, as well as science agencies and users of science. The Committee has representatives from the R and D community and the private sector. The Committee has no funding role. The public sector, however, provides the bulk of funding for climate change research. It gives advice on R and D needs in all areas, including climate science, related social sciences and economics, and technological R and D on mitigation options. The Government has committed itself to increasing the proportion of R and D to GDP from 0.6 to 0.8 per cent by 2010, and it is envisaged that the proportion of climate change-related R and D will not decline. To date, the priority has been given to understanding the fundamental processes of climate change, particularly as they relate to the southern hemisphere. The need for a better understanding of mitigation options and the effects of particular measures is recognized.

64. The Committee's advice is given in the light of the special responsibility mentioned above and the strengths of national institutions, and it also seeks to utilize in an optimal way the efforts made by international society. New Zealand considers cooperation in the southern hemisphere important, and recognizes that a better understanding of climate change in that hemisphere will also increase understanding in the northern hemisphere.

IX. EDUCATION, TRAINING AND PUBLIC AWARENESS

65. The team noted that increasing public awareness is an integral part of the policy initiatives. Education, training and public awareness in the area of climate change are the responsibility of the Ministry of the Environment, which does not limit the participation of other bodies and levels of government in this effort. The Ministry's activities are well documented in the communication. The Energy Efficiency and Conservation Authority, together with its partners, is promoting efficiency and renewables through the media, publications, seminars and demonstrations, and is working on school curricula as well. The team noted the initiatives of local and regional authorities, the emphasis on communication of results from scientific programmes, and the important role of non-governmental organizations in increasing public awareness.

66. The Resource Management Act provides members of the public with the right to propose changes to plans and enforcement procedures. New Zealand also has a particularly strong law (the Official Information Act) ensuring public access to internal ministry documents, including those relating to policy development for climate change. This legislation should ensure openness in most governmental operations, and it goes hand in hand with the considerable stakeholder involvement, including regular consultations with both business and environmental non-governmental organizations, that is sought from the Government's side in its climate change-related activities. Recently, the Minister for the Environment set up a private sector/public sector working group on carbon dioxide policy.

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1. In accordance with decision 2/CP.1, the full draft of this report was communicated to the

Government of New Zealand, which had no further comments.

Climate Change 2023 Synthesis Report

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Section 1
Introduction

1. Introduction

This Synthesis Report (SYR) of the IPCC Sixth Assessment Report (AR6) summarises the state of knowledge of climate change, its widespread impacts and risks, and climate change mitigation and adaptation, based on the peer-reviewed scientific, technical and socio-economic literature since the publication of the IPCC's Fifth Assessment Report (AR5) in 2014.

The assessment is undertaken within the context of the evolving international landscape, in particular, developments in the UN Framework Convention on Climate Change (UNFCCC) process, including the outcomes of the Kyoto Protocol and the adoption of the Paris Agreement. It reflects the increasing diversity of those involved in climate action.

This report integrates the main findings of the AR6 Working Group reports[58] and the three AR6 Special Reports[59]. It recognizes the interdependence of climate, ecosystems and biodiversity, and human societies; the value of diverse forms of knowledge; and the close linkages between climate change adaptation, mitigation, ecosystem health, human well-being and sustainable development. Building on multiple analytical frameworks, including those from the physical and social sciences, this report identifies opportunities for transformative action which are effective, feasible, just and equitable using concepts of systems transitions and resilient development pathways[60]. Different regional classification schemes[61] are used for physical, social and economic aspects, reflecting the underlying literature.

After this introduction, Section 2, '*Current Status and Trends*', opens with the assessment of observational evidence for our changing climate, historical and current drivers of human-induced climate change, and its impacts. It assesses the current implementation of adaptation and mitigation response options. Section 3, '*Long-Term Climate and Development Futures*', provides a long-term assessment of climate change to 2100 and beyond in a broad range of socio-economic futures. It considers long-term characteristics, impacts, risks and costs in adaptation and mitigation pathways in the context of sustainable development. Section 4, '*Near- Term Responses in a Changing Climate*', assesses opportunities for scaling up effective action in the period up to 2040, in the context of climate pledges, and commitments, and the pursuit of sustainable development.

Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language[62]. The scientific findings are drawn from the underlying reports and arise from their Summary for Policymakers (hereafter SPM), Technical Summary (hereafter TS), and underlying chapters and are indicated by {} brackets. Figure 1.1 shows the Synthesis Report Figures Key, a guide to visual icons that are used across multiple figures within this report.

58 The three Working Group contributions to AR6 are: Climate Change 2021: The Physical Science Basis; Climate Change 2022: Impacts, Adaptation and Vulnerability; and Climate Change 2022: Mitigation of Climate Change, respectively. Their assessments cover scientific literature accepted for publication respectively by 31 January 2021, 1 September 2021 and 11 October 2021.

59 The three Special Reports are : Global Warming of 1.5°C (2018): 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 (SR1.5); Climate Change and Land (2019): an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL); and The Ocean and Cryosphere in a Changing Climate (2019) (SROCC). The Special Reports cover scientific literature accepted for publication respectively by 15 May 2018, 7 April 2019 and 15 May 2019.

60 The Glossary (Annex I) includes definitions of these, and other terms and concepts used in this report drawn from the AR6 joint Working Group Glossary.

61 Depending on the climate information context, geographical regions in AR6 may refer to larger areas, such as sub-continents and oceanic regions, or to typological regions, such as monsoon regions, coastlines, mountain ranges or cities. A new set of standard AR6 WGI reference land and ocean regions have been defined. WGIII allocates countries to geographical regions, based on the UN Statistics Division Classification {*WGI 1.4.5, WGI 10.1, WGI 11.9, WGI 12.1–12.4, WGI Atlas.1.3.3–1.3.4*}.

62 Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or result: virtually certain 99–100% probability; very likely 90–100%; likely 66–100%; more likely than not >50-100%; about as likely as not 33–66%; unlikely 0–33%; very unlikely 0–10%; and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100% and extremely unlikely 0–5%) are also used when appropriate. Assessed likelihood also is typeset in italics: for example, very likely. This is consistent with AR5. In this Report, unless stated otherwise, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

Figure 1.1: The Synthesis Report figures key.

Section 2
Current Status and Trends

Section 2: Current Status and Trends

2.1 Observed Changes, Impacts and Attribution

Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850–1900 in 2011–2020. Global greenhouse gas emissions have continued to increase over 2010–2019, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and between individuals (*high confidence*). Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. This has led to widespread adverse impacts on food and water security, human health and on economies and society and related losses and damages[63] to nature and people (*high confidence*). Vulnerable communities who have historically contributed the least to current climate change are disproportionately affected (*high confidence*).

2.1.1. Observed Warming and its Causes

Global surface temperature was around 1.1°C above 1850–1900 in 2011–2020 (1.09 [0.95 to 1.20]°C)[64], with larger increases over land (1.59 [1.34 to 1.83]°C) than over the ocean (0.88 [0.68 to 1.01]°C)[65]. Observed warming is human-caused, with warming from greenhouse gases (GHG), dominated by CO_2 and methane (CH_4), partly masked by aerosol cooling (Figure 2.1). Global surface temperature in the first two decades of the 21st century (2001–2020) was 0.99 [0.84 to 1.10]°C higher than 1850–1900. Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (*high confidence*). The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019[66] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs[67] contributed a warming of 1.0°C to 2.0°C, and other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural (solar and volcanic) drivers changed global surface temperature by ±0.1°C and internal variability changed it by ±0.2°C. {*WGI SPM A.1, WGI SPM A.1.2, WGI SPM A.1.3, WGI SPM A.2.2, WGI Figure SPM.2; SRCCL TS.2*}

Observed increases in well-mixed GHG concentrations since around 1750 are unequivocally caused by GHG emissions from human activities. Land and ocean sinks have taken up a near-constant proportion (globally about 56% per year) of CO_2 emissions from human activities over the past six decades, with regional differences (*high confidence*). In 2019, atmospheric CO_2 concentrations reached 410 parts per million (ppm), CH_4 reached 1866 parts per billion (ppb) and nitrous oxide (N_2O) reached 332 ppb[68]. Other major contributors to warming are tropospheric ozone (O_3) and halogenated gases. Concentrations of CH_4 and N_2O have increased to levels unprecedented in at least 800,000 years (*very high confidence*), and there is *high confidence* that current CO_2 concentrations are higher than at any time over at least the past two million years. Since 1750, increases in CO_2 (47%) and CH_4 (156%) concentrations far exceed – and increases in N_2O (23%) are similar to – the natural multi-millennial changes between glacial and interglacial periods over at least the past 800,000 years (*very high confidence*). The net cooling effect which arises from anthropogenic aerosols peaked in the late 20th century (*high confidence*). {*WGI SPM A1.1, WGI SPM A1.3, WGI SPM A.2.1, WGI Figure SPM.2, WGI TS 2.2, WGI 2ES, WGI Figure 6.1*}

[63] In this report, the term 'losses and damages' refers to adverse observed impacts and/or projected risks and can be economic and/or non-economic. (See Annex I: Glossary)

[64] The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22]°C). Additionally, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5 {*WGI SPM A1.2 and footnote 10*}

[65] For 1850–1900 to 2013–2022 the updated calculations are 1.15 [1.00 to 1.25]°C for global surface temperature, 1.65 [1.36 to 1.90]°C for land temperatures and 0.93 [0.73 to 1.04]°C for ocean temperatures above 1850–1900 using the exact same datasets (updated by 2 years) and methods as employed in WGI.

[66] The period distinction with the observed assessment arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21]°C. {*WGI SPM footnote 11*}

[67] Contributions from emissions to the 2010–2019 warming relative to 1850–1900 assessed from radiative forcing studies are: CO_2 0.8 [0.5 to 1.2]°C; methane 0.5 [0.3 to 0.8]°C; nitrous oxide 0.1 [0.0 to 0.2]°C and fluorinated gases 0.1 [0.0 to 0.2]°C.

[68] For 2021 (the most recent year for which final numbers are available) concentrations using the same observational products and methods as in AR6 WGI are: 415 ppm CO_2; 1896 ppb CH_4; and 335 ppb N_2O. Note that the CO_2 is reported here using the WMO-CO_2-X2007 scale to be consistent with WGI. Operational CO_2 reporting has since been updated to use the WMO-CO_2-X2019 scale.

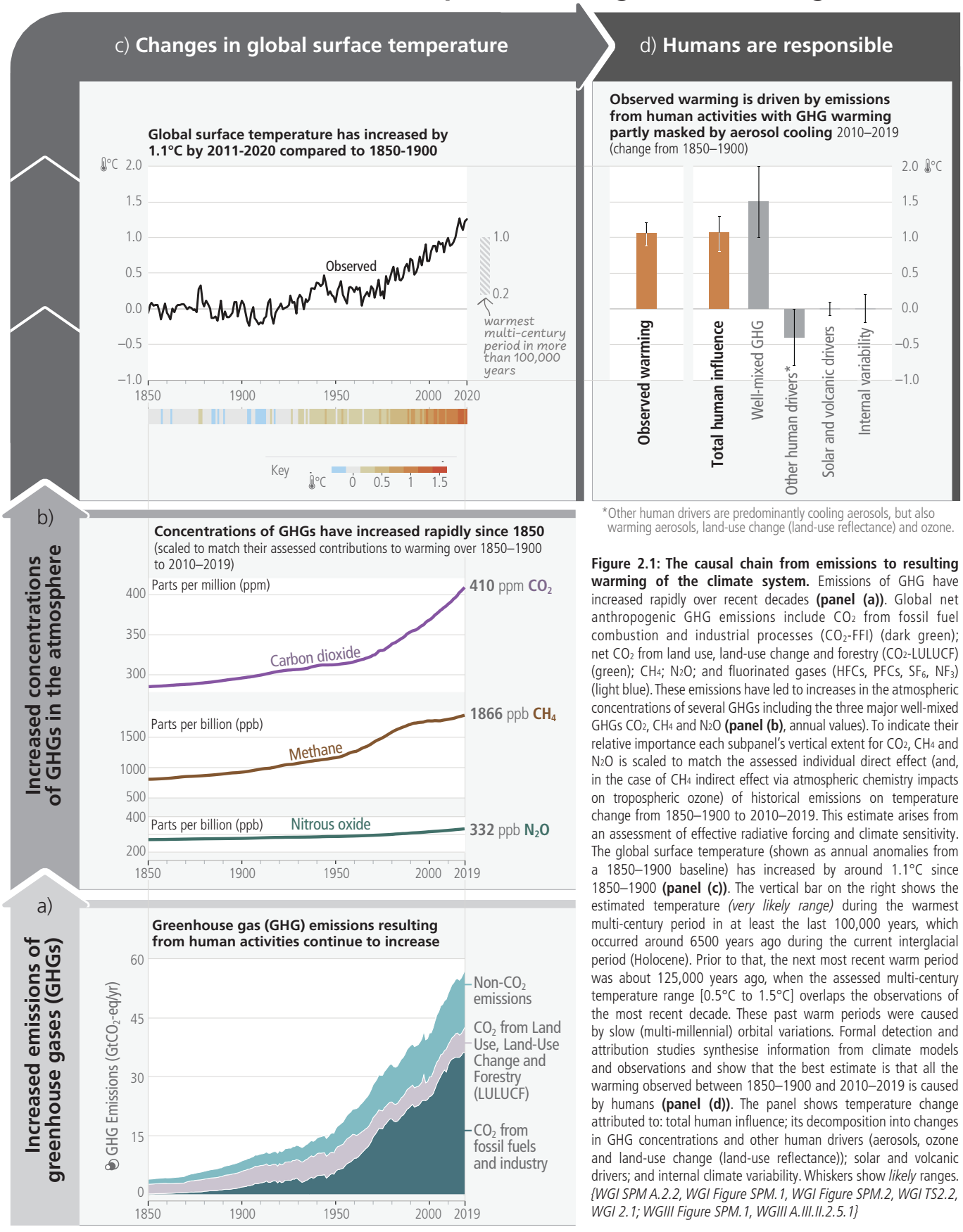

Figure 2.1: The causal chain from emissions to resulting warming of the climate system. Emissions of GHG have increased rapidly over recent decades **(panel (a))**. Global net anthropogenic GHG emissions include CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI) (dark green); net CO_2 from land use, land-use change and forestry (CO_2-LULUCF) (green); CH_4; N_2O; and fluorinated gases (HFCs, PFCs, SF_6, NF_3) (light blue). These emissions have led to increases in the atmospheric concentrations of several GHGs including the three major well-mixed GHGs CO_2, CH_4 and N_2O **(panel (b)**, annual values). To indicate their relative importance each subpanel's vertical extent for CO_2, CH_4 and N_2O is scaled to match the assessed individual direct effect (and, in the case of CH_4 indirect effect via atmospheric chemistry impacts on tropospheric ozone) of historical emissions on temperature change from 1850–1900 to 2010–2019. This estimate arises from an assessment of effective radiative forcing and climate sensitivity. The global surface temperature (shown as annual anomalies from a 1850–1900 baseline) has increased by around 1.1°C since 1850–1900 **(panel (c))**. The vertical bar on the right shows the estimated temperature *(very likely range)* during the warmest multi-century period in at least the last 100,000 years, which occurred around 6500 years ago during the current interglacial period (Holocene). Prior to that, the next most recent warm period was about 125,000 years ago, when the assessed multi-century temperature range [0.5°C to 1.5°C] overlaps the observations of the most recent decade. These past warm periods were caused by slow (multi-millennial) orbital variations. Formal detection and attribution studies synthesise information from climate models and observations and show that the best estimate is that all the warming observed between 1850–1900 and 2010–2019 is caused by humans **(panel (d))**. The panel shows temperature change attributed to: total human influence; its decomposition into changes in GHG concentrations and other human drivers (aerosols, ozone and land-use change (land-use reflectance)); solar and volcanic drivers; and internal climate variability. Whiskers show *likely* ranges. *{WGI SPM A.2.2, WGI Figure SPM.1, WGI Figure SPM.2, WGI TS2.2, WGI 2.1; WGIII Figure SPM.1, WGIII A.III.II.2.5.1}*

Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 (1.3% yr^{-1}) was lower than that between 2000 and 2009 (2.1% yr^{-1})[69]**.** Historical cumulative net CO_2 emissions from 1850 to 2019 were 2400 ±240 $GtCO_2$. Of these, more than half (58%) occurred between 1850 and 1989 [1400 ±195 $GtCO_2$], and about 42% between 1990 and 2019 [1000 ±90 $GtCO_2$]. Global net anthropogenic GHG emissions have been estimated to be 59±6.6 $GtCO_2$-eq in 2019, about 12% (6.5 $GtCO_2$-eq) higher than in 2010 and 54% (21 $GtCO_2$-eq) higher than in 1990. By 2019, the largest growth in gross emissions occurred in CO_2 from fossil fuels and industry (CO_2-FFI) followed by CH_4, whereas the highest relative growth occurred in fluorinated gases (F-gases), starting from low levels in 1990. (*high confidence*) {*WGIII SPM B1.1, WGIII SPM B.1.2, WGIII SPM B.1.3, WGIII Figure SPM.1, WGIII Figure SPM.2*}

Regional contributions to global human-caused GHG emissions continue to differ widely. Historical contributions of CO_2 emissions vary substantially across regions in terms of total magnitude, but also in terms of contributions to CO_2-FFI (1650 ± 73 $GtCO_2$-eq) and net CO_2-LULUCF (760 ± 220 $GtCO_2$-eq) emissions (Figure 2.2). Variations in regional and national per capita emissions partly reflect different development stages, but they also vary widely at similar income levels. Average per capita net anthropogenic GHG emissions in 2019 ranged from 2.6 tCO_2-eq to 19 tCO_2-eq across regions (Figure 2.2). Least Developed Countries (LDCs) and Small Island Developing States (SIDS) have much lower per capita emissions (1.7 tCO_2-eq and 4.6 tCO_2-eq, respectively) than the global average (6.9 tCO_2-eq), excluding CO_2-LULUCF. Around 48% of the global population in 2019 lives in countries emitting on average more than 6 tCO_2-eq per capita, 35% of the global population live in countries emitting more than 9 tCO_2-eq per capita[70] (excluding CO_2-LULUCF) while another 41% live in countries emitting less than 3 tCO_2-eq per capita. A substantial share of the population in these low-emitting countries lack access to modern energy services. (*high confidence*) {*WGIII SPM B.3, WGIII SPM B3.1, WGIII SPM B.3.2, WGIII SPM B.3.3*}

Net GHG emissions have increased since 2010 across all major sectors (*high confidence*). In 2019, approximately 34% (20 $GtCO_2$-eq) of net global GHG emissions came from the energy sector, 24% (14 $GtCO_2$-eq) from industry, 22% (13 $GtCO_2$-eq) from AFOLU, 15% (8.7 $GtCO_2$-eq) from transport and 6% (3.3 $GtCO_2$-eq) from buildings[71] (*high confidence*). Average annual GHG emissions growth between 2010 and 2019 slowed compared to the previous decade in energy supply (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%) but remained roughly constant at about 2% yr^{-1} in the transport sector (*high confidence*). About half of total net AFOLU emissions are from CO_2 LULUCF, predominantly from deforestation (*medium confidence*). Land overall constituted a net sink of –6.6 (±4.6) $GtCO_2$ yr^{-1} for the period 2010–2019[72] (*medium confidence*). {*WGIII SPM B.2, WGIII SPM B.2.1, WGIII SPM B.2.2, WGIII TS 5.6.1*}

Human-caused climate change is a consequence of more than a century of net GHG emissions from energy use, land-use and land use change, lifestyle and patterns of consumption, and production. Emissions reductions in CO_2 from fossil fuels and industrial processes (CO_2-FFI), due to improvements in energy intensity of GDP and carbon intensity of energy, have been less than emissions increases from rising global activity levels in industry, energy supply, transport, agriculture and buildings. The 10% of households with the highest per capita emissions contribute 34–45% of global consumption-based household GHG emissions, while the middle 40% contribute 40–53%, and the bottom 50% contribute 13–15%. An increasing share of emissions can be attributed to urban areas (a rise from about 62% to 67–72% of the global share between 2015 and 2020). The drivers of urban GHG emissions[73] are complex and include population size, income, state of urbanisation and urban form. (*high confidence*) {*WGIII SPM B.2, WGIII SPM B.2.3, WGIII SPM B.3.4, WGIII SPM D.1.1*}

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[69] GHG emission metrics are used to express emissions of different GHGs in a common unit. Aggregated GHG emissions in this report are stated in CO_2-equivalents (CO_2-eq) using the Global Warming Potential with a time horizon of 100 years (GWP100) with values based on the contribution of Working Group I to the AR6. The AR6 WGI and WGIII reports contain updated emission metric values, evaluations of different metrics with regard to mitigation objectives, and assess new approaches to aggregating gases. The choice of metric depends on the purpose of the analysis and all GHG emission metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. {*WGI SPM D.1.8, WGI 7.6; WGIII SPM B.1, WGIII Cross-Chapter Box 2.2*} (*Annex I: Glossary*)

[70] Territorial emissions

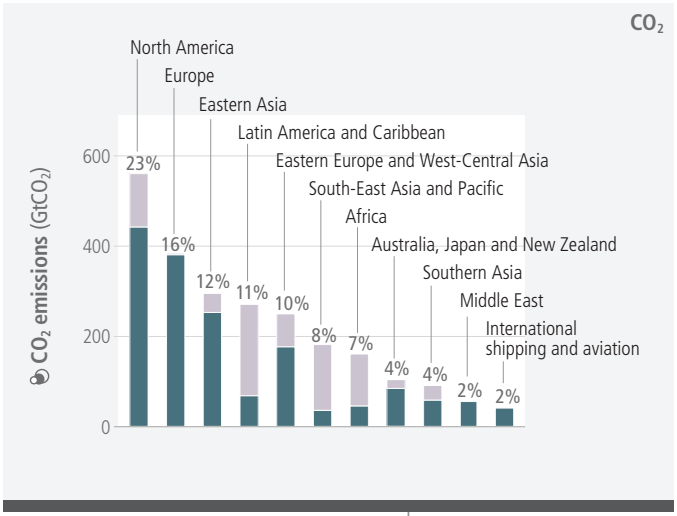
[71] GHG emission levels are rounded to two significant digits; as a consequence, small differences in sums due to rounding may occur. {*WGIII SPM footnote 8*}

[72] Comprising a gross sink of -12.5 (±3.2) $GtCO_2$ yr^{-1} resulting from responses of all land to both anthropogenic environmental change and natural climate variability, and net anthropogenic CO_2-LULUCF emissions +5.9 (±4.1) $GtCO_2$ yr^{-1} based on book-keeping models. {*WGIII SPM Footnote 14*}

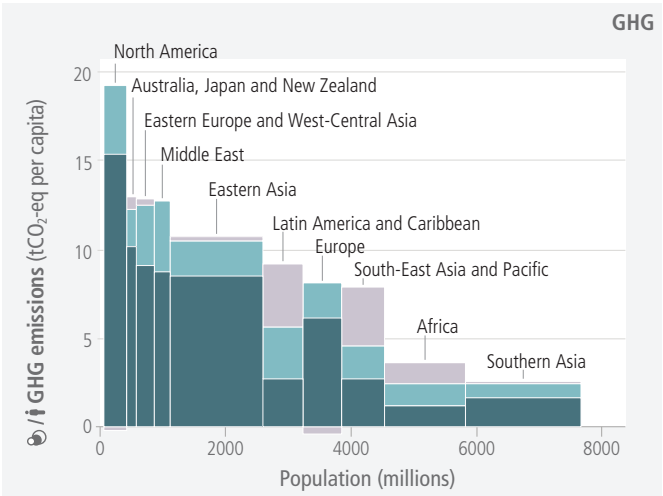
[73] This estimate is based on consumption-based accounting, including both direct emissions from within urban areas, and indirect emissions from outside urban areas related to the production of electricity, goods and services consumed in cities. These estimates include all CO_2 and CH_4 emission categories except for aviation and marine bunker fuels, land-use change, forestry and agriculture. {*WGIII SPM footnote 15*}

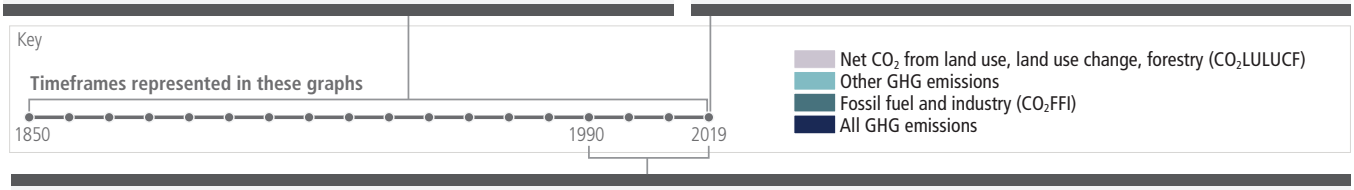
Emissions have grown in most regions but are distributed unevenly, both in the present day and cumulatively since 1850

a) Historical cumulative net anthropogenic CO_2 emissions per region (1850–2019)

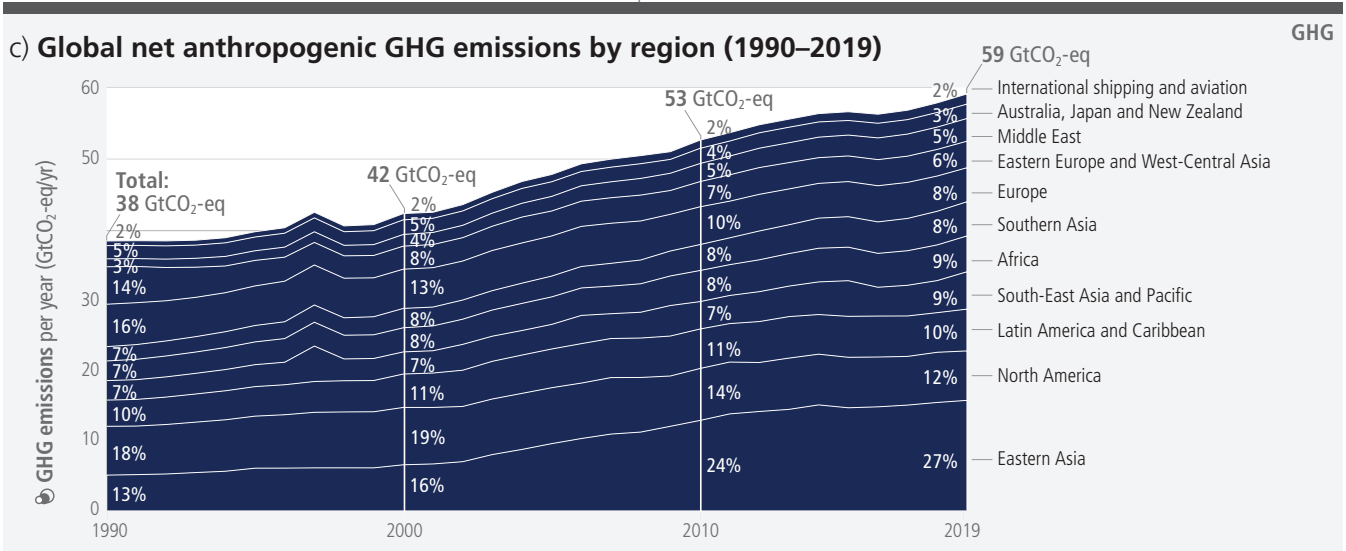


b) Net anthropogenic GHG emissions per capita and for total population, per region (2019)





c) Global net anthropogenic GHG emissions by region (1990–2019)



d) Regional indicators (2019) and regional production vs consumption accounting (2018)

	Africa	Australia, Japan, New Zealand	Eastern Asia	Eastern Europe, West-Central Asia	Europe	Latin America and Caribbean	Middle East	North America	South-East Asia and Pacific	Southern Asia
Population (million persons, 2019)	1292	157	1471	291	620	646	252	366	674	1836
GDP per capita (USD1000$_{PPP}$ 2017 per person) [1]	5.0	43	17	20	43	15	20	61	12	6.2
Net GHG 2019 [2] (production basis)										
GHG emissions intensity (tCO$_2$-eq / USD1000$_{PPP}$ 2017)	0.78	0.30	0.62	0.64	0.18	0.61	0.64	0.31	0.65	0.42
GHG per capita (tCO$_2$-eq per person)	3.9	13	11	13	7.8	9.2	13	19	7.9	2.6
CO_2FFI, 2018, per person										
Production-based emissions (tCO$_2$FFI per person, based on 2018 data)	1.2	10	8.4	9.2	6.5	2.8	8.7	16	2.6	1.6
Consumption-based emissions (tCO$_2$FFI per person, based on 2018 data)	0.84	11	6.7	6.2	7.8	2.8	7.6	17	2.5	1.5

[1] GDP per capita in 2019 in USD2017 currency purchasing power basis.
[2] Includes CO_2FFI, CO_2LULUCF and Other GHGs, excluding international aviation and shipping.

The regional groupings used in this figure are for statistical purposes only and are described in WGIII Annex II, Part I.

Figure 2.2: Regional GHG emissions, and the regional proportion of total cumulative production-based CO_2 emissions from 1850 to 2019. Panel (a) shows the share of historical cumulative net anthropogenic CO_2 emissions per region from 1850 to 2019 in $GtCO_2$. This includes CO_2-FFI and CO_2-LULUCF. Other GHG emissions are not included. CO_2-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ±70% (90% confidence interval). **Panel (b)** shows the distribution of regional GHG emissions in tonnes CO_2-eq per capita by region in 2019. GHG emissions are categorised into: CO_2-FFI; net CO_2-LULUCF; and other GHG emissions (CH_4, N_2O, fluorinated gases, expressed in CO_2-eq using GWP100-AR6). The height of each rectangle shows per capita emissions, the width shows the population of the region, so that the area of the rectangles refers to the total emissions for each region. Emissions from international aviation and shipping are not included. In the case of two regions, the area for CO_2-LULUCF is below the axis, indicating net CO_2 removals rather than emissions. **Panel (c)** shows global net anthropogenic GHG emissions by region (in $GtCO_2$-eq yr^{-1} (GWP100-AR6)) for the time period 1990–2019. Percentage values refer to the contribution of each region to total GHG emissions in each respective time period. The single-year peak of emissions in 1997 was due to higher CO_2-LULUCF emissions from a forest and peat fire event in South East Asia. Regions are as grouped in Annex II of WGIII. **Panel (d)** shows population, gross domestic product (GDP) per person, emission indicators by region in 2019 for total GHG per person, and total GHG emissions intensity, together with production-based and consumption-based CO_2-FFI data, which is assessed in this report up to 2018. Consumption-based emissions are emissions released to the atmosphere in order to generate the goods and services consumed by a certain entity (e.g., region). Emissions from international aviation and shipping are not included. *{WGIII Figure SPM.2}*

2.1.2. Observed Climate System Changes and Impacts to Date

It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred (Table 2.1). The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years. It is *very likely* that GHG emissions were the main driver[74] of tropospheric warming and *extremely likely* that human-caused stratospheric ozone depletion was the main driver of stratospheric cooling between 1979 and the mid-1990s. It is *virtually certain* that the global upper ocean (0-700m) has warmed since the 1970s and *extremely likely* that human influence is the main driver. Ocean warming accounted for 91% of the heating in the climate system, with land warming, ice loss and atmospheric warming accounting for about 5%, 3% and 1%, respectively (*high confidence*). Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1]mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to –4.2] mm yr^{-1} between 2006 and 2018 (*high confidence*). Human influence was *very likely* the main driver of these increases since at least 1971 (Figure 3.4). Human influence is *very likely* the main driver of the global retreat of glaciers since the 1990s and the decrease in Arctic sea ice area between 1979–1988 and 2010–2019. Human influence has also *very likely* contributed to decreased Northern Hemisphere spring snow cover and surface melting of the Greenland ice sheet. It is *virtually* certain that human-caused CO_2 emissions are the main driver of current global acidification of the surface open ocean. {*WGI SPM A.1, WGI SPM A.1.3, WGI SPM A.1.5, WGI SPM A.1.6, WG1 SPM A1.7, WGI SPM A.2, WG1.SPM A.4.2; SROCC SPM.A.1, SROCC SPM A.2*}

Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5 (Figure 2.3). It is *virtually* certain that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s (Figure 2.3), while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-caused climate change is the main driver of these changes. Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006. The frequency and intensity of heavy precipitation events have increased since the 1950s over most land areas for which observational data are sufficient for trend analysis (*high confidence*), and human-caused climate change is *likely* the main driver (Figure 2.3). Human-caused climate change has contributed to increases in agricultural and ecological droughts in some regions due to increased land evapotranspiration (*medium confidence*) (Figure 2.3). It is *likely* that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades. {*WGI SPM A.3, WGI SPM A3.1, WGI SPM A3.2; WGI SPM A3.4; SRCCL SPM.A.2.2; SROCC SPM. A.2*}

Climate change has caused substantial damages, and increasingly irreversible[75] losses, in terrestrial, freshwater, cryospheric and coastal and open ocean ecosystems (*high confidence*). The extent and magnitude of climate change impacts are larger than estimated in previous assessments (*high confidence*). Approximately half of the species assessed globally have shifted polewards or, on land, also to higher elevations (*very high confidence*). Biological responses including changes in geographic placement and shifting seasonal timing are often not sufficient to cope with recent climate change (*very high confidence*). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (*high confidence*) and mass mortality events on land and in the ocean (*very high confidence*). Impacts on some ecosystems are approaching irreversibility such as the impacts of hydrological changes resulting from the retreat of glaciers, or the changes in some mountain (*medium confidence*) and Arctic ecosystems driven by permafrost thaw (*high confidence*). Impacts in ecosystems from slow-onset processes such as ocean acidification, sea level rise or regional decreases in precipitation have also been attributed to human-caused climate change (*high confidence*). Climate change has contributed to desertification and exacerbated land degradation, particularly in low lying coastal areas, river deltas, drylands and in permafrost areas (*high confidence*). Nearly 50% of coastal wetlands have been lost over the last 100 years, as a result of the combined effects of localised human pressures, sea level rise, warming and extreme climate events (*high confidence*). {*WGII SPM B.1.1, WGII SPM B.1.2, WGII Figure SPM.2.A, WGII TS.B.1; SRCCL SPM A.1.5, SRCCL SPM A.2, SRCCL SPM A.2.6, SRCCL Figure SPM.1; SROCC SPM A.6.1, SROCC SPM, A.6.4, SROCC SPM A.7*}

[74] 'Main driver' means responsible for more than 50% of the change. {*WGI SPM footnote 12*}

[75] See Annex I: Glossary.

Table 2.1: Assessment of observed changes in large-scale indicators of mean climate across climate system components, and their attribution to human influence. The colour coding indicates the assessed confidence in / likelihood[76] of the observed change and the human contribution as a driver or main driver (specified in that case) where available (see colour key). Otherwise, explanatory text is provided. {*WGI Table TS.1*}

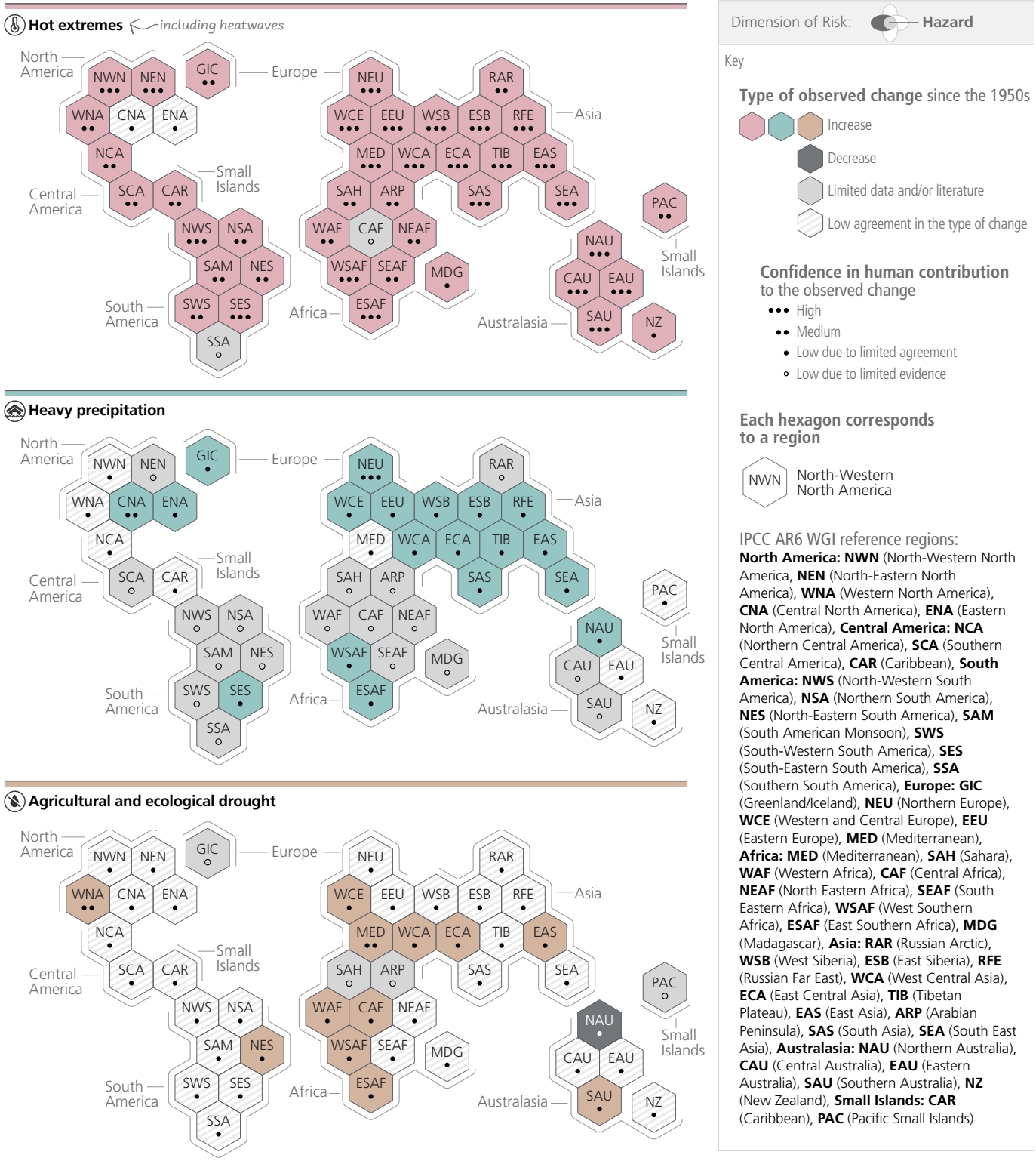
Change in indicator		Observed change assessment	Human contribution assessment
Atmosphere and water cycle	Warming of global mean surface air temperature since 1850-1900		*likely* range of human contribution ([0.8-1.3°C]) encompasses the very likely range of observed warming ([0.9-1.2°C])
	Warming of the troposphere since 1979		Main driver
	Cooling of the lower stratosphere since the mid-20th century		Main driver 1979 - mid-1990s
	Large-scale precipitation and upper troposphere humidity changes since 1979		
	Expansion of the zonal mean Hadley Circulation since the 1980s		Southern Hemisphere
Ocean	Ocean heat content increase since the 1970s		Main driver
	Salinity changes since the mid-20th century		
	Global mean sea level rise since 1970		Main driver
Cryosphere	Arctic sea ice loss since 1979		Main driver
	Reduction in Northern Hemisphere springtime snow cover since 1950		
	Greenland ice sheet mass loss since 1990s		
	Antarctic ice sheet mass loss since 1990s		*Limited evidence & medium agreement*
	Retreat of glaciers		Main driver
Carbon cycle	Increased amplitude of the seasonal cycle of atmospheric CO_2 since the early 1960s		Main driver
	Acidification of the global surface ocean		Main driver
Land climate	Mean surface air temperature over land (about 40% larger than global mean warming)		Main driver
Synthesis	Warming of the global climate system since preindustrial times		

Key: *medium confidence* | *likely / high confidence* | *very likely* | *extremely likely* | *virtually certain* | fact

[76] Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence indicated using the IPCC calibrated language.

Climate change has impacted human and natural systems across the world with those who have generally least contributed to climate change being most vulnerable

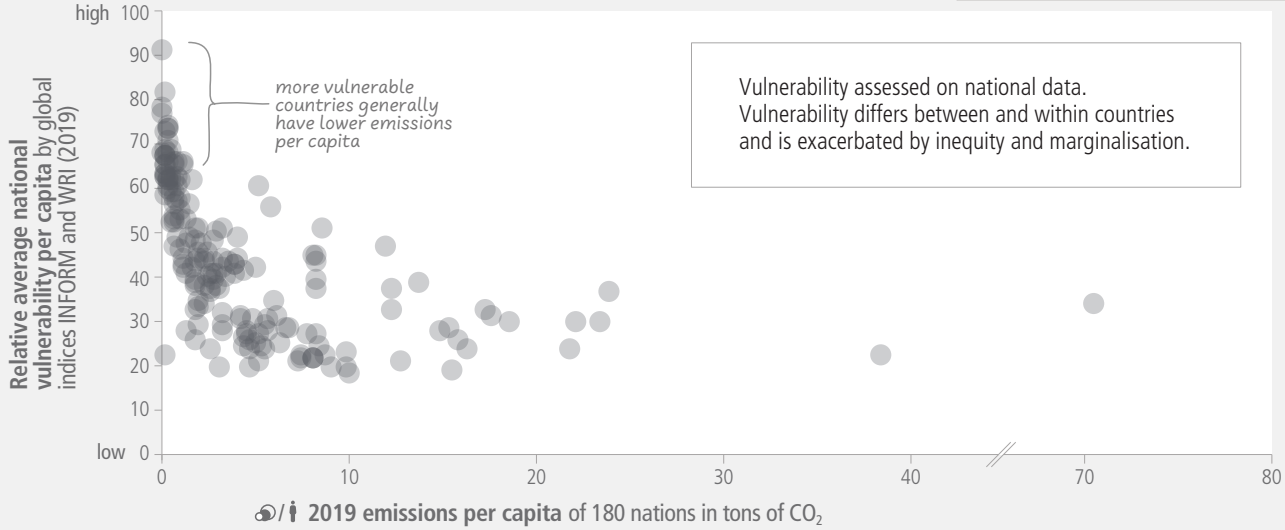
a) **Synthesis of assessment of observed change in hot extremes, heavy precipitation and drought, and confidence in human contribution to the observed changes in the world's regions**



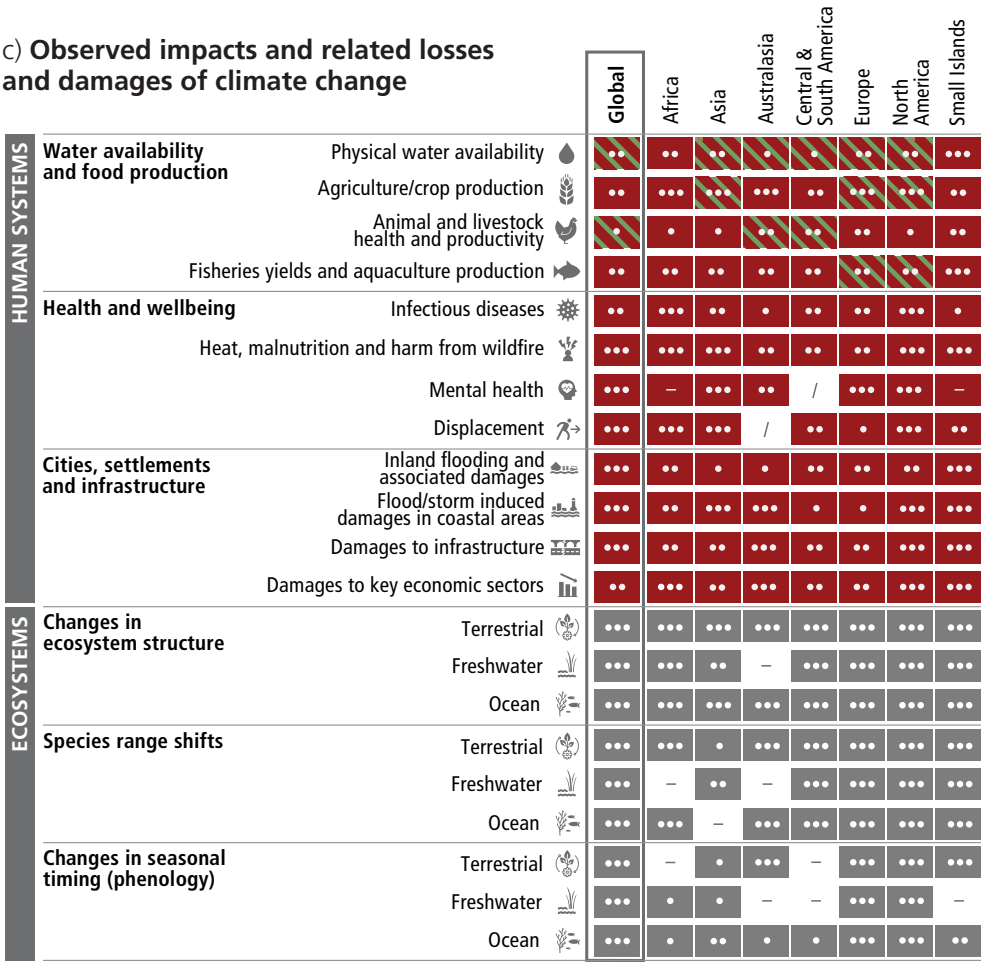
IPCC AR6 WGI reference regions:
North America: NWN (North-Western North America, **NEN** (North-Eastern North America), **WNA** (Western North America), **CNA** (Central North America), **ENA** (Eastern North America), **Central America: NCA** (Northern Central America), **SCA** (Southern Central America), **CAR** (Caribbean), **South America: NWS** (North-Western South America), **NSA** (Northern South America), **NES** (North-Eastern South America), **SAM** (South American Monsoon), **SWS** (South-Western South America), **SES** (South-Eastern South America), **SSA** (Southern South America), **Europe: GIC** (Greenland/Iceland), **NEU** (Northern Europe), **WCE** (Western and Central Europe), **EEU** (Eastern Europe), **MED** (Mediterranean), **Africa: MED** (Mediterranean), **SAH** (Sahara), **WAF** (Western Africa), **CAF** (Central Africa), **NEAF** (North Eastern Africa), **SEAF** (South Eastern Africa), **WSAF** (West Southern Africa), **ESAF** (East Southern Africa), **MDG** (Madagascar), **Asia: RAR** (Russian Arctic), **WSB** (West Siberia), **ESB** (East Siberia), **RFE** (Russian Far East), **WCA** (West Central Asia), **ECA** (East Central Asia), **TIB** (Tibetan Plateau), **EAS** (East Asia), **ARP** (Arabian Peninsula), **SAS** (South Asia), **SEA** (South East Asia), **Australasia: NAU** (Northern Australia), **CAU** (Central Australia), **EAU** (Eastern Australia), **SAU** (Southern Australia), **NZ** (New Zealand), **Small Islands: CAR** (Caribbean), **PAC** (Pacific Small Islands)

b) **Vulnerability of population & per capita emissions per country in 2019**

Dimension of Risk: **Vulnerability**



c) **Observed impacts and related losses and damages of climate change**



Dimension of Risk: **Impact**

Key

Increased climate impacts

HUMAN SYSTEMS
- Adverse impacts
- Adverse and positive impacts

ECOSYSTEMS
- Climate-driven changes observed, no assessment of impact direction

Confidence in attribution to climate change
- ••• *High or very high*
- •• *Medium*
- • *Low*
- – Evidence limited, insufficient
- / Not assessed

Figure 2.3: Both vulnerability to current climate extremes and historical contribution to climate change are highly heterogeneous with many of those who have least contributed to climate change to date being most vulnerable to its impacts. Panel (a) The IPCC AR6 WGI inhabited regions are displayed as hexagons with identical size in their approximate geographical location (see legend for regional acronyms). All assessments are made for each region as a whole and for the 1950s to the present. Assessments made on different time scales or more local spatial scales might differ from what is shown in the figure. The colours in each panel represent the four outcomes of the assessment on observed changes. Striped hexagons (white and light-grey) are used where there is *low agreement* in the type of change for the region as a whole, and grey hexagons are used when there is limited data and/or literature that prevents an assessment of the region as a whole. Other colours indicate at least *medium confidence* in the observed change. The confidence level for the human influence on these observed changes is based on assessing trend detection and attribution and event attribution literature, and it is indicated by the number of dots: three dots for *high confidence*, two dots for *medium confidence* and one dot for *low confidence* (single, filled dot: *limited agreement*; single, empty dot: *limited evidence*). For hot extremes, the evidence is mostly drawn from changes in metrics based on daily maximum temperatures; regional studies using other indices (heatwave duration, frequency and intensity) are used in addition. For heavy precipitation, the evidence is mostly drawn from changes in indices based on one-day or five-day precipitation amounts using global and regional studies. Agricultural and ecological droughts are assessed based on observed and simulated changes in total column soil moisture, complemented by evidence on changes in surface soil moisture, water balance (precipitation minus evapotranspiration) and indices driven by precipitation and atmospheric evaporative demand. **Panel (b)** shows the average level of vulnerability amongst a country's population against 2019 CO_2-FFI emissions per- capita per country for the 180 countries for which both sets of metrics are available. Vulnerability information is based on two global indicator systems, namely INFORM and World Risk Index. Countries with a relatively low average vulnerability often have groups with high vulnerability within their population and vice versa. The underlying data includes, for example, information on poverty, inequality, health care infrastructure or insurance coverage. **Panel (c)** Observed impacts on ecosystems and human systems attributed to climate change at global and regional scales. Global assessments focus on large studies, multi-species, meta-analyses and large reviews. Regional assessments consider evidence on impacts across an entire region and do not focus on any country in particular. For human systems, the direction of impacts is assessed and both adverse and positive impacts have been observed e.g., adverse impacts in one area or food item may occur with positive impacts in another area or food item (for more details and methodology see WGII SMTS.1). Physical water availability includes balance of water available from various sources including ground water, water quality and demand for water. Global mental health and displacement assessments reflect only assessed regions. Confidence levels reflect the assessment of attribution of the observed impact to climate change. *{WGI Figure SPM.3, Table TS.5, Interactive Atlas; WGII Figure SPM.2, WGII SMTS.1, WGII 8.3.1, Figure 8.5; ; WGIII 2.2.3}*

Climate change has reduced food security and affected water security due to warming, changing precipitation patterns, reduction and loss of cryospheric elements, and greater frequency and intensity of climatic extremes, thereby hindering efforts to meet Sustainable Development Goals (*high confidence*). Although overall agricultural productivity has increased, climate change has slowed this growth in agricultural productivity over the past 50 years globally (*medium confidence*), with related negative crop yield impacts mainly recorded in mid- and low latitude regions, and some positive impacts in some high latitude regions (*high confidence*). Ocean warming in the 20th century and beyond has contributed to an overall decrease in maximum catch potential (*medium confidence*), compounding the impacts from overfishing for some fish stocks (*high confidence*). Ocean warming and ocean acidification have adversely affected food production from shellfish aquaculture and fisheries in some oceanic regions (*high confidence*). Current levels of global warming are associated with moderate risks from increased dryland water scarcity (*high confidence*). Roughly half of the world's population currently experiences severe water scarcity for at least some part of the year due to a combination of climatic and non-climatic drivers (*medium confidence*) (Figure 2.3). Unsustainable agricultural expansion, driven in part by unbalanced diets[77], increases ecosystem and human vulnerability and leads to competition for land and/or water resources (*high confidence*). Increasing weather and climate extreme events have exposed millions of people to acute food insecurity[78] and reduced water security, with the largest impacts observed in many locations and/or communities in Africa, Asia, Central and South America, LDCs, Small Islands and the Arctic, and for small-scale food producers, low-income households and Indigenous Peoples globally (*high confidence*). *{WGII SPM B.1.3, WGII SPM.B.2.3, WGII Figure SPM.2, WGII TS B.2.3, WGII TS Figure TS. 6; SRCCL SPM A.2.8, SRCCL SPM A.5.3; SROCC SPM A.5.4., SROCC SPM A.7.1, SROCC SPM A.8.1, SROCC Figure SPM.2}*

In urban settings, climate change has caused adverse impacts on human health, livelihoods and key infrastructure (*high confidence*). Hot extremes including heatwaves have intensified in cities (*high confidence*), where they have also worsened air pollution events (*medium confidence*) and limited functioning of key infrastructure (*high confidence*). Urban infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events[79], with resulting economic losses, disruptions of services and impacts to well-being (*high confidence*). Observed impacts are concentrated amongst economically and socially marginalised urban residents, e.g., those living in informal settlements (*high confidence*). Cities intensify human-caused warming locally (*very high confidence*), while urbanisation also increases mean and heavy precipitation over and/or downwind of cities (*medium confidence*) and resulting runoff intensity (*high confidence*). {*WGI SPM C.2.6; WGII SPM B.1.5, WGII Figure TS.9, WGII 6 ES*}

Climate change has adversely affected human physical health globally and mental health in assessed regions (*very high confidence*), and is contributing to humanitarian crises where climate hazards interact with high vulnerability (*high confidence*). In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*). The occurrence of climate-related food-borne and water-borne diseases has increased (*very high confidence*). The incidence of vector-borne diseases has increased from range expansion and/or increased reproduction of disease vectors (*high confidence*). Animal and human diseases, including zoonoses, are emerging in new areas (*high confidence*). In assessed regions, some mental health challenges are associated with increasing temperatures (*high confidence*), trauma from extreme events (*very high confidence*), and loss of livelihoods and culture

[77] Balanced diets feature plant-based foods, such as those based on coarse grains, legumes fruits and vegetables, nuts and seeds, and animal-source foods produced in resilient, sustainable and low-GHG emissions systems, as described in SRCCL. {*WGII SPM Footnote 32*}

[78] Acute food insecurity can occur at any time with a severity that threatens lives, livelihoods or both, regardless of the causes, context or duration, as a result of shocks risking determinants of food security and nutrition, and is used to assess the need for humanitarian action. {*WGII SPM, footnote 30*}

[79] Slow-onset events are described among the climatic-impact drivers of the AR6 WGI and refer to the risks and impacts associated with e.g., increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization. {*WGII SPM footnote 29*}

(*high confidence*) (Figure 2.3). Climate change impacts on health are mediated through natural and human systems, including economic and social conditions and disruptions (*high confidence*). Climate and weather extremes are increasingly driving displacement in Africa, Asia, North America (*high confidence*), and Central and South America (*medium confidence*) (Figure 2.3), with small island states in the Caribbean and South Pacific being disproportionately affected relative to their small population size (*high confidence*). Through displacement and involuntary migration from extreme weather and climate events, climate change has generated and perpetuated vulnerability (*medium confidence*). {*WGII SPM B.1.4, WGII SPM B.1.7*}

Human influence has *likely* increased the chance of compound extreme events[80] since the 1950s. Concurrent and repeated climate hazards have occurred in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (*high confidence*). Compound extreme events include increases in the frequency of concurrent heatwaves and droughts (*high confidence*); fire weather in some regions (*medium confidence*); and compound flooding in some locations (*medium confidence*). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (*high confidence*). Compound climate hazards can overwhelm adaptive capacity and substantially increase damage (*high confidence*)*)*. {*WGI SPM A.3.5; WGII SPM. B.5.1, WGII TS.C.11.3*}

Economic impacts attributable to climate change are increasingly affecting peoples' livelihoods and are causing economic and societal impacts across national boundaries (*high confidence*). Economic damages from climate change have been detected in climate-exposed sectors, with regional effects to agriculture, forestry, fishery, energy, and tourism, and through outdoor labour productivity (*high confidence*) with some exceptions of positive impacts in regions with low energy demand and comparative advantages in agricultural markets and tourism (*high confidence*). Individual livelihoods have been affected through changes in agricultural productivity, impacts on human health and food security, destruction of homes and infrastructure, and loss of property and income, with adverse effects on gender and social equity (*high confidence*). Tropical cyclones have reduced economic growth in the short-term (*high confidence*). Event attribution studies and physical understanding indicate that human-caused climate change increases heavy precipitation associated with tropical cyclones (*high confidence*). Wildfires in many regions have affected built assets, economic activity, and health (*medium* to *high confidence*). In cities and settlements, climate impacts to key infrastructure are leading to losses and damages across water and food systems, and affect economic activity, with impacts extending beyond the area directly impacted by the climate hazard (*high confidence*). {*WGI SPM A.3.4; WGII SPM B.1.6, WGII SPM B.5.2, WGII SPM B.5.3*}

Climate change has caused widespread adverse impacts and related losses and damages to nature and people (*high confidence*). Losses and damages are unequally distributed across systems, regions and sectors (*high confidence*). Cultural losses, related to tangible and intangible heritage, threaten adaptive capacity and may result in irrevocable losses of sense of belonging, valued cultural practices, identity and home, particularly for Indigenous Peoples and those more directly reliant on the environment for subsistence (*medium confidence*). For example, changes in snow cover, lake and river ice, and permafrost in many Arctic regions, are harming the livelihoods and cultural identity of Arctic residents including Indigenous populations (*high confidence*). Infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events, with resulting economic losses, disruptions of services and impacts to well-being (*high confidence*). {*WGII SPM B.1, WGII SPM B.1.2, WGII SPM.B.1.5, WGII SPM C.3.5, WGII TS.B.1.6; SROCC SPM A.7.1*}

Across sectors and regions, the most vulnerable people and systems have been disproportionately affected by the impacts of climate change (*high confidence*). LDCs and SIDS who have much lower per capita emissions (1.7 tCO_2-eq, 4.6 tCO_2-eq, respectively) than the global average (6.9 tCO_2-eq) excluding CO_2-LULUCF, also have high vulnerability to climatic hazards, with global hotspots of high human vulnerability observed in West-, Central- and East Africa, South Asia, Central and South America, SIDS and the Arctic (*high confidence*). Regions and people with considerable development constraints have high vulnerability to climatic hazards (*high confidence*). Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (*high confidence*). Vulnerability at different spatial levels is exacerbated by inequity and marginalisation linked to gender, ethnicity, low income or combinations thereof (*high confidence*), especially for many Indigenous Peoples and local communities (*high confidence*). Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*). Between 2010 and 2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability (*high confidence*). In the Arctic and in some high mountain regions, negative impacts of cryosphere change have been especially felt among Indigenous Peoples (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Vulnerability of ecosystems and people to climate change differs substantially among and within regions (*very high confidence*), driven by patterns of intersecting socio-economic development, unsustainable ocean and land use, inequity, marginalisation, historical and ongoing patterns of inequity such as colonialism, and governance[81] (*high confidence*). {*WGII SPM B.1, WGII SPM B.2, WGII SPM B.2.4; WGIII SPM B.3.1; SROCC SPM A.7.1, SROCC SPM A.7.2*}

[80] See Annex 1: Glossary.

[81] Governance: The structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local. {*WGII SPM Footnote 31*}

2.2 Responses Undertaken to Date

International climate agreements, rising national ambitions for climate action, along with rising public awareness are accelerating efforts to address climate change at multiple levels of governance. Mitigation policies have contributed to a decrease in global energy and carbon intensity, with several countries achieving GHG emission reductions for over a decade. Low-emission technologies are becoming more affordable, with many low or zero emissions options now available for energy, buildings, transport, and industry. Adaptation planning and implementation progress has generated multiple benefits, with effective adaptation options having the potential to reduce climate risks and contribute to sustainable development. Global tracked finance for mitigation and adaptation has seen an upward trend since AR5, but falls short of needs. (*high confidence*)

2.2.1. Global Policy Setting

The United Nations Framework Convention on Climate Change (UNFCCC), Kyoto Protocol, and Paris Agreement are supporting rising levels of national ambition and encouraging the development and implementation of climate policies at multiple levels of governance (*high confidence*). The Kyoto Protocol led to reduced emissions in some countries and was instrumental in building national and international capacity for GHG reporting, accounting and emissions markets (*high confidence*). The Paris Agreement, adopted under the UNFCCC, with near universal participation, has led to policy development and target-setting at national and sub-national levels, particularly in relation to mitigation but also for adaptation, as well as enhanced transparency of climate action and support (*medium confidence*). Nationally Determined Contributions (NDCs), required under the Paris Agreement, have required countries to articulate their priorities and ambition with respect to climate action. {*WGII 17.4, WGII TS D.1.1; WGIII SPM B.5.1, WGIII SPM E.6*}

Loss & Damage[82] was formally recognized in 2013 through establishment of the Warsaw International Mechanism on Loss and Damage (WIM), and in 2015, Article 8 of the Paris Agreement provided a legal basis for the WIM. There is improved understanding of both economic and non-economic losses and damages, which is informing international climate policy and which has highlighted that losses and damages are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries (*high confidence*). {*WGII SPM C.3.5, WGII Cross-Chapter Box LOSS*}

Other recent global agreements that influence responses to climate change include the Sendai Framework for Disaster Risk Reduction (2015-2030), the finance-oriented Addis Ababa Action Agenda (2015) and the New Urban Agenda (2016), and the Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (2016), among others. In addition, the 2030 Agenda for Sustainable Development, adopted in 2015 by UN member states, sets out 17 Sustainable Development Goals (SDGs) and seeks to align efforts globally to prioritise ending extreme poverty, protect the planet and promote more peaceful, prosperous and inclusive societies. If achieved, these agreements would reduce climate change, and the impacts on health, well-being, migration, and conflict, among others (*very high confidence*). {*WGII TS.A.1, WGII 7 ES*}

Since AR5, rising public awareness and an increasing diversity of actors, have overall helped accelerate political commitment and global efforts to address climate change (*medium confidence*). Mass social movements have emerged as catalysing agents in some regions, often building on prior movements including Indigenous Peoples-led movements, youth movements, human rights movements, gender activism, and climate litigation, which is raising awareness and, in some cases, has influenced the outcome and ambition of climate governance (*medium confidence*). Engaging Indigenous Peoples and local communities using just-transition and rights-based decision-making approaches, implemented through collective and participatory decision-making processes has enabled deeper ambition and accelerated action in different ways, and at all scales, depending on national circumstances (*medium confidence*). The media helps shape the public discourse about climate change. This can usefully build public support to accelerate climate action (*medium evidence, high agreement*). In some instances, public discourses of media and organised counter movements have impeded climate action, exacerbating helplessness and disinformation and fuelling polarisation, with negative implications for climate action (*medium confidence*). {*WGII SPM C.5.1, WGII SPM D.2, WGII TS.D.9, WGII TS.D.9.7, WGII TS.E.2.1, WGII 18.4; WGIII SPM D.3.3, WGIII SPM E.3.3, WGIII TS.6.1, WGIII 6.7, WGIII 13 ES, WGIII Box.13.7*}

2.2.2. Mitigation Actions to Date

There has been a consistent expansion of policies and laws addressing mitigation since AR5 (*high confidence*). Climate governance supports mitigation by providing frameworks through which diverse actors interact, and a basis for policy development and implementation (*medium confidence*). Many regulatory and economic instruments have already been deployed successfully (*high confidence*). By 2020, laws primarily focussed on reducing GHG emissions existed in 56 countries covering 53% of global emissions (*medium confidence*). The application of diverse policy instruments for mitigation at the national and sub-national levels has grown consistently across a range of sectors (*high confidence*). Policy coverage is uneven across sectors and remains limited for emissions from agriculture, and from industrial materials and feedstocks (*high confidence*). {*WGIII SPM B.5, WGIII SPM B.5.2, WGIII SPM E.3, WGIII SPM E.4*}

Practical experience has informed economic instrument design and helped to improve predictability, environmental effectiveness, economic efficiency, alignment with distributional goals, and social acceptance (*high confidence*). Low-emission technological innovation is strengthened through the combination of technology-push policies, together with policies that create incentives for behaviour change and market opportunities (*high confidence*) (Section 4.8.3). Comprehensive and consistent policy packages have been found to be more effective

[82] See Annex I: Glossary.

than single policies (*high confidence*). Combining mitigation with policies to shift development pathways, policies that induce lifestyle or behaviour changes, for example, measures promoting walkable urban areas combined with electrification and renewable energy can create health co-benefits from cleaner air and enhanced active mobility (*high confidence*). Climate governance enables mitigation by providing an overall direction, setting targets, mainstreaming climate action across policy domains and levels, based on national circumstances and in the context of international cooperation. Effective governance enhances regulatory certainty, creating specialised organisations and creating the context to mobilise finance (*medium confidence*). These functions can be promoted by climate-relevant laws, which are growing in number, or climate strategies, among others, based on national and sub-national context (*medium confidence*). Effective and equitable climate governance builds on engagement with civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples and local communities (*medium confidence*). {*WGIII SPM E.2.2, WGIII SPM E.3, WGIII SPM E.3.1, WGIII SPM E.4.2, WGIII SPM E.4.3, WGIII SPM E.4.4*}

The unit costs of several low-emission technologies, including solar, wind and lithium-ion batteries, have fallen consistently since 2010 (Figure 2.4). Design and process innovations in combination with the use of digital technologies have led to near-commercial availability of many low or zero emissions options in buildings, transport and industry. From 2010-2019, there have been sustained decreases in the unit costs of solar energy (by 85%), wind energy (by 55%), and lithium-ion batteries (by 85%), and large increases in their deployment, e.g., >10× for solar and >100× for electric vehicles (EVs), albeit varying widely across regions (Figure 2.4). Electricity from PV and wind is now cheaper than electricity from fossil sources in many regions, electric vehicles are increasingly competitive with internal combustion engines, and large-scale battery storage on electricity grids is increasingly viable. In comparison to modular small-unit size technologies, the empirical record shows that multiple large-scale mitigation technologies, with fewer opportunities for learning, have seen minimal cost reductions and their adoption has grown slowly. Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems. (*high confidence*) {*WGIII SPM B.4, WGIII SPM B.4.1, WGIII SPM C.4.2, WGIII SPM C.5.2, WGIII SPM C.7.2, WGIII SPM C.8, WGIII Figure SPM.3, WGIII Figure SPM.3*}

For almost all basic materials – primary metals, building materials and chemicals – many low- to zero-GHG intensity production processes are at the pilot to near-commercial and in some cases commercial stage but they are not yet established industrial practice. Integrated design in construction and retrofit of buildings has led to increasing examples of zero energy or zero carbon buildings. Technological innovation made possible the widespread adoption of LED lighting. Digital technologies including sensors, the internet of things, robotics, and artificial intelligence can improve energy management in all sectors; they can increase energy efficiency, and promote the adoption of many low-emission technologies, including decentralised renewable energy, while creating economic opportunities. However, some of these climate change mitigation gains can be reduced or counterbalanced by growth in demand for goods and services due to the use of digital devices. Several mitigation options, notably solar energy, wind energy, electrification of urban systems, urban green infrastructure, energy efficiency, demand side management, improved forest- and crop/grassland management, and reduced food waste and loss, are technically viable, are becoming increasingly cost effective and are generally supported by the public, and this enables expanded deployment in many regions. (*high confidence*) {*WGIII SPM B.4.3, WGIII SPM C.5.2, WGIII SPM C.7.2, WGIII SPM E.1.1, WGIII TS.6.5*}

The magnitude of global climate finance flows has increased and financing channels have broadened (*high confidence*). Annual tracked total financial flows for climate mitigation and adaptation increased by up to 60% between 2013/14 and 2019/20, but average growth has slowed since 2018 (*medium confidence*) and most climate finance stays within national borders (*high confidence*). Markets for green bonds, environmental, social and governance and sustainable finance products have expanded significantly since AR5 (*high confidence*). Investors, central banks, and financial regulators are driving increased awareness of climate risk to support climate policy development and implementation (*high confidence*). Accelerated international financial cooperation is a critical enabler of low-GHG and just transitions (*high confidence*). {*WGIII SPM B.5.4, WGIII SPM E.5, WGIII TS.6.3, WGIII TS.6.4*}

Economic instruments have been effective in reducing emissions, complemented by regulatory instruments mainly at the national and also sub-national and regional level (*high confidence*). By 2020, over 20% of global GHG emissions were covered by carbon taxes or emissions trading systems, although coverage and prices have been insufficient to achieve deep reductions (*medium confidence*). Equity and distributional impacts of carbon pricing instruments can be addressed by using revenue from carbon taxes or emissions trading to support low-income households, among other approaches (*high confidence*). The mix of policy instruments which reduced costs and stimulated adoption of solar energy, wind energy and lithium-ion batteries includes public R&D, funding for demonstration and pilot projects, and demand-pull instruments such as deployment subsidies to attain scale (*high confidence*) (Figure 2.4). {*WGIII SPM B.4.1, WGIII SPM B.5.2, WGIII SPM E.4.2, WG III TS.3*}

Mitigation actions, supported by policies, have contributed to a decrease in global energy and carbon intensity between 2010 and 2019, with a growing number of countries achieving absolute GHG emission reductions for more than a decade (*high confidence*). While global net GHG emissions have increased since 2010, global energy intensity (total primary energy per unit GDP) decreased by 2% yr^{-1} between 2010 and 2019. Global carbon intensity (CO_2-FFI per unit primary energy) also decreased by 0.3% yr^{-1}, mainly due to fuel switching from coal to gas, reduced expansion of coal capacity, and increased use of renewables, and with large regional variations over the same period. In many countries, policies have enhanced energy efficiency, reduced rates of deforestation and accelerated technology deployment, leading to avoided and in some cases reduced or removed emissions (*high confidence*). At least 18 countries have sustained production-based CO_2 and GHG and consumption-based CO_2 absolute emission reductions for longer than 10 years since 2005 through energy supply decarbonization, energy efficiency gains, and energy demand reduction, which resulted from both policies and changes in economic structure (*high confidence*). Some countries have reduced production-based GHG emissions by a third or more since peaking, and some have achieved reduction rates of around 4% yr^{-1} for several years consecutively (*high confidence*). Multiple lines of evidence suggest that mitigation policies have led to avoided global emissions of several $GtCO_2$-eq yr^{-1} (*medium confidence*).

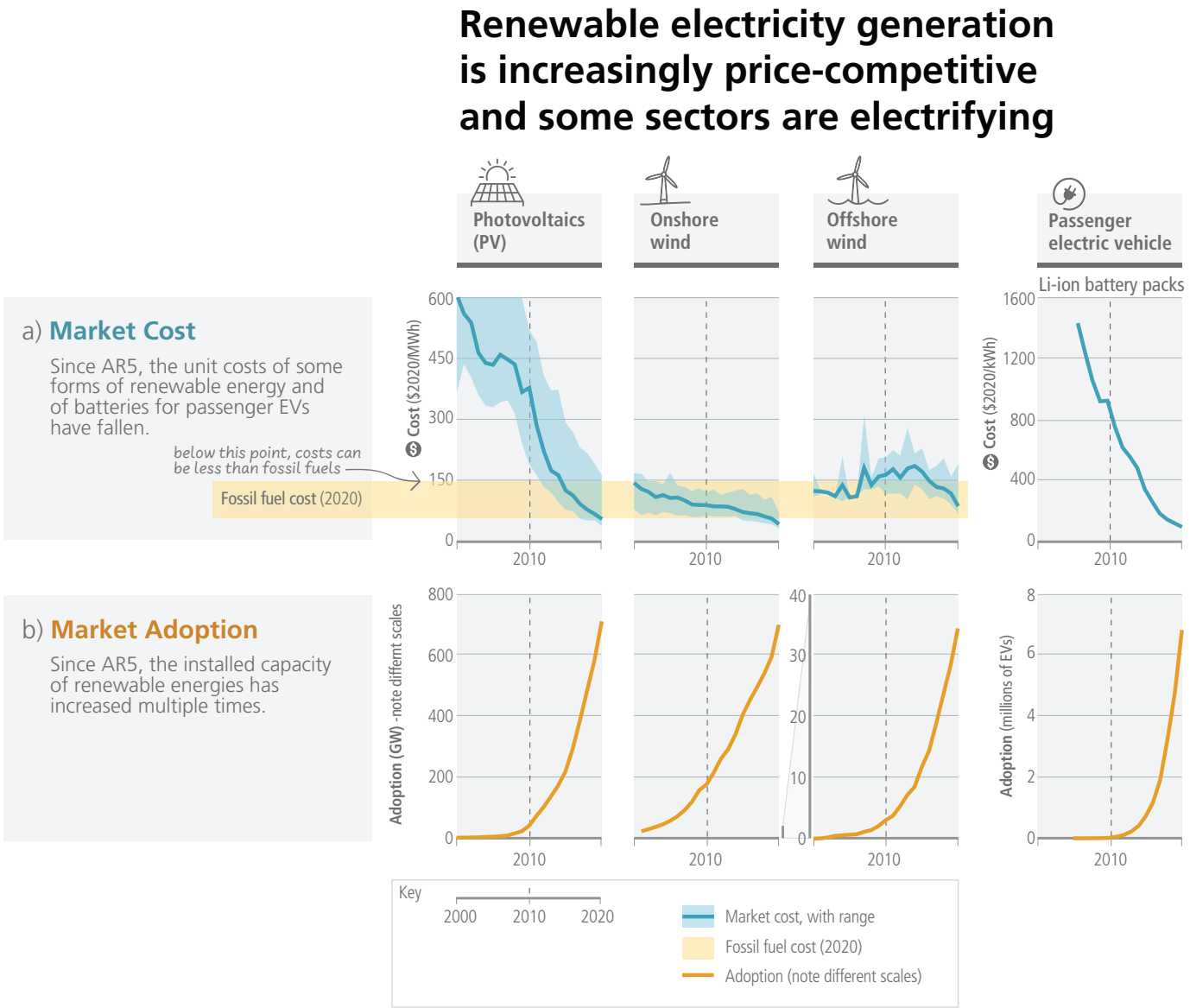


Figure 2.4: Unit cost reductions and use in some rapidly changing mitigation technologies. The **top panel (a)** shows global costs per unit of energy (USD per MWh) for some rapidly changing mitigation technologies. Solid blue lines indicate average unit cost in each year. Light blue shaded areas show the range between the 5th and 95th percentiles in each year. Yellow shading indicates the range of unit costs for new fossil fuel (coal and gas) power in 2020 (corresponding to USD 55 to 148 per MWh). In 2020, the levelised costs of energy (LCOE) of the three renewable energy technologies could compete with fossil fuels in many places. For batteries, costs shown are for 1 kWh of battery storage capacity; for the others, costs are LCOE, which includes installation, capital, operations, and maintenance costs per MWh of electricity produced. The literature uses LCOE because it allows consistent comparisons of cost trends across a diverse set of energy technologies to be made. However, it does not include the costs of grid integration or climate impacts. Further, LCOE does not take into account other environmental and social externalities that may modify the overall (monetary and non-monetary) costs of technologies and alter their deployment. The **bottom panel (b)** shows cumulative global adoption for each technology, in GW of installed capacity for renewable energy and in millions of vehicles for battery-electric vehicles. A vertical dashed line is placed in 2010 to indicate the change over the past decade. The electricity production share reflects different capacity factors; for example, for the same amount of installed capacity, wind produces about twice as much electricity as solar PV. Renewable energy and battery technologies were selected as illustrative examples because they have recently shown rapid changes in costs and adoption, and because consistent data are available. Other mitigation options assessed in the WGIII report are not included as they do not meet these criteria. {*WGIII Figure SPM.3*, *WGIII 2.5, 6.4*}

At least 1.8 $GtCO_2$-eq yr^{-1} of avoided emissions can be accounted for by aggregating separate estimates for the effects of economic and regulatory instruments (*medium confidence*). Growing numbers of laws and executive orders have impacted global emissions and are estimated to have resulted in 5.9 $GtCO_2$-eq yr^{-1} of avoided emissions in 2016 *(medium confidence)*. These reductions have only partly offset global emissions growth (*high confidence*). {*WGIII SPM B.1, WGIII SPM B.2.4, WGIII SPM B.3.5, WGIII SPM B.5.1, WGIII SPM B.5.3, WGIII 1.3.2, WGIII 2.2.3*}

2.2.3. Adaptation Actions to Date

Progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits (*very high confidence*). The ambition, scope and progress on adaptation have risen among governments at the local, national and international levels, along with businesses, communities and civil society (*high confidence*). Various tools, measures and processes are available that can enable, accelerate and sustain adaptation implementation (*high confidence*). Growing public and political awareness of climate impacts and risks has resulted in at least 170 countries and many cities including adaptation in their climate policies and planning processes (*high confidence*). Decision support tools and climate services are increasingly being used (*very high confidence*) and pilot projects and local experiments are being implemented in different sectors (*high confidence*). {*WGII SPM C.1, WGII SPM.C.1.1, WGII TS.D.1.3, WGII TS.D.10*}

Adaptation to water-related risks and impacts make up the majority (~60%) of all documented[83] adaptation (*high confidence*). A large number of these adaptation responses are in the agriculture sector and these include on-farm water management, water storage, soil moisture conservation, and irrigation. Other adaptations in agriculture include cultivar improvements, agroforestry, community-based adaptation and farm and landscape diversification among others (*high confidence*). For inland flooding, combinations of non-structural measures like early warning systems, enhancing natural water retention such as by restoring wetlands and rivers, and land use planning such as no build zones or upstream forest management, can reduce flood risk (*medium confidence*). Some land-related adaptation actions such as sustainable food production, improved and sustainable forest management, soil organic carbon management, ecosystem conservation and land restoration, reduced deforestation and degradation, and reduced food loss and waste are being undertaken, and can have mitigation co-benefits (*high confidence*). Adaptation actions that increase the resilience of biodiversity and ecosystem services to climate change include responses like minimising additional stresses or disturbances, reducing fragmentation, increasing natural habitat extent, connectivity and heterogeneity, and protecting small-scale refugia where microclimate conditions can allow species to persist (*high confidence*). Most innovations in urban adaptation have occurred through advances in disaster risk management, social safety nets and green/blue infrastructure (*medium confidence*). Many adaptation measures that benefit health and well-being are found in other sectors (e.g., food, livelihoods, social protection, water and sanitation, infrastructure) (*high confidence*). {*WGII SPM C.2.1, WGII SPM C.2.2, WGII TS.D.1.2, WGII TS.D.1.4, WGII TS.D.4.2, WGII TS.D.8.3, WGII 4 ES; SRCCL SPM B.1.1*}

Adaptation can generate multiple additional benefits such as improving agricultural productivity, innovation, health and well-being, food security, livelihood, and biodiversity conservation as well as reduction of risks and damages (*very high confidence*). {*WGII SPM C1.1*}

Globally tracked adaptation finance has shown an upward trend since AR5, but represents only a small portion of total climate finance, is uneven and has developed heterogeneously across regions and sectors (*high confidence*). Adaptation finance has come predominantly from public sources, largely through grants, concessional and non-concessional instruments (*very high confidence*). Globally, private-sector financing of adaptation from a variety of sources such as commercial financial institutions, institutional investors, other private equity, non-financial corporations, as well as communities and households has been limited, especially in developing countries (*high confidence*). Public mechanisms and finance can leverage private sector finance for adaptation by addressing real and perceived regulatory, cost and market barriers, for example via public-private partnerships (*high confidence*). Innovations in adaptation and resilience finance, such as forecast-based/anticipatory financing systems and regional risk insurance pools, have been piloted and are growing in scale (*high confidence*). {*WGII SPM C.3.2, WGII SPM C.5.4; WGII TS.D.1.6, WGII Cross-Chapter Box FINANCE; WGIII SPM E.5.4*}

There are adaptation options which are effective[84] in reducing climate risks[85] for specific contexts, sectors and regions and contribute positively to sustainable development and other societal goals. In the agriculture sector, cultivar improvements, on-farm water management and storage, soil moisture conservation, irrigation[86], agroforestry, community-based adaptation, and farm and landscape level diversification, and sustainable land management approaches, provide multiple benefits and reduce climate risks. Reduction of food loss and waste, and adaptation measures in support of balanced diets contribute to nutrition, health, and biodiversity benefits. (*high confidence*) {*WGII SPM C.2, WGII SPM C.2.1, WGII SPM C.2.2; SRCCL B.2, SRCCL SPM C.2.1*}

Ecosystem-based Adaptation[87] approaches such as urban greening, restoration of wetlands and upstream forest ecosystems reduce a range of climate change risks, including flood risks, urban heat and provide multiple co-benefits. Some land-based adaptation options provide immediate benefits (e.g., conservation of peatlands,

[83] Documented adaptation refers to published literature on adaptation policies, measures and actions that has been implemented and documented in peer reviewed literature, as opposed to adaptation that may have been planned, but not implemented.

[84] Effectiveness refers here to the extent to which an adaptation option is anticipated or observed to reduce climate-related risk.

[85] See Annex I: Glossary.

[86] Irrigation is effective in reducing drought risk and climate impacts in many regions and has several livelihood benefits, but needs appropriate management to avoid potential adverse outcomes, which can include accelerated depletion of groundwater and other water sources and increased soil salinization (*medium confidence*).

[87] EbA is recognised internationally under the Convention on Biological Diversity (CBD14/5). A related concept is Nature-based Solutions (NbS), see Annex I: Glossary.

wetlands, rangelands, mangroves and forests); while afforestation and reforestation, restoration of high-carbon ecosystems, agroforestry, and the reclamation of degraded soils take more time to deliver measurable results. Significant synergies exist between adaptation and mitigation, for example through sustainable land management approaches. Agroecological principles and practices and other approaches that work with natural processes support food security, nutrition, health and well-being, livelihoods and biodiversity, sustainability and ecosystem services. (*high confidence*) {*WGII SPM C.2.1, WGII SPM C.2.2, WGII SPM C.2.5, WGII TS.D.4.1; SRCCL SPM B.1.2, SRCCL SPM.B.6.1; SROCC SPM C.2*}

Combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives in case of inland flooding (*medium confidence*) and early warning systems along with flood-proofing of buildings have proven to be cost-effective in the context of coastal flooding under current sea level rise (*high confidence*). Heat Health Action Plans that include early warning and response systems are effective adaptation options for extreme heat (*high confidence*). Effective adaptation options for water, food and vector-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to extreme weather events, and improved early warning systems, surveillance, and vaccine development (*very high confidence*). Adaptation options such as disaster risk management, early warning systems, climate services and social safety nets have broad applicability across multiple sectors (*high confidence*). {*WGII SPM C.2.1, WGII SPM C.2.5, WGII SPM C.2.9, WGII SPM C.2.11, WGII SPM C.2.13; SROCC SPM C.3.2*}

Integrated, multi-sectoral solutions that address social inequities, differentiate responses based on climate risk and cut across systems, increase the feasibility and effectiveness of adaptation in multiple sectors (*high confidence*). {*WGII SPM C.2*}

2.3 Current Mitigation and Adaptation Actions and Policies are not Sufficient

At the time of the present assessment[88] there are gaps between global ambitions and the sum of declared national ambitions. These are further compounded by gaps between declared national ambitions and current implementation for all aspects of climate action. For mitigation, global GHG emissions in 2030 implied by NDCs announced by October 2021 would make it *likely* that warming will exceed 1.5°C during the 21st century and would make it harder to limit warming below 2°C.[89] Despite progress, adaptation gaps[90] persist, with many initiatives prioritising short-term risk reduction, hindering transformational adaptation. Hard and soft limits to adaptation are being reached in some sectors and regions, while maladaptation is also increasing and disproportionately affecting vulnerable groups. Systemic barriers such as funding, knowledge, and practice gaps, including lack of climate literacy and data hinders adaptation progress. Insufficient financing, especially for adaptation, constraints climate action in particular in developing countries. (*high confidence*)

2.3.1. The Gap Between Mitigation Policies, Pledges and Pathways that Limit Warming to 1.5°C or Below 2°C

Global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26[91] would make it *likely* that warming will exceed 1.5°C during the 21st century and would make it harder to limit warming below 2°C – if no additional commitments are made or actions taken (Figure 2.5, Table 2.2). A substantial 'emissions gap' exists as global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26 would be similar to or only slightly below 2019 emission levels and higher than those associated with modelled mitigation pathways that limit warming to 1.5°C (>50%) with no or limited overshoot or to 2°C (>67%), assuming immediate action, which implies deep, rapid, and sustained global GHG emission reductions this decade (*high confidence*) (Table 2.2, Table 3.1, 4.1).[92] The magnitude of the emissions gap depends on the global warming level considered and whether only unconditional or also conditional elements of NDCs[93] are considered (*high confidence*) (Table 2.2). Modelled pathways that are consistent with NDCs announced prior to COP26 until 2030 and assume no increase in ambition thereafter have higher emissions, leading to a median global warming of 2.8 [2.1 to 3.4]°C by 2100 (*medium confidence*). If the 'emission gap' is not reduced, global GHG emissions in 2030 consistent with NDCs announced prior to COP26 make it *likely* that warming will exceed 1.5°C during the 21st century, while limiting warming to 2°C (>67%) would imply an unprecedented acceleration of mitigation efforts during 2030–2050 (*medium confidence*) (see Section 4.1, Cross-Section Box.2). {*WGIII SPM B.6, WGIII SPM B.6.1, WGIII SPM B.6.3, WGIII SPM B.6.4, WGIII SPM C.1.1*}

Policies implemented by the end of 2020 are projected to result in higher global GHG emissions in 2030 than those implied by NDCs, indicating an 'implementation gap[94]' (*high confidence*) (Table 2.2, Figure 2.5). Projected global emissions implied by policies implemented by the end of 2020 are 57 (52–60) $GtCO_2$-eq in 2030 (Table 2.2). This points to an implementation gap compared with the NDCs of 4 to 7 $GtCO_2$-eq in 2030 (Table 2.2); without a strengthening of policies, emissions are projected to rise, leading to a median global warming of 2.2°C to 3.5°C (*very likely range*) by 2100 (*medium confidence*) (see Section 3.1.1). {*WGIII SPM B.6.1, WGIII SPM C.1*}

88 The timing of various cut-offs for assessment differs by WG report and the aspect assessed. See footnote 58 in Section 1.

89 See CSB.2 for a discussion of scenarios and pathways.

90 See Annex I: Glossary.

91 NDCs announced prior to COP26 refer to the most recent NDCs submitted to the UNFCCC up to the literature cut-off date of the WGIII report, 11 October 2021, and revised NDCs announced by China, Japan and the Republic of Korea prior to October 2021 but only submitted thereafter. 25 NDC updates were submitted between 12 October 2021 and the start of COP26. {*WGIII SPM footnote 24*}

92 Immediate action in modelled global pathways refers to the adoption between 2020 and at latest before 2025 of climate policies intended to limit global warming to a given level. Modelled pathways that limit warming to 2°C (>67%) based on immediate action are summarised in category C3a in Table 3.1. All assessed modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assume immediate action as defined here (Category C1 in Table 3.1). {*WGIII SPM footnote 26*}

93 In this report, 'unconditional' elements of NDCs refer to mitigation efforts put forward without any conditions. 'Conditional' elements refer to mitigation efforts that are contingent on international cooperation, for example bilateral and multilateral agreements, financing or monetary and/or technological transfers. This terminology is used in the literature and the UNFCCC's NDC Synthesis Reports, not by the Paris Agreement. {*WGIII SPM footnote 27*}

94 Implementation gaps refer to how far currently enacted policies and actions fall short of reaching the pledges. The policy cut-off date in studies used to project GHG emissions of 'policies implemented by the end of 2020' varies between July 2019 and November 2020. {*WGIII Table 4.2, WGIII SPM footnote 25*}

Projected cumulative future CO_2 emissions over the lifetime of existing fossil fuel infrastructure without additional abatement[95] exceed the total cumulative net CO_2 emissions in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. They are approximately equal to total cumulative net CO_2 emissions in pathways that limit warming to 2°C with a likelihood of 83%[96] (see Figure 3.5). Limiting warming to 2°C (>67%) or lower will result in stranded assets. About 80% of coal, 50% of gas, and 30% of oil reserves cannot be burned and emitted if warming is limited to 2°C. Significantly more reserves are expected to remain unburned if warming is limited to 1.5°C. (*high confidence*) {*WGIII SPM B.7*, *WGIII Box 6.3*}

Table 2.2 Projected global emissions in 2030 associated with policies implemented by the end of 2020 and NDCs announced prior to COP26, and associated emissions gaps. Emissions projections for 2030 and gross differences in emissions are based on emissions of 52–56 $GtCO_2$-eq yr^{-1} in 2019 as assumed in underlying model studies[97]. (*medium confidence*) {*WGIII Table SPM.1*} (*Table 3.1*, *Cross-Section Box.2*)

Emission and implementation gaps associated with projected global emissions in 2030 under Nationally Determined Contributions (NDCs) and implemented policies

	Implied by policies implemented by the end of 2020 ($GtCO_2$-eq/yr)	Implied by Nationally Determined Contributions (NDCs) announced prior to COP26	
		Unconditional elements ($GtCO_2$-eq/yr)	Including conditional elements ($GtCO_2$-eq/yr)
Median projected global emissions (min–max)*	57 [52–60]	53 [50–57]	50 [47–55]
Implementation gap between implemented policies and NDCs (median)	–	4	7
Emissions gap between NDCs and pathways that limit warming to 2°C (>67%) with immediate action	–	10–16	6–14
Emissions gap between NDCs and pathways that limit warming to 1.5°C (>50%) with no or limited overshoot with immediate action	–	19–26	16–23

*Emissions projections for 2030 and gross differences in emissions are based on emissions of 52–56 $GtCO_2$-eq/yr in 2019 as assumed in underlying model studies. (*medium confidence*)

[95] Abatement here refers to human interventions that reduce the amount of GHGs that are released from fossil fuel infrastructure to the atmosphere. {*WGIII SPM footnote 34*}

[96] WGI provides carbon budgets that are in line with limiting global warming to temperature limits with different likelihoods, such as 50%, 67% or 83%. {*WGI Table SPM.2*}

[97] The 2019 range of harmonised GHG emissions across the pathways [53–58 $GtCO_2$-eq] is within the uncertainty ranges of 2019 emissions assessed in WGIII Chapter 2 [53–66 $GtCO_2$-eq].

Projected global GHG emissions from NDCs announced prior to COP26 would make it *likely* that warming will exceed 1.5°C and also make it harder after 2030 to limit warming to below 2°C

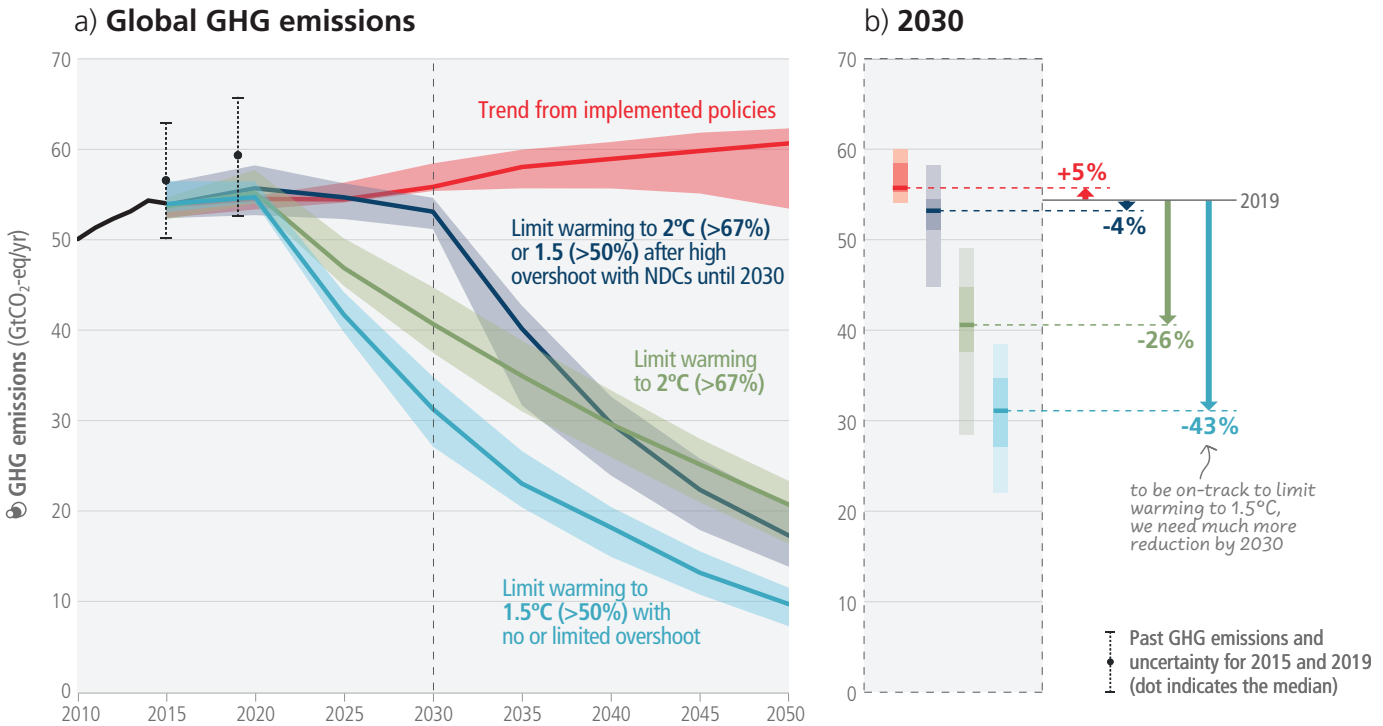


Figure 2.5 Global GHG emissions of modelled pathways (funnels in Panel a), and projected emission outcomes from near-term policy assessments for 2030 (Panel b). **Panel a** shows global GHG emissions over 2015-2050 for four types of assessed modelled global pathways:

- Trend from implemented policies: Pathways with projected near-term GHG emissions in line with policies implemented until the end of 2020 and extended with comparable ambition levels beyond 2030 (29 scenarios across categories C5–C7, WGIII Table SPM.2).
- Limit to 2°C (>67%) or return warming to 1.5°C (>50%) after a high overshoot, NDCs until 2030: Pathways with GHG emissions until 2030 associated with the implementation of NDCs announced prior to COP26, followed by accelerated emissions reductions *likely* to limit warming to 2°C (C3b, WGIII Table SPM.2) or to return warming to 1.5°C with a probability of 50% or greater after high overshoot (subset of 42 scenarios from C2, WGIII Table SPM.2).
- Limit to 2°C (>67%) with immediate action: Pathways that limit warming to 2°C (>67%) with immediate action after 2020 (C3a, WGIII Table SPM.2).
- Limit to 1.5°C (>50%) with no or limited overshoot: Pathways limiting warming to 1.5°C with no or limited overshoot (C1, WGIII Table SPM.2 C1).

All these pathways assume immediate action after 2020. Past GHG emissions for 2010-2015 used to project global warming outcomes of the modelled pathways are shown by a black line. **Panel b** shows a snapshot of the GHG emission ranges of the modelled pathways in 2030 and projected emissions outcomes from near-term policy assessments in 2030 from WGIII Chapter 4.2 (Tables 4.2 and 4.3; median and full range). GHG emissions are CO_2-equivalent using GWP100 from AR6 WGI. {*WGIII Figure SPM.4, WGIII 3.5, 4.2, Table 4.2, Table 4.3, Cross-Chapter Box 4 in Chapter 4*} (*Table 3.1, Cross-Section Box.2*)

Cross-Section Box.1: Understanding Net Zero CO_2 and Net Zero GHG Emissions

Limiting human-caused global warming to a specific level requires limiting cumulative CO_2 emissions, reaching net zero or net negative CO_2 emissions, along with strong reductions in other GHG emissions (see 3.3.2). Future additional warming will depend on future emissions, with total warming dominated by past and future cumulative CO_2 emissions. {*WGI SPM D.1.1, WGI Figure SPM.4; SR1.5 SPM A.2.2*}

Reaching net zero CO_2 emissions is different from reaching net zero GHG emissions. The timing of net zero for a basket of GHGs depends on the emissions metric, such as global warming potential over a 100-year period, chosen to convert non-CO_2 emissions into CO_2-equivalent (*high confidence*). However, for a given emissions pathway, the physical climate response is independent of the metric chosen (*high confidence*). {*WGI SPM D.1.8; WGIII Box TS.6, WGIII Cross-Chapter Box 2*}

Achieving global net zero GHG emissions requires all remaining CO_2 and metric-weighted[98] non-CO_2 GHG emissions to be counterbalanced by durably stored CO_2 removals (*high confidence*). Some non-CO_2 emissions, such as CH_4 and N_2O from agriculture, cannot be fully eliminated using existing and anticipated technical measures. {*WGIII SPM C.2.4, WGIII SPM C.11.4, WGIII Cross-Chapter Box 3*}

Global net zero CO_2 or GHG emissions can be achieved even if some sectors and regions are net emitters, provided that others reach net negative emissions (see Figure 4.1). The potential and cost of achieving net zero or even net negative emissions vary by sector and region. If and when net zero emissions for a given sector or region are reached depends on multiple factors, including the potential to reduce GHG emissions and undertake carbon dioxide removal, the associated costs, and the availability of policy mechanisms to balance emissions and removals between sectors and countries. (*high confidence*) {*WGIII Box TS.6, WGIII Cross-Chapter Box 3*}

The adoption and implementation of net zero emission targets by countries and regions also depend on equity and capacity considerations (*high confidence*). The formulation of net zero pathways by countries will benefit from clarity on scope, plans-of-action, and fairness. Achieving net zero emission targets relies on policies, institutions, and milestones against which to track progress. Least-cost global modelled pathways have been shown to distribute the mitigation effort unevenly, and the incorporation of equity principles could change the country-level timing of net zero (*high confidence*). The Paris Agreement also recognizes that peaking of emissions will occur later in developing countries than developed countries (Article 4.1). {*WGIII Box TS.6, WGIII Cross-Chapter Box 3, WGIII 14.3*}

More information on country-level net zero pledges is provided in Section 2.3.1, on the timing of global net zero emissions in Section 3.3.2, and on sectoral aspects of net zero in Section 4.1.

[98] See footnote 12 above.

Many countries have signalled an intention to achieve net zero GHG or net zero CO_2 emissions by around mid-century (Cross-Section Box.1). More than 100 countries have either adopted, announced or are discussing net zero GHG or net zero CO_2 emissions commitments, covering more than two-thirds of global GHG emissions. A growing number of cities are setting climate targets, including net zero GHG targets. Many companies and institutions have also announced net zero emissions targets in recent years. The various net zero emission pledges differ across countries in terms of scope and specificity, and limited policies are to date in place to deliver on them. {*WGIII SPM C.6.4, WGIII TS.4.1, WGIII Table TS.1, WGIII 13.9, WGIII 14.3, WGIII 14.5*}

All mitigation strategies face implementation challenges, including technology risks, scaling, and costs (*high confidence*). Almost all mitigation options also face institutional barriers that need to be addressed to enable their application at scale (*medium confidence*). Current development pathways may create behavioural, spatial, economic and social barriers to accelerated mitigation at all scales (*high confidence*). Choices made by policymakers, citizens, the private sector and other stakeholders influence societies' development pathways (*high confidence*). Structural factors of national circumstances and capabilities (e.g., economic and natural endowments, political systems and cultural factors and gender considerations) affect the breadth and depth of climate governance (*medium confidence*). The extent to which civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples, and local communities are engaged influences political support for climate change mitigation and eventual policy outcomes (*medium confidence*). {*WGIII SPM C.3.6, WGIII SPM E.1.1, WGIII SPM E.2.1, WGIII SPM E.3.3*}

The adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity (*medium confidence*). In many countries, especially those with limited institutional capacity, several adverse side-effects have been observed as a result of diffusion of low-emission technology, e.g., low-value employment, and dependency on foreign knowledge and suppliers (*medium confidence*). Low-emission innovation along with strengthened enabling conditions can reinforce development benefits, which can, in turn, create feedbacks towards greater public support for policy (*medium confidence*). Persistent and region-specific barriers also continue to hamper the economic and political feasibility of deploying AFOLU mitigation options (*medium confidence*). Barriers to implementation of AFOLU mitigation include insufficient institutional and financial support, uncertainty over long-term additionality and trade-offs, weak governance, insecure land ownership, low incomes and the lack of access to alternative sources of income, and the risk of reversal (*high confidence*). {*WGIII SPM B.4.2, WGIII SPM C.9.1, WGIII SPM C.9.3*}

2.3.2. Adaptation Gaps and Barriers

Despite progress, adaptation gaps exist between current levels of adaptation and levels needed to respond to impacts and reduce climate risks (*high confidence*). While progress in adaptation implementation is observed across all sectors and regions *(very high confidence)*, many adaptation initiatives prioritise immediate and near-term climate risk reduction, e.g., through hard flood protection, which reduces the opportunity for transformational adaptation[99] (*high confidence*). Most observed adaptation is fragmented, small in scale, incremental, sector-specific, and focused more on planning rather than implementation (*high confidence*). Further, observed adaptation is unequally distributed across regions and the largest adaptation gaps exist among lower population income groups (*high confidence*). In the urban context, the largest adaptation gaps exist in projects that manage complex risks, for example in the food–energy–water–health nexus or the inter-relationships of air quality and climate risk (*high confidence*). Many funding, knowledge and practice gaps remain for effective implementation, monitoring and evaluation and current adaptation efforts are not expected to meet existing goals (*high confidence*). At current rates of adaptation planning and implementation the adaptation gap will continue to grow (*high confidence*). {*WGII SPM C.1, WGII SPM C.1.2, WGII SPM C.4.1, WGII TS.D.1.3, WGII TS.D.1.4*}

Soft and hard adaptation limits[100] have already been reached in some sectors and regions, in spite of adaptation having buffered some climate impacts (*high confidence*). Ecosystems already reaching hard adaptation limits include some warm water coral reefs, some coastal wetlands, some rainforests, and some polar and mountain ecosystems (*high confidence*). Individuals and households in low lying coastal areas in Australasia and Small Islands and smallholder farmers in Central and South America, Africa, Europe and Asia have reached soft limits (*medium confidence*), resulting from financial, governance, institutional and policy constraints and can be overcome by addressing these constraints (*high confidence*). Transitioning from incremental to transformational adaptation can help overcome soft adaptation limits (*high confidence*). {*WGII SPM C.3, WGII SPM C.3.1, WGII SPM C.3.2, WGII SPM C.3.3, WGII SPM.C.3.4, WGII 16 ES*}

Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages are unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries. (*high confidence*) {*WGII SPM.C.3.5*}

There is increased evidence of maladaptation[101] in various sectors and regions. Examples of maladaptation are observed in urban areas (e.g., new urban infrastructure that cannot be adjusted easily or affordably), agriculture (e.g., using high-cost irrigation in areas projected to have more intense drought conditions), ecosystems (e.g. fire suppression in naturally

[99] See Annex I: Glossary.

[100] Adaptation limit: The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions. Hard adaptation limit - No adaptive actions are possible to avoid intolerable risks. Soft adaptation limit - Options are currently not available to avoid intolerable risks through adaptive action.

[101] Maladaptation refers to actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence. See Annex I: Glossary.

fire-adapted ecosystems, or hard defences against flooding) and human settlements (e.g. stranded assets and vulnerable communities that cannot afford to shift away or adapt and require an increase in social safety nets). Maladaptation especially affects marginalised and vulnerable groups adversely (e.g., Indigenous Peoples, ethnic minorities, low-income households, people living in informal settlements), reinforcing and entrenching existing inequities. Maladaptation can be avoided by flexible, multi-sectoral, inclusive and long-term planning and implementation of adaptation actions with benefits to many sectors and systems. (*high confidence*) {*WGII SPM C.4, WGII SPM C.4.3, WGII TS.D.3.1*}

Systemic barriers constrain the implementation of adaptation options in vulnerable sectors, regions and social groups (*high confidence*). Key barriers include limited resources, lack of private-sector and civic engagement, insufficient mobilisation of finance, lack of political commitment, limited research and/or slow and low uptake of adaptation science and a low sense of urgency. Inequity and poverty also constrain adaptation, leading to soft limits and resulting in disproportionate exposure and impacts for most vulnerable groups (*high confidence*). The largest adaptation gaps exist among lower income population groups (*high confidence*). As adaptation options often have long implementation times, long-term planning and accelerated implementation, particularly in this decade, is important to close adaptation gaps, recognising that constraints remain for some regions (*high confidence*). Prioritisation of options and transitions from incremental to transformational adaptation are limited due to vested interests, economic lock-ins, institutional path dependencies and prevalent practices, cultures, norms and belief systems (*high confidence*). Many funding, knowledge and practice gaps remain for effective implementation, monitoring and evaluation of adaptation (*high confidence*), including, lack of climate literacy at all levels and limited availability of data and information (*medium confidence*); for example for Africa, severe climate data constraints and inequities in research funding and leadership reduce adaptive capacity (*very high confidence*). {*WGII SPM C.1.2, WGII SPM C.3.1, WGII TS.D.1.3, WGII TS.D.1.5, WGII TS.D.2.4*}

2.3.3. Lack of Finance as a Barrier to Climate Action

Insufficient financing, and a lack of political frameworks and incentives for finance, are key causes of the implementation gaps for both mitigation and adaptation (*high confidence*). Financial flows remained heavily focused on mitigation, are uneven, and have developed heterogeneously across regions and sectors (*high confidence*). In 2018, public and publicly mobilised private climate finance flows from developed to developing countries were below the collective goal under the UNFCCC and Paris Agreement to mobilise USD 100 billion per year by 2020 in the context of meaningful mitigation action and transparency on implementation (*medium confidence*). Public and private finance flows for fossil fuels are still greater than those for climate adaptation and mitigation (*high confidence*). The overwhelming majority of tracked climate finance is directed towards mitigation (*very high confidence*). Nevertheless, average annual modelled investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels, and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Challenges remain for green bonds and similar products, in particular around integrity and additionality, as well as the limited applicability of these markets to many developing countries (*high confidence*). {*WGII SPM C.3.2, WGII SPM C.5.4; WGIII SPM B.5.4, WGIII SPM E.5.1*}

Current global financial flows for adaptation including from public and private finance sources, are insufficient for and constrain implementation of adaptation options, especially in developing countries (*high confidence*). There are widening disparities between the estimated costs of adaptation and the documented finance allocated to adaptation (*high confidence*). Adaptation finance needs are estimated to be higher than those assessed in AR5, and the enhanced mobilisation of and access to financial resources are essential for implementation of adaptation and to reduce adaptation gaps (*high confidence*). Annual finance flows targeting adaptation for Africa, for example, are billions of USD less than the lowest adaptation cost estimates for near-term climate change (*high confidence*). Adverse climate impacts can further reduce the availability of financial resources by causing losses and damages and impeding national economic growth, thereby further increasing financial constraints for adaptation particularly for developing countries and LDCs (*medium confidence*). {*WGII SPM C.1.2, WGII SPM C.3.2, WGII SPM C.5.4, WGII TS.D.1.6*}

Without effective mitigation and adaptation, losses and damages will continue to disproportionately affect the poorest and most vulnerable populations. Accelerated financial support for developing countries from developed countries and other sources is a critical enabler to enhance mitigation action {WGIII SPM. E.5.3}. Many developing countries lack comprehensive data at the scale needed and lack adequate financial resources needed for adaptation for reducing associated economic and non-economic losses and damages. (*high confidence*) {*WGII Cross-Chapter Box LOSS, WGII SPM C.3.1, WGII SPM C.3.2, WGII TS.D.1.3, WGII TS.D.1.5; WGIII SPM E.5.3*}

There are barriers to redirecting capital towards climate action both within and outside the global financial sector. These barriers include: the inadequate assessment of climate-related risks and investment opportunities, regional mismatch between available capital and investment needs, home bias factors, country indebtedness levels, economic vulnerability, and limited institutional capacities. Challenges from outside the financial sector include: limited local capital markets; unattractive risk-return profiles, in particular due to missing or weak regulatory environments that are inconsistent with ambition levels; limited institutional capacity to ensure safeguards; standardisation, aggregation, scalability and replicability of investment opportunities and financing models; and, a pipeline ready for commercial investments. (*high confidence*) {*WGII SPM C.5.4; WGIII SPM E.5.2; SR1.5 SPM D.5.2*}

Cross-Section Box.2: Scenarios, Global Warming Levels, and Risks

Modelled scenarios and pathways[102] are used to explore future emissions, climate change, related impacts and risks, and possible mitigation and adaptation strategies and are based on a range of assumptions, including socio-economic variables and mitigation options. These are quantitative projections and are neither predictions nor forecasts. Global modelled emission pathways, including those based on cost effective approaches contain regionally differentiated assumptions and outcomes, and have to be assessed with the careful recognition of these assumptions. Most do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution. IPCC is neutral with regard to the assumptions underlying the scenarios in the literature assessed in this report, which do not cover all possible futures[103]. {*WGI Box SPM.1; WGII Box SPM.1; WGIII Box SPM.1; SROCC Box SPM.1; SRCCL Box SPM.1*}

Socio-economic Development, Scenarios, and Pathways

The five Shared Socio-economic Pathways (SSP1 to SSP5) were designed to span a range of challenges to climate change mitigation and adaptation. For the assessment of climate impacts, risk and adaptation, the SSPs are used for future exposure, vulnerability and challenges to adaptation. Depending on levels of GHG mitigation, modelled emissions scenarios based on the SSPs can be consistent with low or high warming levels[104]. There are many different mitigation strategies that could be consistent with different levels of global warming in 2100 (see Figure 4.1). {*WGI Box SPM.1; WGII Box SPM.1; WGIII Box SPM.1, WGIII Box TS.5, WGIII Annex III; SRCCL Box SPM.1, SRCCL Figure SPM.2*}

WGI assessed the climate response to five illustrative scenarios based on SSPs[105] that cover the range of possible future development of anthropogenic drivers of climate change found in the literature. These scenarios combine socio-economic assumptions, levels of climate mitigation, land use and air pollution controls for aerosols and non-CH_4 ozone precursors. The high and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5) have CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively[106]. The intermediate GHG emissions scenario (SSP2-4.5) has CO_2 emissions remaining around current levels until the middle of the century. The very low and low GHG emissions scenarios (SSP1-1.9 and SSP1-2.6) have CO_2 emissions declining to net zero around 2050 and 2070, respectively, followed by varying levels of net negative CO_2 emissions. In addition, Representative Concentration Pathways (RCPs)[107] were used by WGI and WGII to assess regional climate changes, impacts and risks. {*WGI Box SPM.1*} (*Cross-Section Box.2 Figure 1*)

In WGIII, a large number of global modelled emissions pathways were assessed, of which 1202 pathways were categorised based on their projected global warming over the 21st century, with categories ranging from pathways that limit warming to 1.5°C with more than 50% likelihood[108] with no or limited overshoot (C1) to pathways that exceed 4°C (C8). Methods to project global warming associated with the modelled pathways were updated to ensure consistency with the AR6 WGI assessment of the climate system response[109]. {*WGIII Box SPM.1, WGIII Table 3.1*} (*Table 3.1, Cross-Section Box.2 Figure 1*)

[102] In the literature, the terms pathways and scenarios are used interchangeably, with the former more frequently used in relation to climate goals. WGI primarily used the term scenarios and WGIII mostly used the term modelled emissions and mitigation pathways. The SYR primarily uses scenarios when referring to WGI and modelled emissions and mitigation pathways when referring to WGIII. {*WGI Box SPM.1; WGIII footnote 44*}

[103] Around half of all modelled global emissions pathways assume cost-effective approaches that rely on least-cost mitigation/abatement options globally. The other half look at existing policies and regionally and sectorally differentiated actions. The underlying population assumptions range from 8.5 to 9.7 billion in 2050 and 7.4 to 10.9 billion in 2100 (5–95th percentile) starting from 7.6 billion in 2019. The underlying assumptions on global GDP growth range from 2.5 to 3.5% per year in the 2019–2050 period and 1.3 to 2.1% per year in the 2050–2100 (5–95th percentile). {*WGIII Box SPM.1*}

[104] High mitigation challenges, for example, due to assumptions of slow technological change, high levels of global population growth, and high fragmentation as in the Shared Socio-economic Pathway SSP3, may render modelled pathways that limit warming to 2°C (> 67%) or lower infeasible (*medium confidence*). {*WGIII SPM C.1.4; SRCCL Box SPM.1*}

[105] SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway describing the socioeconomic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square metre, or Wm^{-2}) resulting from the scenario in the year 2100. {*WGI SPM footnote 22*}

[106] Very high emission scenarios have become less *likely* but cannot be ruled out. Temperature levels > 4°C may result from very high emission scenarios, but can also occur from lower emission scenarios if climate sensitivity or carbon cycle feedbacks are higher than the best estimate. {*WGIII SPM C.1.3*}

[107] RCP-based scenarios are referred to as RCPy, where 'y' refers to the approximate level of radiative forcing (in watts per square metre, or Wm^{-2}) resulting from the scenario in the year 2100. {*WGII SPM footnote 21*}

[108] Denoted '>50%' in this report.

[109] The climate response to emissions is investigated with climate models, paleoclimatic insights and other lines of evidence. The assessment outcomes are used to categorise thousands of scenarios via simple physically-based climate models (emulators). {*WGI TS.1.2.2*}

Global Warming Levels (GWLs)

For many climate and risk variables, the geographical patterns of changes in climatic impact-drivers[110] and climate impacts for a level of global warming[111] are common to all scenarios considered and independent of timing when that level is reached. This motivates the use of GWLs as a dimension of integration. {*WGI Box SPM.1.4, WGI TS.1.3.2; WGII Box SPM.1*} (*Figure 3.1, Figure 3.2*)

Risks

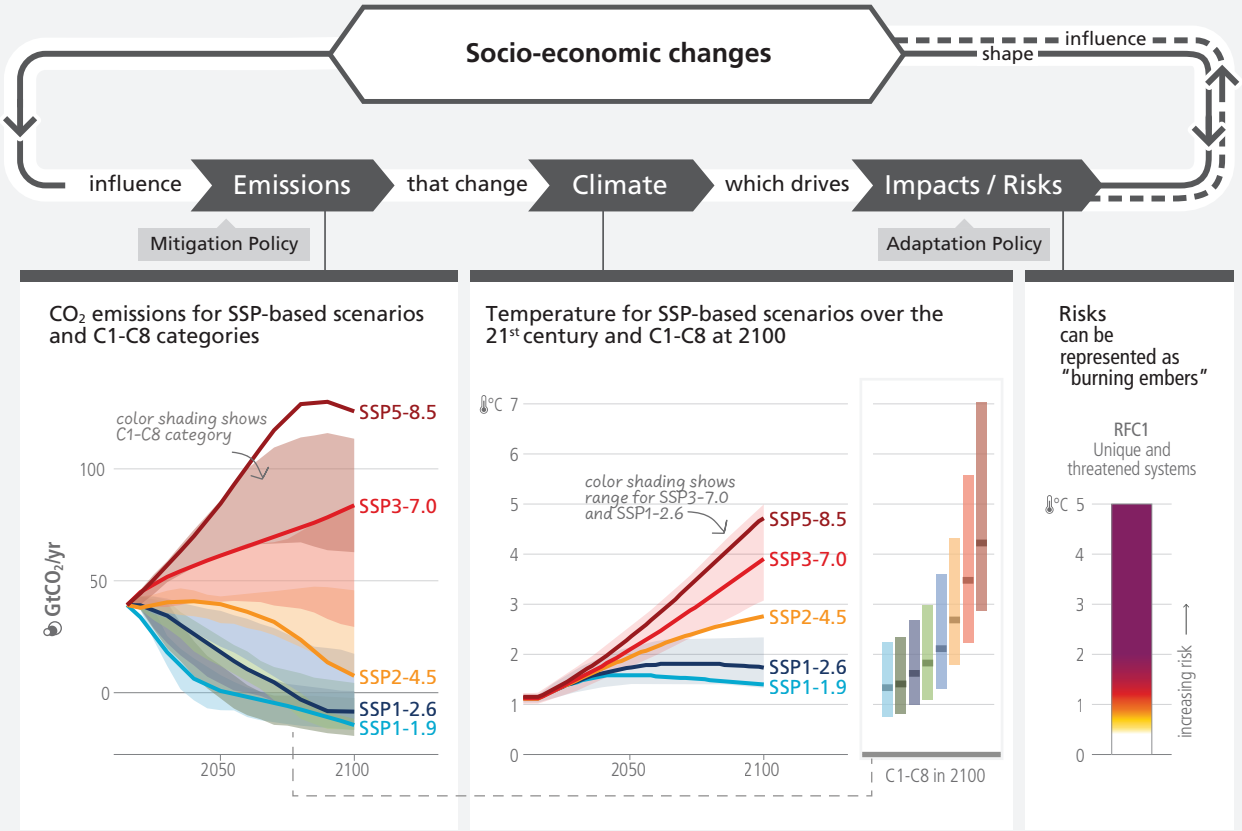
Dynamic interactions between climate-related hazards, exposure and vulnerability of the affected human society, species, or ecosystems result in risks arising from climate change. AR6 assesses key risks across sectors and regions as well as providing an updated assessment of the Reasons for Concern (RFCs) – five globally aggregated categories of risk that evaluate risk accrual with increasing global surface temperature. Risks can also arise from climate change mitigation or adaptation responses when the response does not achieve its intended objective, or when it results in adverse effects for other societal objectives. {*WGII SPM A, WGII Figure SPM.3, WGII Box TS.1, WGII Figure TS.4; SR1.5 Figure SPM.2; SROCC Errata Figure SPM.3; SRCCL Figure SPM.2*} (*3.1.2, Cross-Section Box.2 Figure 1, Figure 3.3*)

[110] See Annex I: Glossary

[111] See Annex I: Glossary. Here, global warming is the 20-year average global surface temperature relative to 1850–1900. The assessed time of when a certain global warming level is reached under a particular scenario is defined here as the mid-point of the first 20-year running average period during which the assessed average global surface temperature change exceeds the level of global warming. {*WGI SPM footnote 26, Cross-Section Box TS.1*}

Scenarios and warming levels structure our understanding across the cause-effect chain from emissions to climate change and risks

a) **AR6 integrated assessment framework on future climate, impacts and mitigation**



b) **Scenarios and pathways across AR6 Working Group reports**

Category in WGIII	Category description	GHG emissions scenarios (SSPx-y*) in WGI & WGII	RCPy** in WGI & WGII
C1	limit warming to 1.5°C (>50%) with no or limited overshoot	Very low (SSP1-1.9)	
C2	return warming to 1.5°C (>50%) after a high overshoot		
C3	limit warming to 2°C (>67%)	Low (SSP1-2.6)	RCP2.6
C4	limit warming to 2°C (>50%)		
C5	limit warming to 2.5°C (>50%)		
C6	limit warming to 3°C (>50%)	Intermediate (SSP2-4.5)	RCP 4.5
C7	limit warming to 4°C (>50%)	High (SSP3-7.0)	
C8	exceed warming of 4°C (>50%)	Very high (SSP5-8.5)	RCP 8.5

c) **Determinants of risk**

* The terminology SSPx-y is used, where 'SSPx' refers to the Shared Socio-economic Pathway or 'SSP' describing the socio-economic trends underlying the scenario, and 'y' refers to the approximate level of radiative forcing (in watts per square metre, or Wm^{-2}) resulting from the scenario in the year 2100.

** The AR5 scenarios (RCPy), which partly inform the AR6 WGI and WGII assessments, are indexed to a similar set of approximate 2100 radiative forcing levels (in $W\ m^{-2}$). The SSP scenarios cover a broader range of GHG and air pollutant futures than the RCPs. They are similar but not identical, with differences in concentration trajectories for different GHGs. The overall radiative forcing tends to be higher for the SSPs compared to the RCPs with the same label (*medium confidence*). {*WGI TS.1.3.1*}

*** Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C, high overshoot by 0.1°C-0.3°C, in both cases for up to several decades.

Cross-Section Box.2 Figure 1: Schematic of the AR6 framework for assessing future greenhouse gas emissions, climate change, risks, impacts and mitigation. Panel (a) The integrated framework encompasses socio-economic development and policy, emissions pathways and global surface temperature responses to the five scenarios considered by WGI (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) and eight global mean temperature change categorisations (C1–C8) assessed by WGIII, and the WGII risk assessment. The dashed arrow indicates that the influence from impacts/risks to socio-economic changes is not yet considered in the scenarios assessed in the AR6. Emissions include GHGs, aerosols, and ozone precursors. CO_2 emissions are shown as an example on the left. The assessed global surface temperature changes across the 21st century relative to 1850-1900 for the five GHG emissions scenarios are shown as an example in the centre. *Very likely* ranges are shown for SSP1-2.6 and SSP3-7.0. Projected temperature outcomes at 2100 relative to 1850-1900 are shown for C1 to C8 categories with median (line) and the combined *very likely* range across scenarios (bar). On the right, future risks due to increasing warming are represented by an example 'burning ember' figure (see 3.1.2 for the definition of RFC1). **Panel (b)** Description and relationship of scenarios considered across AR6 Working Group reports. **Panel (c)** Illustration of risk arising from the interaction of hazard (driven by changes in climatic impact-drivers) with vulnerability, exposure and response to climate change. {*WGI TS1.4, Figure 4.11; WGII Figure 1.5, WGII Figure 14.8; WGIII Table SPM.2, WGIII Figure 3.11*}

Section 3
Long-Term Climate and Development Futures

Section 3: Long-Term Climate and Development Futures

3.1 Long-Term Climate Change, Impacts and Related Risks

Future warming will be driven by future emissions and will affect all major climate system components, with every region experiencing multiple and co-occurring changes. Many climate-related risks are assessed to be higher than in previous assessments, and projected long-term impacts are up to multiple times higher than currently observed. Multiple climatic and non-climatic risks will interact, resulting in compounding and cascading risks across sectors and regions. Sea level rise, as well as other irreversible changes, will continue for thousands of years, at rates depending on future emissions. (*high confidence*)

3.1.1. Long-term Climate Change

The uncertainty range on assessed future changes in global surface temperature is narrower than in the AR5. For the first time in an IPCC assessment cycle, multi-model projections of global surface temperature, ocean warming and sea level are constrained using observations and the assessed climate sensitivity. The *likely* range of equilibrium climate sensitivity has been narrowed to 2.5°C to 4.0°C (with a best estimate of 3.0°C) based on multiple lines of evidence[112], including improved understanding of cloud feedbacks. For related emissions scenarios, this leads to narrower uncertainty ranges for long-term projected global temperature change than in AR5. {*WGI A.4, WGI Box SPM.1, WGI TS.3.2, WGI 4.3*}

Future warming depends on future GHG emissions, with cumulative net CO_2 dominating. The assessed best estimates and *very likely* ranges of warming for 2081-2100 with respect to 1850–1900 vary from 1.4 [1.0 to 1.8]°C in the very low GHG emissions scenario (SSP1-1.9) to 2.7 [2.1 to 3.5]°C in the intermediate GHG emissions scenario (SSP2-4.5) and 4.4 [3.3 to 5.7]°C in the very high GHG emissions scenario (SSP5-8.5)[113]. {*WGI SPM B.1.1, WGI Table SPM.1, WGI Figure SPM.4*} (*Cross-Section Box.2 Figure 1*)

Modelled pathways consistent with the continuation of policies implemented by the end of 2020 lead to global warming of 3.2 [2.2 to 3.5]°C (5–95% range) by 2100 (*medium confidence*) (see also Section 2.3.1). Pathways of >4°C (≥50%) by 2100 would imply a reversal of current technology and/or mitigation policy trends (*medium confidence*). However, such warming could occur in emissions pathways consistent with policies implemented by the end of 2020 if climate sensitivity or carbon cycle feedbacks are higher than the best estimate (*high confidence*). {*WGIII SPM C.1.3*}

Global warming will continue to increase in the near term in nearly all considered scenarios and modelled pathways. Deep, rapid, and sustained GHG emissions reductions, reaching net zero CO_2 emissions and including strong emissions reductions of other GHGs, in particular CH_4, are necessary to limit warming to 1.5°C (>50%) or less than 2°C (>67%) by the end of century (*high confidence*). The best estimate of reaching 1.5°C of global warming lies in the first half of the 2030s in most of the considered scenarios and modelled pathways[114]. In the very low GHG emissions scenario (SSP1-1.9), CO_2 emissions reach net zero around 2050 and the best-estimate end-of-century warming is 1.4°C, after a temporary overshoot (see Section 3.3.4) of no more than 0.1°C above 1.5°C global warming. Global warming of 2°C will be exceeded during the 21st century unless deep reductions in CO_2 and other GHG emissions occur in the coming decades. Deep, rapid, and sustained reductions in GHG emissions would lead to improvements in air quality within a few years, to reductions in trends of global surface temperature discernible after around 20 years, and over longer time periods for many other climate impact-drivers[115] (*high confidence*). Targeted reductions of air pollutant emissions lead to more rapid improvements in air quality compared to reductions in GHG emissions only, but in the long term, further improvements are projected in scenarios that combine efforts to reduce air pollutants as well as GHG emissions (*high confidence*)[116]. {*WGI SPM B.1, WGI SPM B.1.3, WGI SPM D.1, WGI SPM D.2, WGI Figure SPM.4, WGI Table SPM.1, WGI Cross-Section Box TS.1; WGIII SPM C.3, WGIII Table SPM.2, WGIII Figure SPM.5, WGIII Box SPM.1 Figure 1, WGIII Table 3.2*} (*Table 3.1, Cross-Section Box.2 Figure 1*)

Changes in short-lived climate forcers (SLCF) resulting from the five considered scenarios lead to an additional net global warming in the near and long term (*high confidence*). Simultaneous stringent climate change mitigation and air pollution control

[112] Understanding of climate processes, the instrumental record, paleoclimates and model-based emergent constraints (see Annex I: Glossary). {*WGI SPM footnote 21*}

[113] The best estimates [and *very likely* ranges] for the different scenarios are: 1.4 [1.0 to 1.8]°C (SSP1-1.9); 1.8 [1.3 to 2.4]°C (SSP1-2.6); 2.7 [2.1 to 3.5]°C (SSP2-4.5); 3.6 [2.8 to 4.6]°C (SSP3-7.0); and 4.4 [3.3 to 5.7]°C (SSP5-8.5). {*WGI Table SPM.1*} (*Cross-Section Box.2*)

[114] In the near term (2021–2040), the 1.5°C global warming level is *very likely* to be exceeded under the very high GHG emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high GHG emissions scenarios (SSP2-4.5, SSP3-7.0), *more likely than not* to be exceeded under the low GHG emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low GHG emissions scenario (SSP1-1.9). In all scenarios considered by WGI except the very high emissions scenario, the midpoint of the first 20-year running average period during which the assessed global warming reaches 1.5°C lies in the first half of the 2030s. In the very high GHG emissions scenario, this mid-point is in the late 2020s. The median five-year interval at which a 1.5°C global warming level is reached (50% probability) in categories of modelled pathways considered in WGIII is 2030–2035. {*WGI SPM B.1.3, WGI Cross-Section Box TS.1, WGIII Table 3.2*} (*Cross-Section Box.2*)

[115] See Cross-Section Box.2.

[116] Based on additional scenarios.

policies limit this additional warming and lead to strong benefits for air quality (*high confidence*). In high and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5), combined changes in SLCF emissions, such as CH_4, aerosol and ozone precursors, lead to a net global warming by 2100 of *likely* 0.4°C to 0.9°C relative to 2019. This is due to projected increases in atmospheric concentration of CH_4, tropospheric ozone, hydrofluorocarbons and, when strong air pollution control is considered, reductions of cooling aerosols. In low and very low GHG emissions scenarios (SSP1-1.9 and SSP1-2.6), air pollution control policies, reductions in CH_4 and other ozone precursors lead to a net cooling, whereas reductions in anthropogenic cooling aerosols lead to a net warming (*high confidence*). Altogether, this causes a *likely* net warming of 0.0°C to 0.3°C due to SLCF changes in 2100 relative to 2019 and strong reductions in global surface ozone and particulate matter (*high confidence*). {*WGI SPM D.1.7, WGI Box TS.7*} (*Cross-Section Box.2*)

Continued GHG emissions will further affect all major climate system components, and many changes will be irreversible on centennial to millennial time scales. Many changes in the climate system become larger in direct relation to increasing global warming. With every additional increment of global warming, changes in extremes continue to become larger. Additional warming will lead to more frequent and intense marine heatwaves and is projected to further amplify permafrost thawing and loss of seasonal snow cover, glaciers, land ice and Arctic sea ice (*high confidence*). Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation[117], and very wet and very dry weather and climate events and seasons (*high confidence*). The portion of global land experiencing detectable changes in seasonal mean precipitation is projected to increase (*medium confidence*) with more variable precipitation and surface water flows over most land regions within seasons (*high confidence*) and from year to year (*medium confidence*). Many changes due to past and future GHG emissions are irreversible[118] on centennial to millennial time scales, especially in the ocean, ice sheets and global sea level (see 3.1.3). Ocean acidification (*virtually certain*), ocean deoxygenation (*high confidence*) and global mean sea level (*virtually certain*) will continue to increase in the 21st century, at rates dependent on future emissions. {*WGI SPM B.2, WGI SPM B.2.2, WGI SPM B.2.3, WGI SPM B.2.5, WGI SPM B.3, WGI SPM B.3.1, WGI SPM B.3.2, WGI SPM B.4, WGI SPM B.5, WGI SPM B.5.1, WGI SPM B.5.3, WGI Figure SPM.8*} (*Figure 3.1*)

With further global warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Increases in hot and decreases in cold climatic impact-drivers, such as temperature extremes, are projected in all regions (*high confidence*). At 1.5°C global warming, heavy precipitation and flooding events are projected to intensify and become more frequent in most regions in Africa, Asia (*high confidence*), North America (*medium* to *high confidence*) and Europe (*medium confidence*). At 2°C or above, these changes expand to more regions and/or become more significant (*high confidence*), and more frequent and/or severe agricultural and ecological droughts are projected in Europe, Africa, Australasia and North, Central and South America (*medium* to *high confidence*). Other projected regional changes include intensification of tropical cyclones and/or extratropical storms (*medium confidence*), and increases in aridity and fire weather[119] (*medium* to *high confidence*). Compound heatwaves and droughts become *likely* more frequent, including concurrently at multiple locations (*high confidence*). {*WGI SPM C.2, WGI SPM C.2.1, WGI SPM C.2.2, WGI SPM C.2.3, WGI SPM C.2.4, WGI SPM C.2.7*}

[117] Particularly over South and South East Asia, East Asia and West Africa apart from the far west Sahel. {*WGI SPM B.3.3*}

[118] See Annex I: Glossary.

[119] See Annex I: Glossary.

With every increment of global warming, regional changes in mean climate and extremes become more widespread and pronounced

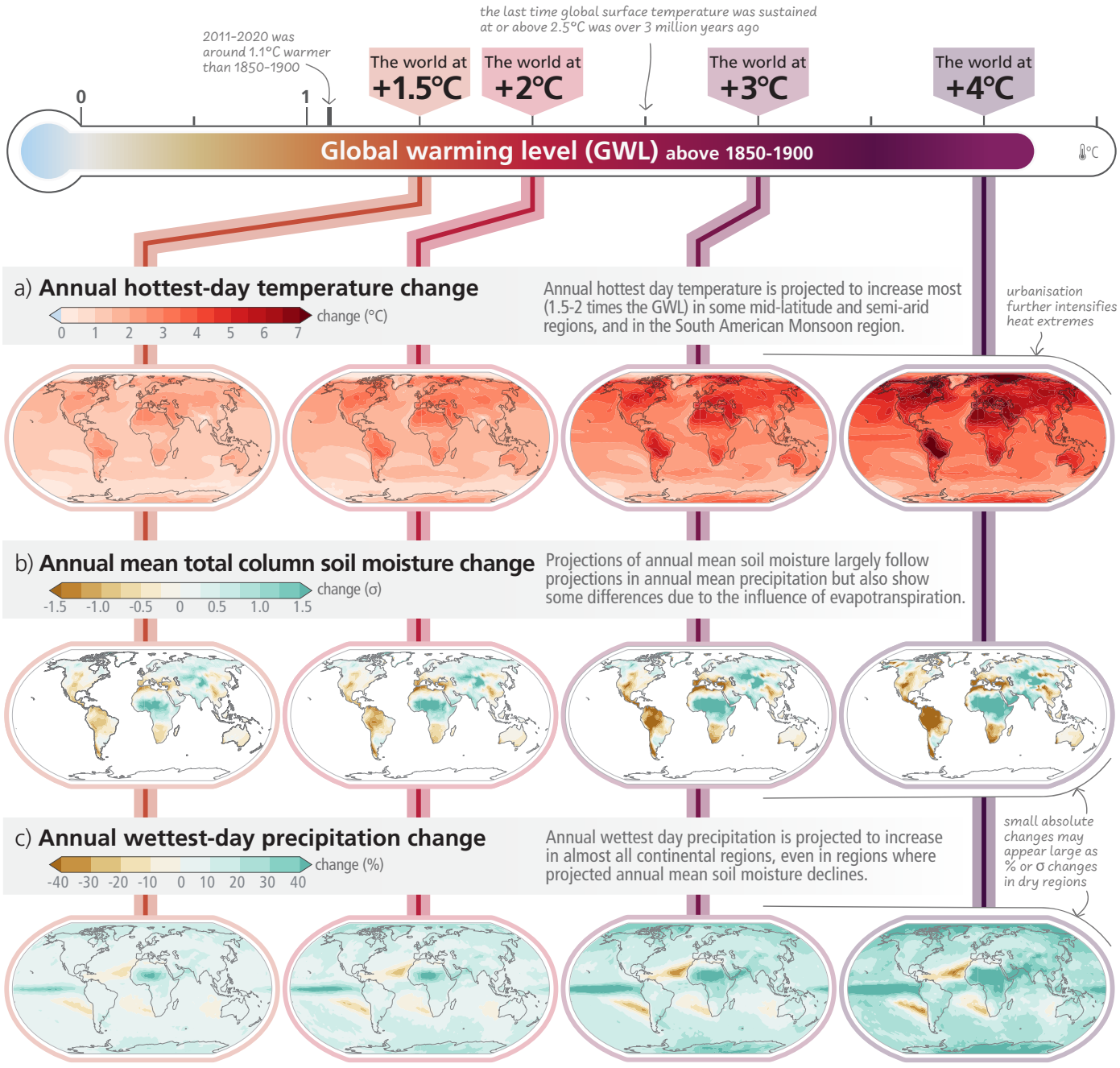


Figure 3.1: Projected changes of annual maximum daily temperature, annual mean total column soil moisture CMIP and annual maximum daily precipitation at global warming levels of 1.5°C, 2°C, 3°C, and 4°C relative to 1850-1900. Simulated (a) annual maximum temperature change (°C), **(b)** annual mean total column soil moisture (standard deviation), **(c)** annual maximum daily precipitation change (%). Changes correspond to CMIP6 multi-model median changes. In panels (b) and (c), large positive relative changes in dry regions may correspond to small absolute changes. In panel (b), the unit is the standard deviation of interannual variability in soil moisture during 1850-1900. Standard deviation is a widely used metric in characterising drought severity. A projected reduction in mean soil moisture by one standard deviation corresponds to soil moisture conditions typical of droughts that occurred about once every six years during 1850-1900. The WGI Interactive Atlas (https://interactive-atlas.ipcc.ch/) can be used to explore additional changes in the climate system across the range of global warming levels presented in this figure. {*WGI Figure SPM.5, WGI Figure TS.5, WGI Figure 11.11, WGI Figure 11.16, WGI Figure 11.19*} (*Cross-Section Box.2*)

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3.1.2 Impacts and Related Risks

For a given level of warming, many climate-related risks are assessed to be higher than in AR5 (*high confidence*). Levels of risk[120] for all Reasons for Concern[121] (RFCs) are assessed to become high to very high at lower global warming levels compared to what was assessed in AR5 (*high confidence*). This is based upon recent evidence of observed impacts, improved process understanding, and new knowledge on exposure and vulnerability of human and natural systems, including limits to adaptation. Depending on the level of global warming, the assessed long-term impacts will be up to multiple times higher than currently observed (*high confidence*) for 127 identified key risks, e.g., in terms of the number of affected people and species. Risks, including cascading risks (see 3.1.3) and risks from overshoot (see 3.3.4), are projected to become increasingly severe with every increment of global warming (*very high confidence*). {*WGII SPM B.3.3, WGII SPM B.4, WGII SPM B.5, WGII 16.6.3; SRCCL SPM A5.3*} (*Figure 3.2, Figure 3.3*)

Climate-related risks for natural and human systems are higher for global warming of 1.5°C than at present (1.1°C) but lower than at 2°C (*high confidence*) (see Section 2.1.2). 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. In terrestrial ecosystems, 3 to 14% of the tens of thousands of species assessed will *likely* face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island developing states and Least Developed Countries (*high confidence*). {*WGII SPM B.3, WGII SPM B.4.1, WGII TS.C.4.2; SR1.5 SPM A.3, SR1.5 SPM B.4.2, SR1.5 SPM B.5, SR1.5 SPM B.5.1*} (*Figure 3.3*)

At 2°C of global warming, overall risk levels associated with the unequal distribution of impacts (RFC3), global aggregate impacts (RFC4) and large-scale singular events (RFC5) would be transitioning to high (*medium confidence*), those associated with extreme weather events (RFC2) would be transitioning to very high (*medium confidence*), and those associated with unique and threatened systems (RFC1) would be very high (*high confidence*) (Figure 3.3, panel a). With about 2°C warming, climate-related changes in food availability and diet quality are estimated to increase nutrition-related diseases and the number of undernourished people, affecting tens (under low vulnerability and low warming) to hundreds of millions of people (under high vulnerability and high warming), particularly among low-income households in low- and middle-income countries in sub-Saharan Africa, South Asia and Central America (*high confidence*). For example, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20% (*medium confidence*). Climate change risks to cities, settlements and key infrastructure will rise sharply in the mid and long term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (*high confidence*). {*WGII SPM B.3.3, WGII SPM B.4.2, WGII SPM B.4.5, WGII TS C.3.3, WGII TS.C.12.2*} (*Figure 3.3*)

At global warming of 3°C, additional risks in many sectors and regions reach high or very high levels, implying widespread systemic impacts, irreversible change and many additional adaptation limits (see Section 3.2) (*high confidence*). For example, very high extinction risk for endemic species in biodiversity hotspots is projected to increase at least tenfold if warming rises from 1.5°C to 3°C (*medium confidence*). Projected increases in direct flood damages are higher by 1.4 to 2 times at 2°C and 2.5 to 3.9 times at 3°C, compared to 1.5°C global warming without adaptation (*medium confidence*). {*WGII SPM B.4.1, WGII SPM B.4.2, WGII Figure SPM.3, WGII TS Appendix AII, WGII Appendix I Global to Regional Atlas Figure AI.46*} (*Figure 3.2, Figure 3.3*)

Global warming of 4°C and above is projected to lead to far-reaching impacts on natural and human systems (*high confidence*). Beyond 4°C of warming, projected impacts on natural systems include local extinction of ~50% of tropical marine species (*medium confidence*) and biome shifts across 35% of global land area (*medium confidence*). At this level of warming, approximately 10% of the global land area is projected to face both increasing high and decreasing low extreme streamflow, affecting, without additional adaptation, over 2.1 billion people (*medium confidence*) and about 4 billion people are projected to experience water scarcity (*medium confidence*). At 4°C of warming, the global burned area is projected to increase by 50 to 70% and the fire frequency by ~30% compared to today (*medium confidence*). {*WGII SPM B.4.1, WGII SPM B.4.2, WGII TS.C.1.2, WGII TS.C.2.3, WGII TS.C.4.1, WGII TS.C.4.4*} (*Figure 3.2, Figure 3.3*)

[120] Undetectable risk level indicates no associated impacts are detectable and attributable to climate change; moderate risk indicates associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks; high risk indicates severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks; and very high risk level indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks. {*WGII Figure SPM.3*}

[121] The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories (WGII Figure SPM.3). RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous Peoples, mountain glaciers and biodiversity hotspots. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet instability or thermohaline circulation slowing. Assessment methods include a structured expert elicitation based on the literature described in WGII SM16.6 and are identical to AR5 but are enhanced by a structured approach to improve robustness and facilitate comparison between AR5 and AR6. For further explanations of global risk levels and Reasons for Concern, see WGII TS.AII. {*WGII Figure SPM.3*}

Projected adverse impacts and related losses and damages from climate change escalate with every increment of global warming (*very high confidence*), but they will also strongly depend on socio-economic development trajectories and adaptation actions to reduce vulnerability and exposure (*high confidence*). For example, development pathways with higher demand for food, animal feed, and water, more resource-intensive consumption and production, and limited technological improvements result in higher risks from water scarcity in drylands, land degradation and food insecurity (*high confidence*). Changes in, for example, demography or investments in health systems have effect on a variety of health-related outcomes including heat-related morbidity and mortality (Figure 3.3 Panel d). {*WGII SPM B.3, WGII SPM B.4, WGII Figure SPM.3; SRCCL SPM A.6*}

With every increment of warming, climate change impacts and risks will become increasingly complex and more difficult to manage. Many regions are projected to experience an increase in the probability of compound events with higher global warming, such as concurrent heatwaves and droughts, compound flooding and fire weather. In addition, multiple climatic and non-climatic risk drivers such as biodiversity loss or violent conflict will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Furthermore, risks can arise from some responses that are intended to reduce the risks of climate change, e.g., adverse side effects of some emission reduction and carbon dioxide removal (CDR) measures (see 3.4.1). (*high confidence*) {*WGI SPM C.2.7, WGI Figure SPM.6, WGI TS.4.3; WGII SPM B.1.7, WGII B.2.2, WGII SPM B.5, WGII SPM B.5.4, WGII SPM C.4.2, WGII SPM B.5, WGII CCB2*}

Solar Radiation Modification (SRM) approaches, if they were to be implemented, introduce a widespread range of new risks to people and ecosystems, which are not well understood. SRM has the potential to offset warming within one or two decades and ameliorate some climate hazards but would not restore climate to a previous state, and substantial residual or overcompensating climate change would occur at regional and seasonal scales (*high confidence*). Effects of SRM would depend on the specific approach used[122], and a sudden and sustained termination of SRM in a high CO_2 emissions scenario would cause rapid climate change (*high confidence*). SRM would not stop atmospheric CO_2 concentrations from increasing nor reduce resulting ocean acidification under continued anthropogenic emissions (*high confidence*). Large uncertainties and knowledge gaps are associated with the potential of SRM approaches to reduce climate change risks. Lack of robust and formal SRM governance poses risks as deployment by a limited number of states could create international tensions. {*WGI 4.6; WGII SPM B.5.5; WGIII 14.4.5.1; WGIII 14 Cross-Working Group Box Solar Radiation Modification; SR1.5 SPM C.1.4*}

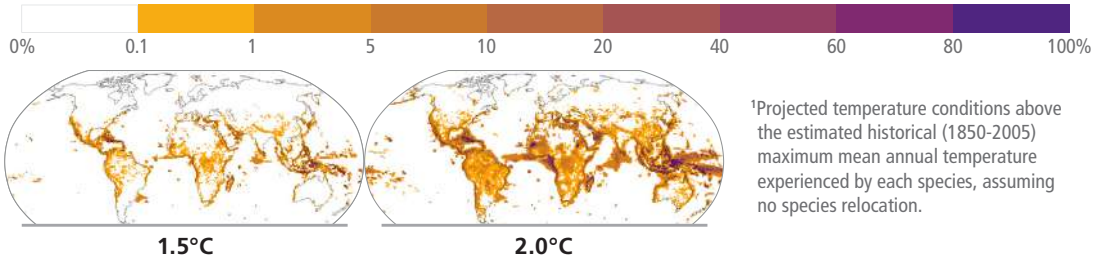
[122] Several SRM approaches have been proposed, including stratospheric aerosol injection, marine cloud brightening, ground-based albedo modifications, and ocean albedo change. See Annex I: Glossary.

Future climate change is projected to increase the severity of impacts across natural and human systems and will increase regional differences

Examples of impacts without additional adaptation

a) Risk of species losses

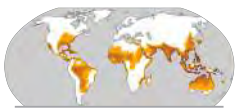
Percentage of animal species and seagrasses exposed to potentially dangerous temperature conditions[1, 2]



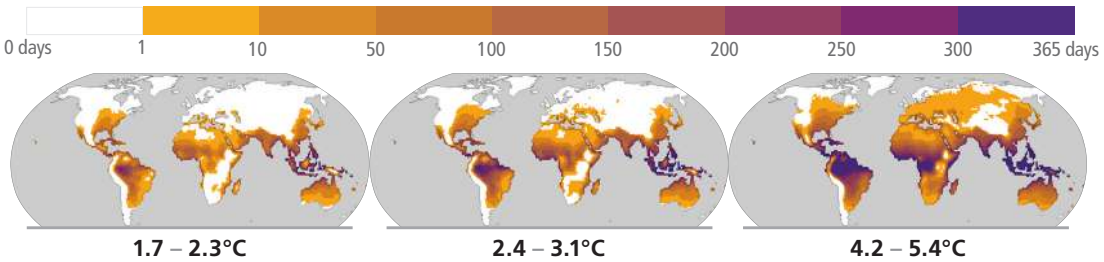
[1]Projected temperature conditions above the estimated historical (1850-2005) maximum mean annual temperature experienced by each species, assuming no species relocation.

[2]Includes 30,652 species of birds, mammals, reptiles, amphibians, marine fish, benthic marine invertebrates, krill, cephalopods, corals, and seagrasses.

b) Heat-humidity risks to human health



Days per year where combined temperature and humidity conditions pose a risk of mortality to individuals[3]

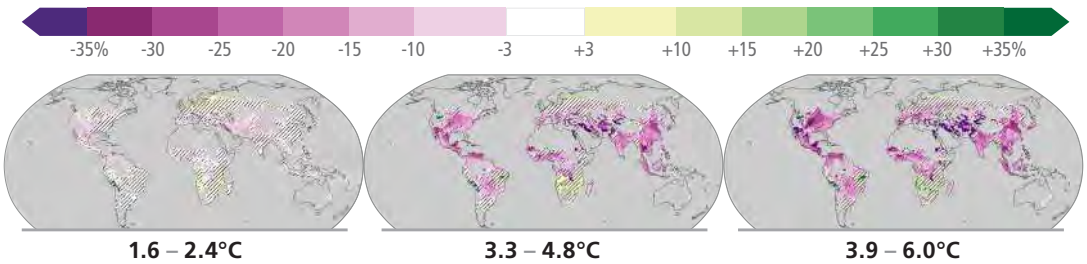


[3]Projected regional impacts utilize a global threshold beyond which daily mean surface air temperature and relative humidity may induce hyperthermia that poses a risk of mortality. The duration and intensity of heatwaves are not presented here. Heat-related health outcomes vary by location and are highly moderated by socio-economic, occupational and other non-climatic determinants of individual health and socio-economic vulnerability. The threshold used in these maps is based on a single study that synthesized data from 783 cases to determine the relationship between heat-humidity conditions and mortality drawn largely from observations in temperate climates.

c) Food production impacts

c1) Maize yield[4]

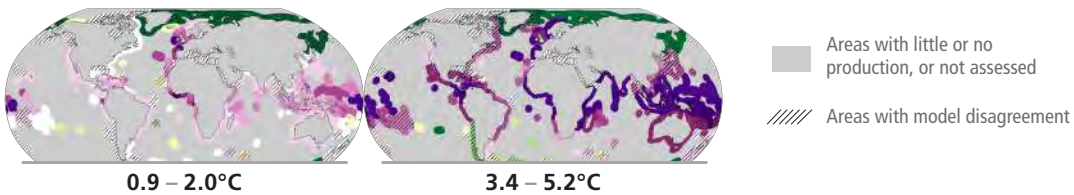
Changes (%) in yield



[4]Projected regional impacts reflect biophysical responses to changing temperature, precipitation, solar radiation, humidity, wind, and CO_2 enhancement of growth and water retention in currently cultivated areas. Models assume that irrigated areas are not water-limited. Models do not represent pests, diseases, future agro-technological changes and some extreme climate responses.

c2) Fisheries yield[5]

Changes (%) in maximum catch potential



[5]Projected regional impacts reflect fisheries and marine ecosystem responses to ocean physical and biogeochemical conditions such as temperature, oxygen level and net primary production. Models do not represent changes in fishing activities and some extreme climatic conditions. Projected changes in the Arctic regions have low confidence due to uncertainties associated with modelling multiple interacting drivers and ecosystem responses.

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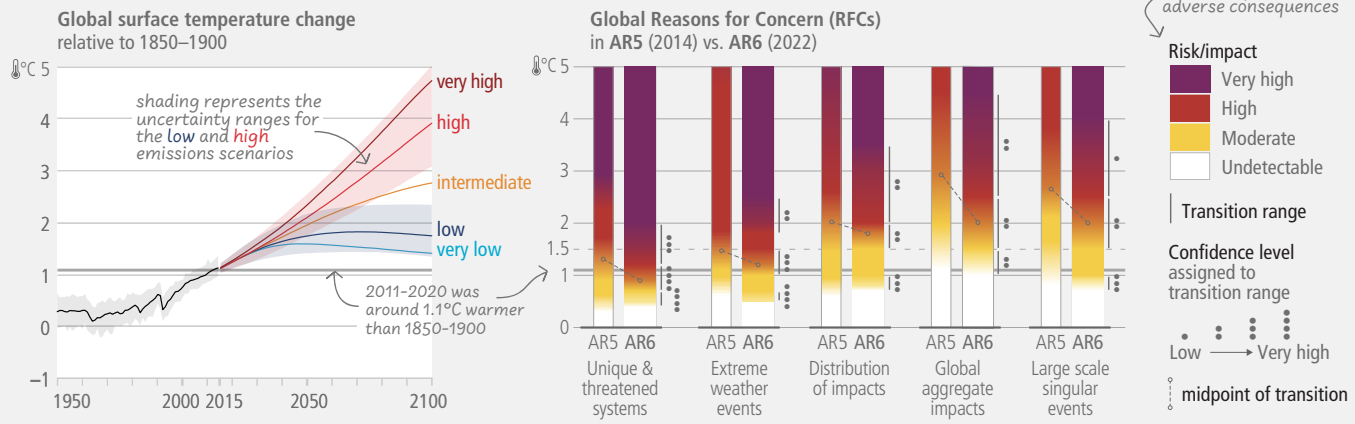
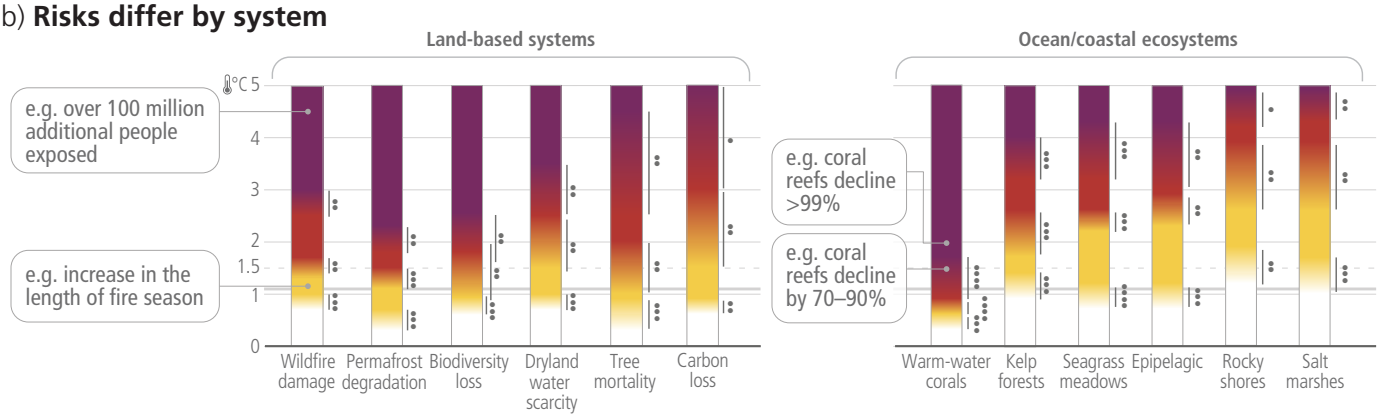
Figure 3.2: Projected risks and impacts of climate change on natural and human systems at different global warming levels (GWLs) relative to 1850-1900 levels. Projected risks and impacts shown on the maps are based on outputs from different subsets of Earth system models that were used to project each impact indicator without additional adaptation. WGII provides further assessment of the impacts on human and natural systems using these projections and additional lines of evidence. **(a)** Risks of species losses as indicated by the percentage of assessed species exposed to potentially dangerous temperature conditions, as defined by conditions beyond the estimated historical (1850–2005) maximum mean annual temperature experienced by each species, at GWLs of 1.5°C, 2°C, 3°C and 4°C. Underpinning projections of temperature are from 21 Earth system models and do not consider extreme events impacting ecosystems such as the Arctic. **(b)** Risk to human health as indicated by the days per year of population exposure to hypothermic conditions that pose a risk of mortality from surface air temperature and humidity conditions for historical period (1991–2005) and at GWLs of 1.7°C to 2.3°C (mean = 1.9°C; 13 climate models), 2.4°C to 3.1°C (2.7°C; 16 climate models) and 4.2°C to 5.4°C (4.7°C; 15 climate models). Interquartile ranges of WGLs by 2081–2100 under RCP2.6, RCP4.5 and RCP8.5. The presented index is consistent with common features found in many indices included within WGI and WGII assessments. **(c)** Impacts on food production: (c1) Changes in maize yield at projected GWLs of 1.6°C to 2.4°C (2.0°C), 3.3°C to 4.8°C (4.1°C) and 3.9°C to 6.0°C (4.9°C). Median yield changes from an ensemble of 12 crop models, each driven by bias-adjusted outputs from 5 Earth system models from the Agricultural Model Intercomparison and Improvement Project (AgMIP) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). Maps depict 2080–2099 compared to 1986–2005 for current growing regions (>10 ha), with the corresponding range of future global warming levels shown under SSP1-2.6, SSP3-7.0 and SSP5-8.5, respectively. Hatching indicates areas where <70% of the climate-crop model combinations agree on the sign of impact. (c2) Changes in maximum fisheries catch potential by 2081–2099 relative to 1986-2005 at projected GWLs of 0.9°C to 2.0°C (1.5°C) and 3.4°C to 5.2°C (4.3°C). GWLs by 2081–2100 under RCP2.6 and RCP8.5. Hatching indicates where the two climate-fisheries models disagree in the direction of change. Large relative changes in low yielding regions may correspond to small absolute changes. Biodiversity and fisheries in Antarctica were not analysed due to data limitations. Food security is also affected by crop and fishery failures not presented here. {*WGII Fig. TS.5, WGII Fig TS.9, WGII Annex I: Global to Regional Atlas Figure AI.15, Figure AI.22, Figure AI.23, Figure AI.29; WGII 7.3.1.2, 7.2.4.1, SROCC Figure SPM.3*} (*3.1.2, Cross-Section Box.2*)

Risks are increasing with every increment of warming

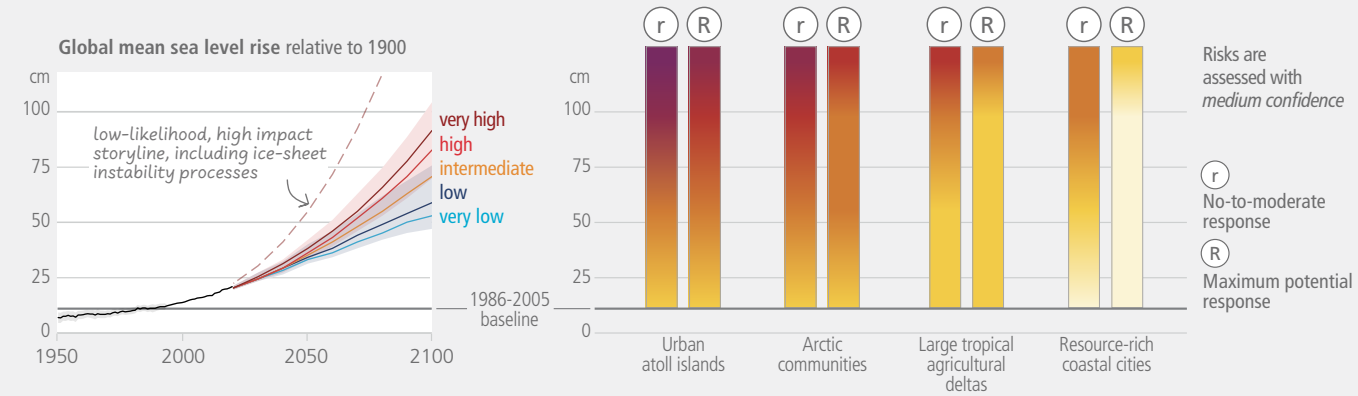
a) High risks are now assessed to occur at lower global warming levels



b) Risks differ by system

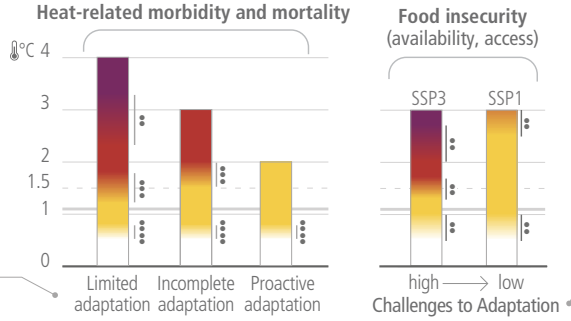


c) Risks to coastal geographies increase with sea level rise and depend on responses



d) Adaptation and socio-economic pathways affect levels of climate related risks

Limited adaptation (failure to proactively adapt; low investment in health systems); incomplete adaptation (incomplete adaptation planning; moderate investment in health systems); proactive adaptation (proactive adaptation management; higher investment in health systems)



The SSP1 pathway illustrates a world with low population growth, high income, and reduced inequalities, food produced in low GHG emission systems, effective land use regulation and high adaptive capacity (i.e., low challenges to adaptation). The SSP3 pathway has the opposite trends.

e) Examples of key risks in different regions

Absence of risk diagrams does not imply absence of risks within a region. The development of synthetic diagrams for Small Islands, Asia and Central and South America was limited due to the paucity of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socioeconomic contexts across countries within a region, and the resulting few numbers of impact and risk projections for different warming levels.

The risks listed are of at least *medium confidence* level:

Small Islands
- Loss of terrestrial, marine and coastal biodiversity and ecosystem services
- Loss of lives and assets, risk to food security and economic disruption due to destruction of settlements and infrastructure
- Economic decline and livelihood failure of fisheries, agriculture, tourism and from biodiversity loss from traditional agroecosystems
- Reduced habitability of reef and non-reef islands leading to increased displacement
- Risk to water security in almost every small island

North America
- Climate-sensitive mental health outcomes, human mortality and morbidity due to increasing average temperature, weather and climate extremes, and compound climate hazards
- Risk of degradation of marine, coastal and terrestrial ecosystems, including loss of biodiversity, function, and protective services
- Risk to freshwater resources with consequences for ecosystems, reduced surface water availability for irrigated agriculture, other human uses, and degraded water quality
- Risk to food and nutritional security through changes in agriculture, livestock, hunting, fisheries, and aquaculture productivity and access
- Risks to well-being, livelihoods and economic activities from cascading and compounding climate hazards, including risks to coastal cities, settlements and infrastructure from sea level rise

Europe
- Risks to people, economies and infrastructures due to coastal and inland flooding
- Stress and mortality to people due to increasing temperatures and heat extremes
- Marine and terrestrial ecosystems disruptions
- Water scarcity to multiple interconnected sectors
- Losses in crop production, due to compound heat and dry conditions, and extreme weather

Central and South America
- Risk to water security
- Severe health effects due to increasing epidemics, in particular vector-borne diseases
- Coral reef ecosystems degradation due to coral bleaching
- Risk to food security due to frequent/extreme droughts
- Damages to life and infrastructure due to floods, landslides, sea level rise, storm surges and coastal erosion

Australasia
- Degradation of tropical shallow coral reefs and associated biodiversity and ecosystem service values
- Loss of human and natural systems in low-lying coastal areas due to sea level rise
- Impact on livelihoods and incomes due to decline in agricultural production
- Increase in heat-related mortality and morbidity for people and wildlife
- Loss of alpine biodiversity in Australia due to less snow

Asia
- Urban infrastructure damage and impacts on human well-being and health due to flooding, especially in coastal cities and settlements
- Biodiversity loss and habitat shifts as well as associated disruptions in dependent human systems across freshwater, land, and ocean ecosystems
- More frequent, extensive coral bleaching and subsequent coral mortality induced by ocean warming and acidification, sea level rise, marine heat waves and resource extraction
- Decline in coastal fishery resources due to sea level rise, decrease in precipitation in some parts and increase in temperature
- Risk to food and water security due to increased temperature extremes, rainfall variability and drought

Africa
- Species extinction and reduction or irreversible loss of ecosystems and their services, including freshwater, land and ocean ecosystems
- Risk to food security, risk of malnutrition (micronutrient deficiency), and loss of livelihood due to reduced food production from crops, livestock and fisheries
- Risks to marine ecosystem health and to livelihoods in coastal communities
- Increased human mortality and morbidity due to increased heat and infectious diseases (including vector-borne and diarrhoeal diseases)
- Reduced economic output and growth, and increased inequality and poverty rates
- Increased risk to water and energy security due to drought and heat

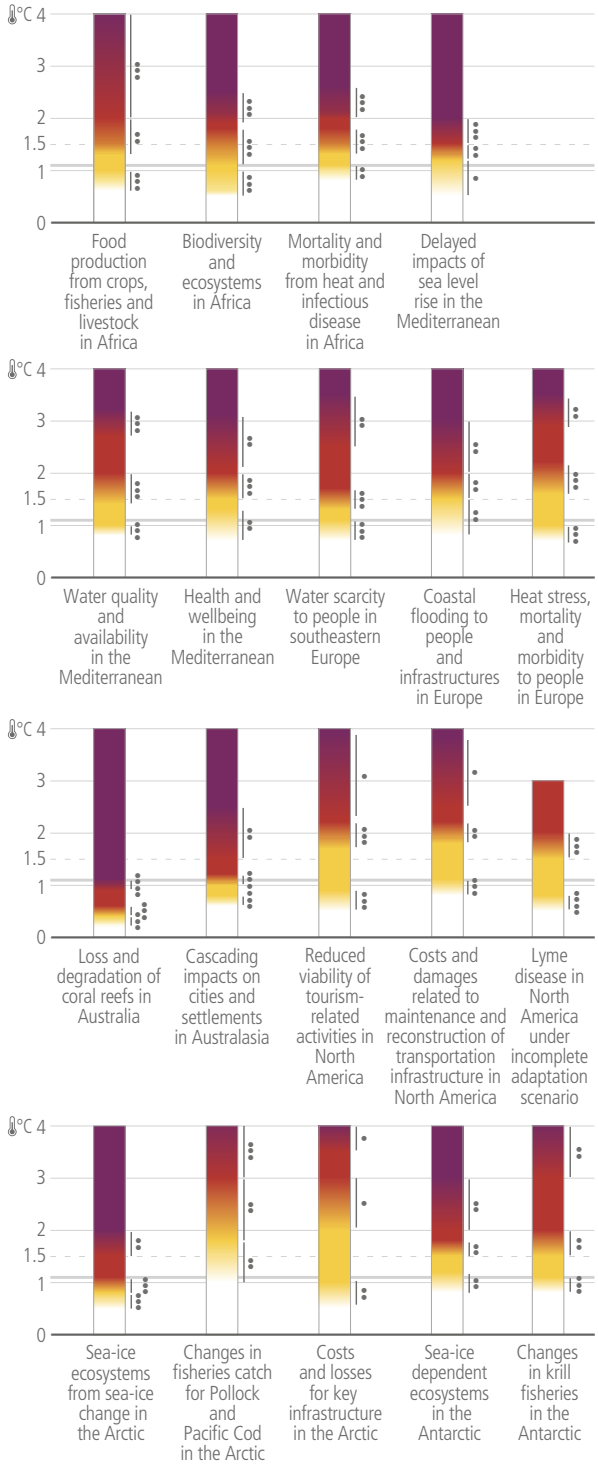


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Figure 3.3: Synthetic risk diagrams of global and sectoral assessments and examples of regional key risks. The burning embers result from a literature based expert elicitation. **Panel (a): Left** - Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity. *Very likely* ranges are shown for the low and high GHG emissions scenarios (SSP1-2.6 and SSP3-7.0). **Right** - Global Reasons for Concern, comparing AR6 (thick embers) and AR5 (thin embers) assessments. Diagrams are shown for each RFC, assuming low to no adaptation (i.e., adaptation is fragmented, localised and comprises incremental adjustments to existing practices). However, the transition to a very high-risk level has an emphasis on irreversibility and adaptation limits. The horizontal line denotes the present global warming of 1.1°C which is used to separate the observed, past impacts below the line from the future projected risks above it. Lines connect the midpoints of the transition from moderate to high risk across AR5 and AR6. **Panel (b)**: Risks for land-based systems and ocean/coastal ecosystems. Diagrams shown for each risk assume low to no adaptation. Text bubbles indicate examples of impacts at a given warming level. **Panel (c): Left -** Global mean sea level change in centimetres, relative to 1900. The historical changes (black) are observed by tide gauges before 1992 and altimeters afterwards. The future changes to 2100 (coloured lines and shading) are assessed consistently with observational constraints based on emulation of CMIP, ice-sheet, and glacier models, and *likely* ranges are shown for SSP1-2.6 and SSP3-7.0. **Right** - Assessment of the combined risk of coastal flooding, erosion and salinization for four illustrative coastal geographies in 2100, due to changing mean and extreme sea levels, under two response scenarios, with respect to the SROCC baseline period (1986–2005) and indicating the IPCC AR6 baseline period (1995–2014). The assessment does not account for changes in extreme sea level beyond those directly induced by mean sea level rise; risk levels could increase if other changes in extreme sea levels were considered (e.g., due to changes in cyclone intensity). "No-to-moderate response" describes efforts as of today (i.e., no further significant action or new types of actions). "Maximum potential response" represents a combination of responses implemented to their full extent and thus significant additional efforts compared to today, assuming minimal financial, social and political barriers. The assessment criteria include exposure and vulnerability (density of assets, level of degradation of terrestrial and marine buffer ecosystems), coastal hazards (flooding, shoreline erosion, salinization), in-situ responses (hard engineered coastal defences, ecosystem restoration or creation of new natural buffers areas, and subsidence management) and planned relocation. Planned relocation refers to managed retreat or resettlement. Forced displacement is not considered in this assessment. The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation. **Panel (d): Left** - Heat-sensitive human health outcomes under three scenarios of adaptation effectiveness. The diagrams are truncated at the nearest whole °C within the range of temperature change in 2100 under three SSP scenarios. **Right** - Risks associated with food security due to climate change and patterns of socio-economic development. Risks to food security include availability and access to food, including population at risk of hunger, food price increases and increases in disability adjusted life years attributable to childhood underweight. Risks are assessed for two contrasted socio-economic pathways (SSP1 and SSP3) excluding the effects of targeted mitigation and adaptation policies. **Panel (e)**: Examples of regional key risks. Risks identified are of at least *medium confidence* level. Key risks are identified based on the magnitude of adverse consequences (pervasiveness of the consequences, degree of change, irreversibility of consequences, potential for impact thresholds or tipping points, potential for cascading effects beyond system boundaries); likelihood of adverse consequences; temporal characteristics of the risk; and ability to respond to the risk, e.g., by adaptation. {*WGI Figure SPM.8; WGII SPM B.3.3, WGII Figure SPM.3, WGII SM 16.6, WGII SM 16.7.4; SROCC Figure SPM.3d, SROCC SPM.5a, SROCC 4SM; SRCCL Figure SPM.2, SRCCL 7.3.1, SRCCL 7 SM*} (*Cross-Section Box.2*)

3.1.3 The Likelihood and Risks of Abrupt and Irreversible Change

The likelihood of abrupt and irreversible changes and their impacts increase with higher global warming levels (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems such as forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C to 2.5°C (*medium confidence*) and to very high risk between 2.5°C to 4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*). {*WGI SPM C.3.2, WGI Box TS.9, WGI TS.2.6; WGII Figure SPM.3, WGII SPM B.3.1, WGII SPM B.4.1, WGII SPM B.5.2, WGII Table TS.1, WGII TS.C.1, WGII TS.C.13.3; SROCC SPM B.4*}

Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*). Global mean sea level rise will continue in the 21st century (*virtually certain*), with projected regional relative sea level rise within 20% of the global mean along two-thirds of the global coastline (*medium confidence*). The magnitude, the rate, the timing of threshold exceedances, and the long-term commitment of sea level rise depend on emissions, with higher emissions leading to greater and faster rates of sea level rise. Due to relative sea level rise, extreme sea level events that occurred once per century in the recent past are projected to occur at least annually at more than half of all tide gauge locations by 2100 and risks for coastal ecosystems, people and infrastructure will continue to increase beyond 2100 (*high confidence*). At sustained warming levels between 2°C and 3°C, the Greenland and West Antarctic ice sheets will be lost almost completely and irreversibly over multiple millennia (*limited evidence*). The probability and rate of ice mass loss increase with higher global surface temperatures (*high confidence*). Over the next 2000 years, global mean sea level will rise by about 2 to 3 m if warming is limited to 1.5°C and 2 to 6 m if limited to 2°C (*low confidence*). Projections of multi-millennial global mean sea level rise are consistent with reconstructed levels during past warm climate periods: global mean sea level was *very likely* 5 to 25 m higher than today roughly 3 million years ago, when global temperatures were 2.5°C to 4°C higher than 1850–1900 (*medium confidence*). Further examples of unavoidable changes in the climate system due to multi-decadal or longer response timescales include continued glacier melt (*very high confidence*) and permafrost carbon loss (*high confidence*). {*WGI SPM B.5.2, WGI SPM B.5.3, WGI SPM B.5.4, WGI SPM C.2.5, WGI Box TS.4, WGI Box TS.9, WGI 9.5.1; WGII TS C.5; SROCC SPM B.3, SROCC SPM B.6, SROCC SPM B.9*} (*Figure 3.4*)

The probability of low-likelihood outcomes associated with potentially very large impacts increases with higher global warming levels (*high confidence*). Warming substantially above the assessed *very likely* range for a given scenario cannot be ruled out, and there is *high confidence* this would lead to regional changes greater than assessed in many aspects of the climate system. Low-likelihood, high-impact outcomes could occur at regional scales even for global warming within the *very likely* assessed range for a given GHG emissions scenario. Global mean sea level rise above the *likely* range – approaching 2 m by 2100 and in excess of 15 m by 2300 under a very high GHG emissions scenario (SSP5-8.5) (*low confidence*) – cannot be ruled out due to deep uncertainty in ice-sheet processes[123] and would have severe

[123] This outcome is characterised by deep uncertainty: Its likelihood defies quantitative assessment but is considered due to its high potential impact. {*WGI Box TS.1; WGII Cross-Chapter Box DEEP*}

impacts on populations in low elevation coastal zones. If global warming increases, some compound extreme events[124] will become more frequent, with higher likelihood of unprecedented intensities, durations or spatial extent (*high confidence*). The Atlantic Meridional Overturning Circulation is *very likely* to weaken over the 21st century for all considered scenarios (*high confidence*), however an abrupt collapse is not expected before 2100 (*medium confidence*). If such a low probability event were to occur, it would *very likely* cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and large impacts on ecosystems and human activities. A sequence of large explosive volcanic eruptions within decades, as have occurred in the past, is a low-likelihood high-impact event that would lead to substantial cooling globally and regional climate perturbations over several decades. {*WGI SPM B.5.3, WGI SPM C.3, WGI SPM C.3.1, WGI SPM C.3.2, WGI SPM C.3.3, WGI SPM C.3.4, WGI SPM C.3.5, WGI Figure SPM.8, WGI Box TS.3, WGI Figure TS.6, WGI Box 9.4; WGII SPM B.4.5, WGII SPM C.2.8; SROCC SPM B.2.7*} (*Figure 3.4, Cross-Section Box.2*)

3.2 Long-term Adaptation Options and Limits

With increasing warming, adaptation options will become more constrained and less effective. At higher levels of warming, losses and damages will increase, and additional human and natural systems will reach adaptation limits. Integrated, cross-cutting multi-sectoral solutions increase the effectiveness of adaptation. Maladaptation can create lock-ins of vulnerability, exposure and risks but can be avoided by long-term planning and the implementation of adaptation actions that are flexible, multi-sectoral and inclusive. (*high confidence*)

The effectiveness of adaptation to reduce climate risk is documented for specific contexts, sectors and regions and will decrease with increasing warming (*high confidence*)[125]. For example, common adaptation responses in agriculture – adopting improved cultivars and agronomic practices, and changes in cropping patterns and crop systems – will become less effective from 2°C to higher levels of warming (*high confidence*). The effectiveness of most water-related adaptation options to reduce projected risks declines with increasing warming (*high confidence*). Adaptations for hydropower and thermo-electric power generation are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming (*medium confidence*). Ecosystem-based Adaptation is vulnerable to climate change impacts, with effectiveness declining with increasing global warming (*high confidence*). Globally, adaptation options related to agroforestry and forestry have a sharp decline in effectiveness at 3°C, with a substantial increase in residual risk (*medium confidence*). {*WGII SPM C.2, WGII SPM C.2.1, WGII SPM C.2.5, WGII SPM C.2.10, WGII Figure TS.6 Panel (e), 4.7.2*}

With increasing global warming, more limits to adaptation will be reached and losses and damages, strongly concentrated among the poorest vulnerable populations, will increase (*high confidence*). Already below 1.5°C, autonomous and evolutionary adaptation responses by terrestrial and aquatic ecosystems will increasingly face hard limits (*high confidence*) (Section 2.1.2). Above 1.5°C, some ecosystem-based adaptation measures will lose their effectiveness in providing benefits to people as these ecosystems will reach hard adaptation limits (*high confidence*). Adaptation to address the risks of heat stress, heat mortality and reduced capacities for outdoor work for humans face soft and hard limits across regions that become significantly more severe at 1.5°C, and are particularly relevant for regions with warm climates (*high confidence*). Above 1.5°C global warming level, limited freshwater resources pose potential hard limits for small islands and for regions dependent on glacier and snow melt (*medium confidence*). By 2°C, soft limits are projected for multiple staple crops, particularly in tropical regions (*high confidence*). By 3°C, soft limits are projected for some water management measures for many regions, with hard limits projected for parts of Europe (*medium confidence*). {*WGII SPM C.3, WGII SPM C.3.3, WGII SPM C.3.4, WGII SPM C.3.5, WGII TS.D.2.2, WGII TS.D.2.3; SR1.5 SPM B.6; SROCC SPM C.1*}

Integrated, cross-cutting multi-sectoral solutions increase the effectiveness of adaptation. For example, inclusive, integrated and long-term planning at local, municipal, sub-national and national scales, together with effective regulation and monitoring systems and financial and technological resources and capabilities foster urban and rural system transition. There are a range of cross-cutting adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing that have broad applicability across sectors and provide greater benefits to other adaptation options when combined. Transitioning from incremental to transformational adaptation, and addressing a range of constraints, primarily in the financial, governance, institutional and policy domains, can help overcome soft adaptation limits. However, adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. (*high confidence*) {*WGII SPM C.2, WGII SPM C.2.6, WGII SPM.C.2.13, WGII SPM C.3.1, WGII SPM.C.3.4, WGII SPM C.3.5, WGII Figure TS.6 Panel (e)*}

Maladaptive responses to climate change can create lock-ins of vulnerability, exposure and risks that are difficult and expensive to change and exacerbate existing inequalities. Actions that focus on sectors and risks in isolation and on short-term gains often lead to maladaptation. Adaptation options can become maladaptive due to their environmental impacts that constrain ecosystem services and decrease biodiversity and ecosystem resilience to climate change or by causing adverse outcomes for different groups, exacerbating inequity. Maladaptation can be avoided by flexible, multi-sectoral, inclusive and

[124] See Annex I: Glossary. Examples of compound extreme events are concurrent heatwaves and droughts or compound flooding. {*WGI SPM Footnote 18*}

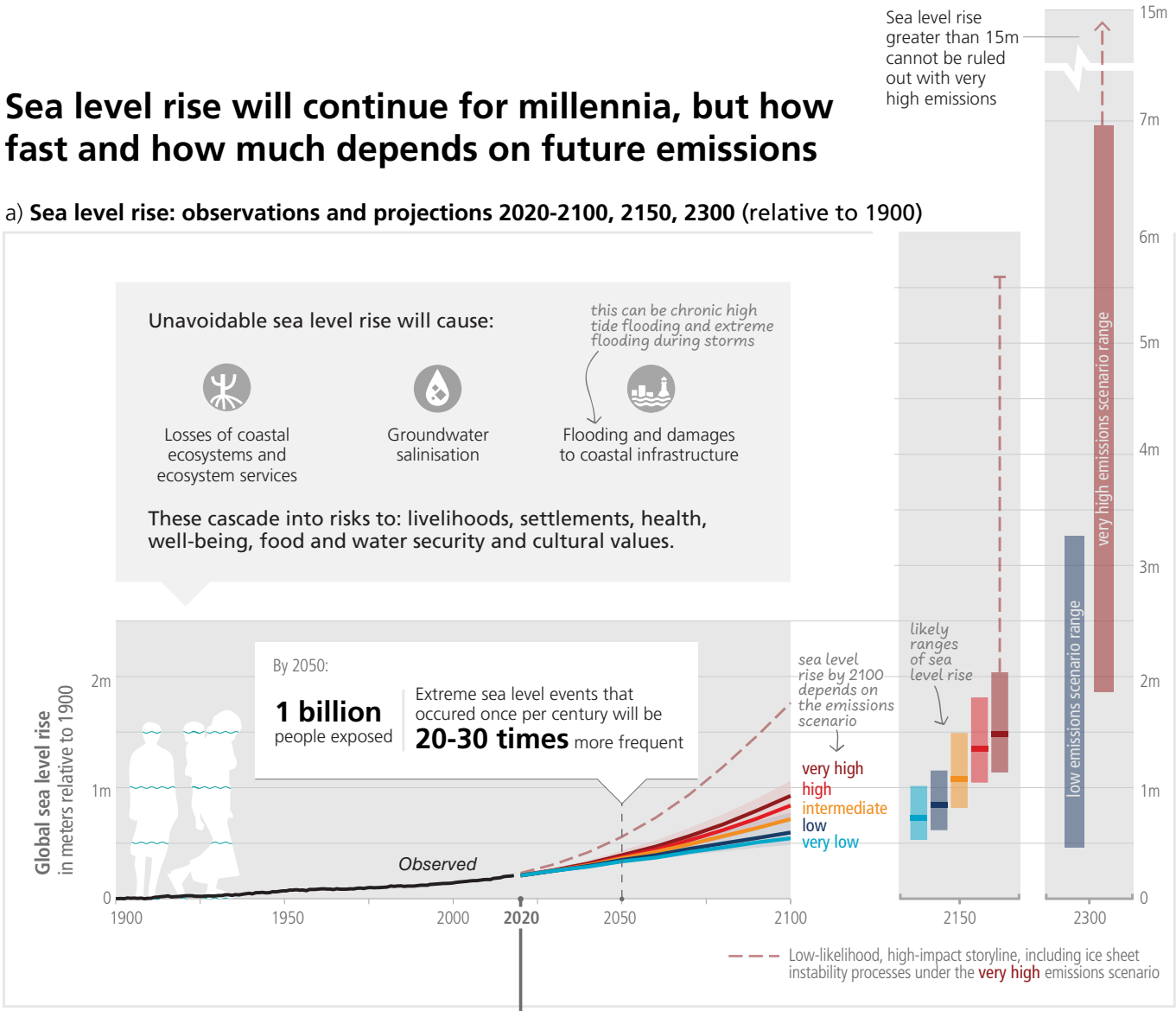
[125] There are limitations to assessing the full scope of adaptation options available in the future since not all possible future adaptation responses can be incorporated in climate impact models, and projections of future adaptation depend on currently available technologies or approaches. {*WGII 4.7.2*}

long-term planning and implementation of adaptation actions with benefits to many sectors and systems. (*high confidence*) {*WGII SPM C.4, WGII SPM.C.4.1, WGII SPM C.4.2, WGII SPM C.4.3*}

Sea level rise poses a distinctive and severe adaptation challenge as it implies both dealing with slow onset changes and increases in the frequency and magnitude of extreme sea level events (*high confidence*). Such adaptation challenges would occur much earlier under high rates of sea level rise (*high confidence*). Responses to ongoing sea level rise and land subsidence include protection, accommodation, advance and planned relocation (*high confidence*). These responses are more effective if combined and/or sequenced, planned well ahead, aligned with sociocultural values and underpinned by inclusive community engagement processes (*high confidence*). Ecosystem-based solutions such as wetlands provide co-benefits for the environment and climate mitigation, and reduce costs for flood defences (*medium confidence)*, but have site-specific physical limits, at least above 1.5ºC of global warming (*high confidence*) and lose effectiveness at high rates of sea level rise beyond 0.5 to 1 cm yr^{-1} (*medium confidence*). Seawalls can be maladaptive as they effectively reduce impacts in the short term but can also result in lock-ins and increase exposure to climate risks in the long term unless they are integrated into a long-term adaptive plan (*high confidence*). {*WGI SPM C.2.5; WGII SPM C.2.8, WGII SPM C.4.1; WGII 13.10, WGII Cross-Chapter Box SLR; SROCC SPM B.9, SROCC SPM C.3.2, SROCC Figure SPM.4, SROCC Figure SPM.5c*} (*Figure 3.4*)

Sea level rise will continue for millennia, but how fast and how much depends on future emissions

a) **Sea level rise: observations and projections 2020-2100, 2150, 2300** (relative to 1900)



Responding to sea level rise requires long-term planning

b) **Typical timescales of coastal risk-management measures**

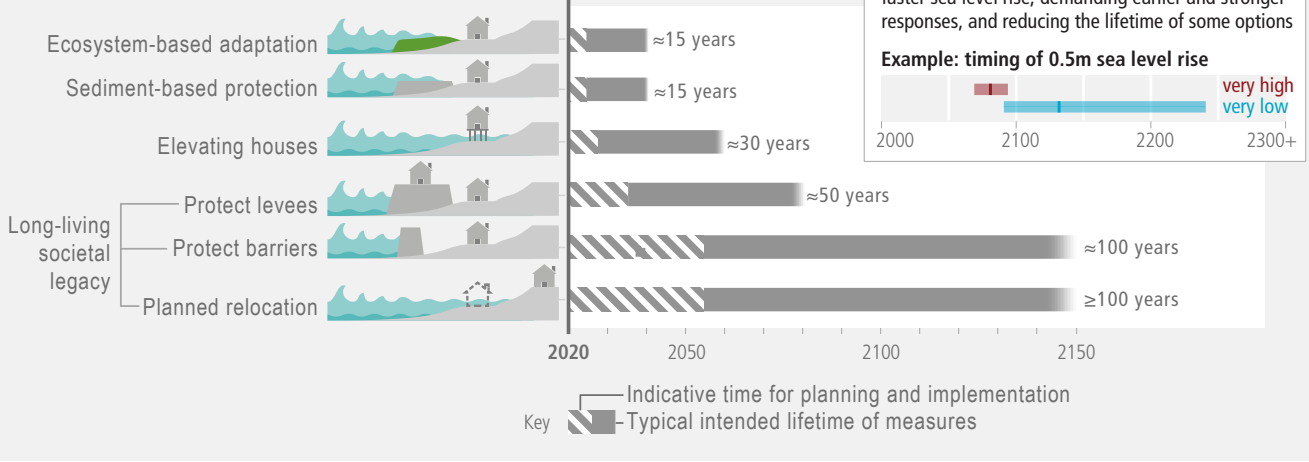


Figure 3.4: Observed and projected global mean sea level change and its impacts, and time scales of coastal risk management. Panel (a): Global mean sea level change in metres relative to 1900. The historical changes (black) are observed by tide gauges before 1992 and altimeters afterwards. The future changes to 2100 and for 2150 (coloured lines and shading) are assessed consistently with observational constraints based on emulation of CMIP, ice-sheet, and glacier models, and median values and *likely* ranges are shown for the considered scenarios. Relative to 1995-2014, the *likely* global mean sea level rise by 2050 is between 0.15 to 0.23 m in the very low GHG emissions scenario (SSP1-1.9) and 0.20 to 0.29 m in the very high GHG emissions scenario (SSP5-8.5); by 2100 between 0.28 to 0.55 m under SSP1-1.9 and 0.63 to 1.01 m under SSP5-8.5; and by 2150 between 0.37 to 0.86 m under SSP1-1.9 and 0.98 to 1.88 m under SSP5-8.5 *(medium confidence)*. Changes relative to 1900 are calculated by adding 0.158 m (observed global mean sea level rise from 1900 to 1995-2014) to simulated changes relative to 1995-2014. The future changes to 2300 (bars) are based on literature assessment, representing the 17th–83rd percentile range for SSP1-2.6 (0.3 to 3.1 m) and SSP5-8.5 (1.7 to 6.8 m). Red dashed lines: Low-likelihood, high-impact storyline, including ice sheet instability processes. These indicate the potential impact of deeply uncertain processes, and show the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact processes that cannot be ruled out; because of *low confidence* in projections of these processes, this is not part of a *likely* range. IPCC AR6 global and regional sea level projections are hosted at https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool. The low-lying coastal zone is currently home to around 896 million people (nearly 11% of the 2020 global population), projected to reach more than one billion by 2050 across all five SSPs. **Panel (b):** Typical time scales for the planning, implementation (dashed bars) and operational lifetime of current coastal risk-management measures (blue bars). Higher rates of sea level rise demand earlier and stronger responses and reduce the lifetime of measures (inset). As the scale and pace of sea level rise accelerates beyond 2050, long-term adjustments may in some locations be beyond the limits of current adaptation options and for some small islands and low-lying coasts could be an existential risk. {*WGI SPM B.5, WGI C.2.5, WGI Figure SPM.8, WGI 9.6; WGII SPM B.4.5, WGII B.5.2, WGII C.2.8, WGII D.3.3, WGII TS.D.7, WGII Cross-Chapter Box SLR*} (*Cross-Section Box.2*)

3.3 Mitigation Pathways

Limiting human-caused global warming requires net zero anthropogenic CO_2 emissions. Pathways consistent with 1.5°C and 2°C carbon budgets imply rapid, deep, and in most cases immediate GHG emission reductions in all sectors (*high confidence*). Exceeding a warming level and returning (i.e. overshoot) implies increased risks and potential irreversible impacts; achieving and sustaining global net negative CO_2 emissions would reduce warming (*high confidence*).

3.3.1 Remaining Carbon Budgets

Limiting global temperature increase to a specific level requires limiting cumulative net CO_2 emissions to within a finite carbon budget[126], along with strong reductions in other GHGs. For every 1000 $GtCO_2$ emitted by human activity, global mean temperature rises by *likely* 0.27°C to 0.63°C (best estimate of 0.45°C). This relationship implies that there is a finite carbon budget that cannot be exceeded in order to limit warming to any given level. {*WGI SPM D.1, WGI SPM D.1.1; SR1.5 SPM C.1.3*} (*Figure 3.5*)

The best estimates of the remaining carbon budget (RCB) from the beginning of 2020 for limiting warming to 1.5°C with a 50% likelihood[127] is estimated to be 500 $GtCO_2$; for 2°C (67% likelihood) this is 1150 $GtCO_2$.[128] Remaining carbon budgets have been quantified based on the assessed value of TCRE and its uncertainty, estimates of historical warming, climate system feedbacks such as emissions from thawing permafrost, and the global surface temperature change after global anthropogenic CO_2 emissions reach net zero, as well as variations in projected warming from non-CO_2 emissions due in part to mitigation action. The stronger the reductions in non-CO_2 emissions the lower the resulting temperatures are for a given RCB or the larger RCB for the same level of temperature change. For instance, the RCB for limiting warming to 1.5°C with a 50% likelihood could vary between 300 to 600 $GtCO_2$ depending on non-CO_2 warming[129]. Limiting warming to 2°C with a 67% (or 83%) likelihood would imply a RCB of 1150 (900) $GtCO_2$ from the beginning of 2020. To stay below 2°C with a 50% likelihood, the RCB is higher, i.e., 1350 $GtCO_2$[130]. {*WGI SPM D.1.2, WGI Table SPM.2; WGIII Box SPM.1, WGIII Box 3.4; SR1.5 SPM C.1.3*}

If the annual CO_2 emissions between 2020–2030 stayed, on average, at the same level as 2019, the resulting cumulative emissions would almost exhaust the remaining carbon budget for 1.5°C (50%), and exhaust more than a third of the remaining carbon budget for 2°C (67%) (Figure 3.5). Based on central estimates only, historical cumulative net CO_2 emissions between 1850 and 2019 (2400 ±240 $GtCO_2$) amount to about four-fifths[131] of the total carbon budget for a 50% probability of limiting global warming to 1.5°C (central estimate about 2900 $GtCO_2$) and to about two-thirds[132] of the total carbon budget for a 67% probability to limit global warming to 2°C (central estimate about 3550 $GtCO_2$). {*WGI Table SPM.2; WGIII SPM B.1.3, WGIII Table 2.1*}

In scenarios with increasing CO_2 emissions, the land and ocean carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere (*high confidence*). While natural land and ocean carbon sinks are projected to take up, in absolute terms, a progressively larger amount of CO_2 under higher compared to lower CO_2 emissions scenarios, they become less effective, that is, the proportion of emissions taken up by land and ocean decreases with increasing cumulative net CO_2 emissions (*high confidence*). Additional ecosystem responses to warming not yet fully included in climate models, such as GHG fluxes from wetlands, permafrost thaw, and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*). In scenarios where CO_2 concentrations peak and decline during the 21st century, the land and ocean begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 in the very low GHG emissions scenario (*medium confidence*)[133]. {*WGI SPM B.4, WGI SPM B.4.1, WGI SPM B.4.2, WGI SPM B.4.3*}

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126 See Annex I: Glossary.

127 This likelihood is based on the uncertainty in transient climate response to cumulative net CO_2 emissions and additional Earth system feedbacks and provides the probability that global warming will not exceed the temperature levels specified. {*WGI Table SPM.1*}

128 Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Most countries report their anthropogenic land CO_2 fluxes including fluxes due to human-caused environmental change (e.g., CO_2 fertilisation) on 'managed' land in their National GHG inventories. Using emissions estimates based on these inventories, the remaining carbon budgets must be correspondingly reduced. {*WGIII SPM Footnote 9, WGIII TS.3, WGIII Cross-Chapter Box 6*}

129 The central case RCB assumes future non-CO_2 warming (the net additional contribution of aerosols and non-CO_2 GHG) of around 0.1°C above 2010–2019 in line with stringent mitigation scenarios. If additional non-CO_2 warming is higher, the RCB for limiting warming to 1.5°C with a 50% likelihood shrinks to around 300 $GtCO_2$. If, however, additional non-CO_2 warming is limited to only 0.05°C (via stronger reductions of CH_4 and N_2O through a combination of deep structural and behavioural changes, e.g., dietary changes), the RCB could be around 600 $GtCO_2$ for 1.5°C warming. {*WGI Table SPM.2, WGI Box TS.7; WGIII Box 3.4*}

130 When adjusted for emissions since previous reports, these RCB estimates are similar to SR1.5 but larger than AR5 values due to methodological improvements. {*WGI SPM D.1.3*}

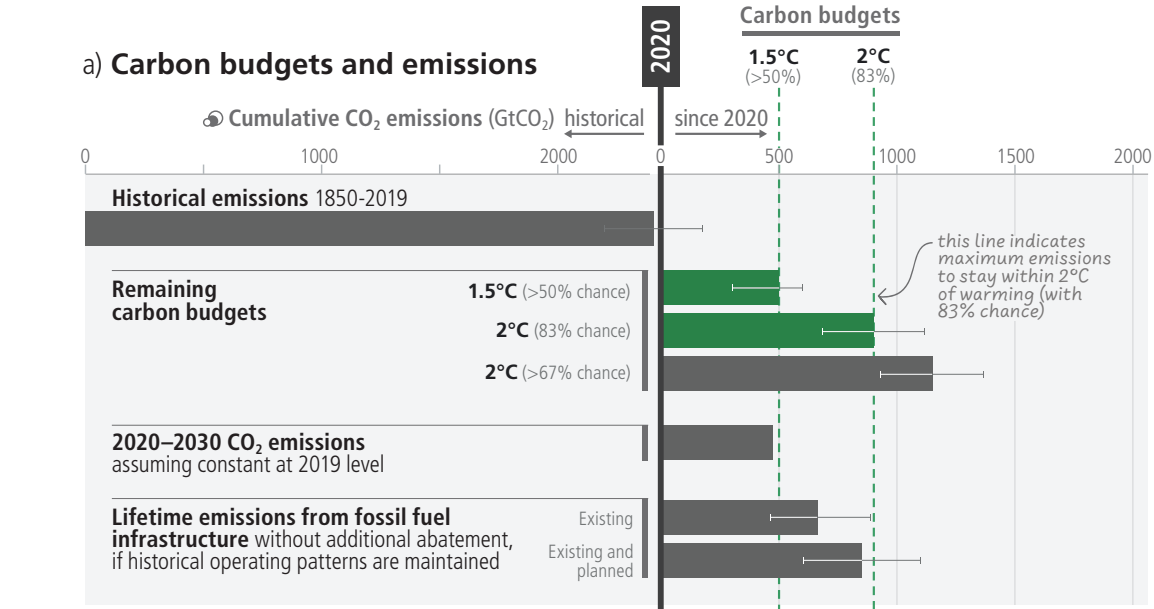
131 Uncertainties for total carbon budgets have not been assessed and could affect the specific calculated fractions.

132 See footnote 131.

133 These projected adjustments of carbon sinks to stabilisation or decline of atmospheric CO_2 concentrations are accounted for in calculations of remaining carbon budgets. {*WGI SPM footnote 32*}

Remaining carbon budgets to limit warming to 1.5°C could soon be exhausted, and those for 2°C largely depleted

Remaining carbon budgets are similar to emissions from use of existing and planned fossil fuel infrastructure, without additional abatement



Every ton of CO_2 adds to global warming

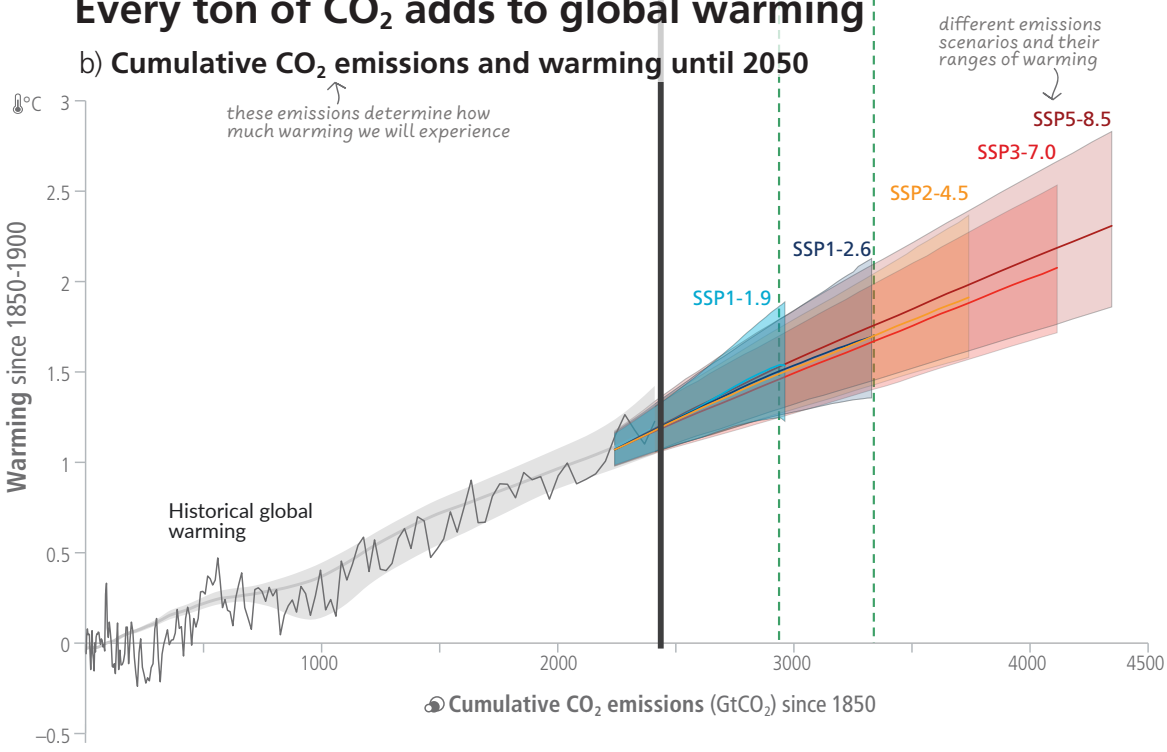


Figure 3.5: Cumulative past, projected, and committed emissions, and associated global temperature changes. Panel (a) Assessed remaining carbon budgets to limit warming *more likely than not* to 1.5°C, to 2°C with a 83% and 67% likelihood, compared to cumulative emissions corresponding to constant 2019 emissions until 2030, existing and planned fossil fuel infrastructures (in $GtCO_2$). For remaining carbon budgets, thin lines indicate the uncertainty due to the contribution of non-CO_2 warming. For lifetime emissions from fossil fuel infrastructure, thin lines indicate the assessed sensitivity range. **Panel (b)** Relationship between cumulative CO_2 emissions and the increase in global surface temperature. Historical data (thin black line) shows historical CO_2 emissions versus observed global surface temperature increase relative to the period 1850-1900. The grey range with its central line shows a corresponding estimate of the human-caused share of historical warming. Coloured areas show the assessed *very likely* range of global surface temperature projections, and thick coloured central lines show the median estimate as a function of cumulative CO_2 emissions for the selected scenarios SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Projections until 2050 use the cumulative CO_2 emissions of each respective scenario, and the projected global warming includes the contribution from all anthropogenic forcers. {*WGI SPM D.1, WGI Figure SPM.10, WGI Table SPM.2; WGIII SPM B.1, WGIII SPM B.7, WGIII 2.7; SR1.5 SPM C.1.3*}

Table 3.1: Key characteristics of the modelled global emissions pathways. Summary of projected CO_2 and GHG emissions, projected net zero timings and the resulting global warming outcomes. Pathways are categorised (columns), according to their likelihood of limiting warming to different peak warming levels (if peak temperature occurs before 2100) and 2100 warming levels. Values shown are for the median [p50] and 5–95th percentiles [p5–p95], noting that not all pathways achieve net zero CO_2 or GHGs. {*WGIII Table SPM.2*}

p50 [p5-p95] (1)	Category (2) [# pathways]	Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box1. The five illustrative scenarios (SSPx-yy) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.	C1 [97]	C1a [50]	C1b [47]	C2 [133]	C3 [311]	C3a [204]	C3b [97]	C4 [159]	C5 [212]	C6 [97]
	Category/ subset label		limit warming to 1.5°C (>50%) with no or limited overshoot	… with net zero GHGs	… without net zero GHGs	return warming to 1.5°C (>50%) after a high overshoot	limit warming to 2°C (>67%)	… with action starting in 2020	… NDCs until 2030	limit warming to 2°C (>50%)	limit warming to 2.5°C (>50%)	limit warming to 3°C (>50%)
GHG emissions reductions from 2019 (%) (3)	2030	Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th-95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019	43 [34-60]	41 [31-59]	48 [35-61]	23 [0-44]	21 [1-42]	27 [13-45]	5 [0-14]	10 [0-27]	6 [-1 to 18]	2 [-10 to 11]
	2040		69 [58-90]	66 [58-89]	70 [62-87]	55 [40-71]	46 [34-63]	47 [35-63]	46 [34-63]	31 [20-5]	18 [4-33]	3 [-14 to 14]
	2050		84 [73-98]	85 [72-100]	84 [76-93]	75 [62-91]	64 [53-77]	63 [52-76]	68 [56-83]	49 [35-65]	29 [11-48]	5 [-2 to 18]
Emissions milestones (4)	Net zero CO_2 (% net zero pathways)	Median 5-year intervals at which projected CO_2 & GHG emissions of pathways in this category reach net-zero, with the 5th-95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (…) denotes net zero not reached for that percentile.	2050-2055 (100%) [2035-2070]			2055-2060 (100%) [2045-2070]	2070-2075 (93%) [2055-...]	2070-2075 (91%) [2055-...]	2065-2070 (97%) [2055-2090]	2080-2085 (86%) [2065-...]	...-... (41%) [2080-...]	no net-zero
	Net zero GHGs (5) (% net zero pathways)		2095-2100 (52%) [2050-...]	2070-2075 (100%) [2050-2090]	...-... (0%) [...-...]	2070-2075 (87%) [2055-...]	...-... (30%) [2075-...]	...-... (24%) [2080-...]	...-... (41%) [2075-...]	...-... (31%) [2075-...]	...-... (12%) [2090-...]	no net-zero
Cumulative CO_2 emissions [Gt CO_2] (6)	2020 to net zero CO_2	Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net-zero or until 2100, with the 5th-95th percentile interval in square brackets.	510 [330-710]	550 [340-760]	460 [320-590]	720 [530-930]	890 [640-1160]	860 [640-1180]	910 [720-1150]	1210 [970-1490]	1780 [1400-2360]	no net-zero
	2020–2100		320 [-210-570]	160 [-220-620]	360 [10-540]	400 [-90-620]	800 [510-1140]	790 [480-1150]	800 [560-1050]	1160 [700-1490]	1780 [1260-2360]	2790 [2440-3520]
Global mean temperature changes 50% probability (°C)	at peak warming	Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850-1900, at peak warming and in 2100, for the median value across the scenarios and the 5th-95th percentile interval in square brackets.	1.6 [1.4-1.6]	1.6 [1.4-1.6]	1.6 [1.5-1.6]	1.7 [1.5-1.8]	1.7 [1.6-1.8]	1.7 [1.6-1.8]	1.8 [1.6-1.8]	1.9 [1.7-2.0]	2.2 [1.9-2.5]	no peaking by 2100
	2100		1.3 [1.1-1.5]	1.2 [1.1-1.4]	1.4 [1.3-1.5]	1.4 [1.2-1.5]	1.6 [1.5-1.8]	1.6 [1.5-1.8]	1.6 [1.5-1.7]	1.8 [1.5-2.0]	2.1 [1.9-2.5]	2.7 [2.4-2.9]
Likelihood of peak global warming staying below (%)	<1.5°C	Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th-95th percentile interval in square brackets.	38 [33-58]	38 [34-60]	37 [33-56]	24 [15-42]	20 [13-41]	21 [14-42]	17 [12-35]	11 [7-22]	4 [0-10]	0 [0-0]
	<2.0°C		90 [86-97]	90 [85-97]	89 [87-96]	82 [71-93]	76 [68-91]	78 [69-91]	73 [67-87]	59 [50-77]	37 [18-59]	8 [2-18]
	<3.0°C		100 [99-100]	100 [99-100]	100 [99-100]	100 [99-100]	99 [98-100]	100 [98-100]	99 [98-99]	98 [95-99]	91 [83-98]	71 [53-88]

1 Detailed explanations on the Table are provided in WGIII Box SPM.1 and WGIII Table SPM.2. The relationship between the temperature categories and SSP/RCPs is discussed in Cross-Section Box.2. Values in the table refer to the 50th and [5–95th] percentile values across the pathways falling within a given category as defined in WGIII Box SPM.1. The three dots (…) sign denotes that the value cannot be given (as the value is after 2100 or, for net zero, net zero is not reached). Based on the assessment of climate emulators in AR6 WG I (Chapter 7, Box 7.1), two climate emulators were used for the probabilistic assessment of the resulting warming of the pathways. For the 'Temperature Change' and 'Likelihood' columns, the non-bracketed values represent the 50th percentile across the pathways in that category and the median [50th percentile] across the warming estimates of the probabilistic MAGICC climate model emulator. For the bracketed ranges in the "likelihood" column, the median warming for every pathway in that category is calculated for each of the two climate model emulators (MAGICC and FaIR). These ranges cover both the uncertainty of the emissions pathways as well as the climate emulators' uncertainty. All global warming levels are relative to 1850-1900.

2 C3 pathways are sub-categorised according to the timing of policy action to match the emissions pathways in WGIII Figure SPM.4.

3 Global emission reductions in mitigation pathways are reported on a pathway-by-pathway basis relative to harmonised modelled global emissions in 2019 rather than

the global emissions reported in WGIII SPM Section B and WGIII Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WGI (see WGIII SPM Footnote 49). Negative values (e.g., in C5, C6) represent an increase in emissions. The modelled GHG emissions in 2019 are 55 [53–58] $GtCO_2$-eq, thus within the uncertainty ranges of estimates for 2019 emissions [53-66] $GtCO_2$-eq (see 2.1.1).

4 Emissions milestones are provided for 5-year intervals in order to be consistent with the underlying 5-year time-step data of the modelled pathways. Ranges in square brackets underneath refer to the range across the pathways, comprising the lower bound of the 5th percentile 5-year interval and the upper bound of the 95th percentile 5-year interval. Numbers in round brackets signify the fraction of pathways that reach specific milestones over the 21st century. Percentiles reported across all pathways in that category include those that do not reach net zero before 2100.

5 For cases where models do not report all GHGs, missing GHG species are infilled and aggregated into a Kyoto basket of GHG emissions in CO_2-eq defined by the 100-year global warming potential. For each pathway, reporting of CO_2, CH_4, and N_2O emissions was the minimum required for the assessment of the climate response and the assignment to a climate category. Emissions pathways without climate assessment are not included in the ranges presented here. See WGIII Annex III.II.5.

6 Cumulative emissions are calculated from the start of 2020 to the time of net zero and 2100, respectively. They are based on harmonised net CO_2 emissions, ensuring consistency with the WG I assessment of the remaining carbon budget. {*WGIII Box 3.4, WGIII SPM Footnote 50*}

3.3.2 Net Zero Emissions: Timing and Implications

From a physical science perspective, limiting human-caused global warming to a specific level requires limiting cumulative CO_2 emissions, reaching net zero or net negative CO_2 emissions, along with strong reductions of other GHG emissions (see Cross-Section Box.1). Global modelled pathways that reach and sustain net zero GHG emissions are projected to result in a gradual decline in surface temperature (*high confidence*). Reaching net zero GHG emissions primarily requires deep reductions in CO_2, methane, and other GHG emissions, and implies net negative CO_2 emissions.[134] Carbon dioxide removal (CDR) will be necessary to achieve net negative CO_2 emissions[135]. Achieving global net zero CO_2 emissions, with remaining anthropogenic CO_2 emissions balanced by durably stored CO_2 from anthropogenic removal, is a requirement to stabilise CO_2-induced global surface temperature increase (see 3.3.3) (*high confidence*). This is different from achieving net zero GHG emissions, where metric-weighted anthropogenic GHG emissions (see Cross-Section Box.1) equal CO_2 removal (*high confidence*). Emissions pathways that reach and sustain net zero GHG emissions defined by the 100-year global warming potential imply net negative CO_2 emissions and are projected to result in a gradual decline in surface temperature after an earlier peak (*high confidence*). While reaching net zero CO_2 or net zero GHG emissions requires deep and rapid reductions in gross emissions, the deployment of CDR to counterbalance hard-to-abate residual emissions (e.g., some emissions from agriculture, aviation, shipping, and industrial processes) is unavoidable (*high confidence*). {*WGI SPM D.1, WGI SPM D.1.1, WGI SPM D.1.8; WGIII SPM C.2, WGIII SPM C.3, WGIII SPM C.11, WGIII Box TS.6; SR1.5 SPM A.2.2*}

In modelled pathways, the timing of net zero CO_2 emissions, followed by net zero GHG emissions, depends on several variables, including the desired climate outcome, the mitigation strategy and the gases covered (*high confidence*). Global net zero CO_2 emissions are reached in the early 2050s in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and around the early 2070s in pathways that limit warming to 2°C (>67%). While non-CO_2 GHG emissions are strongly reduced in all pathways that limit warming to 2°C (>67%) or lower, residual emissions of CH_4 and N_2O and F-gases of about 8 [5–11] $GtCO_2$-eq yr^{-1} remain at the time of net zero GHG, counterbalanced by net negative CO_2 emissions. As a result, net zero CO_2 would be reached before net zero GHGs (*high confidence*). {*WGIII SPM C.2, WGIII SPM C.2.3, WGIII SPM C.2.4, WGIII Table SPM.2, WGIII 3.3*} *(Figure 3.6)*

[134] Net zero GHG emissions defined by the 100-year global warming potential. See footnote 70.

[135] See Section 3.3.3 and 3.4.1.

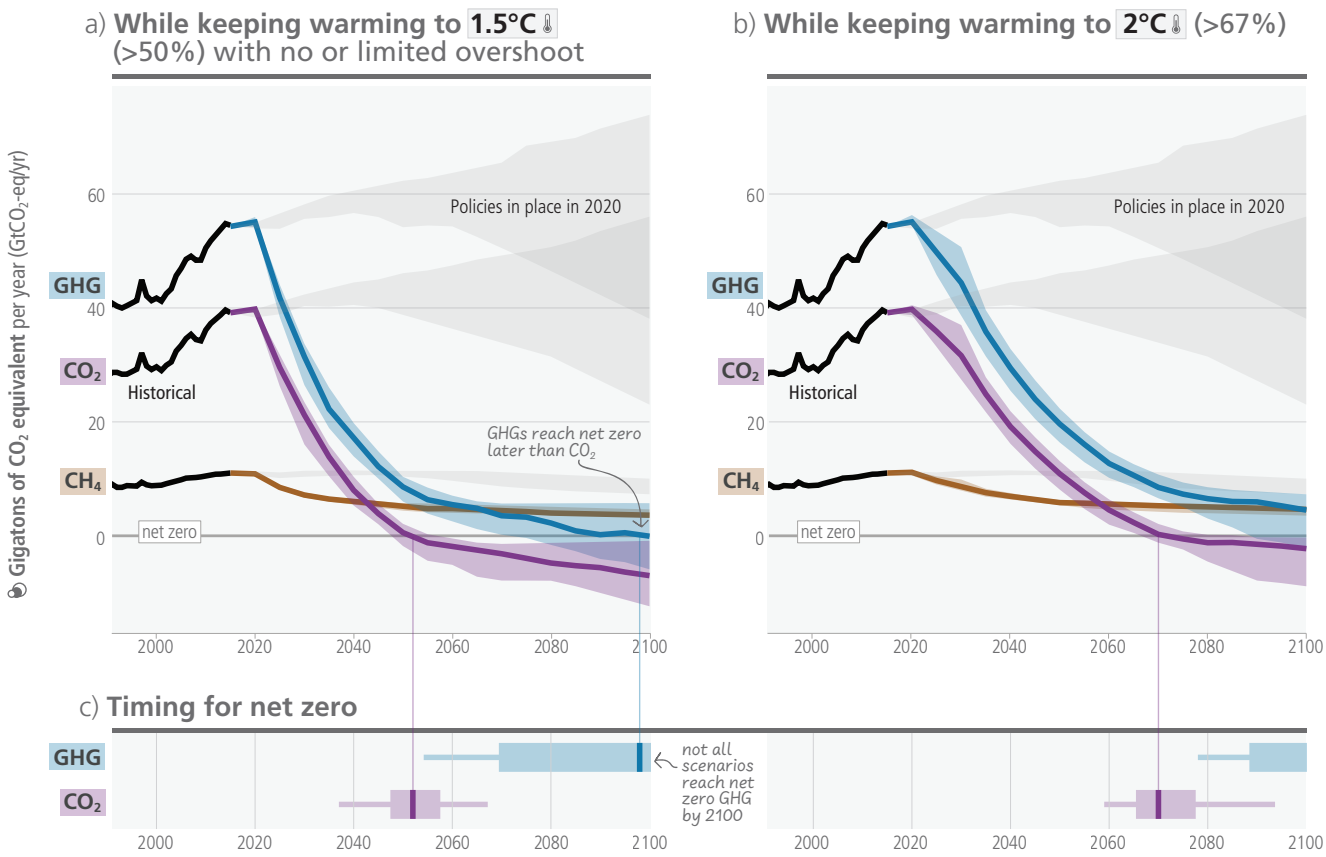


Figure 3.6: Total GHG, CO_2 and CH_4 emissions and timing of reaching net zero in different mitigation pathways. Top row: GHG, CO_2 and CH_4 emissions over time (in $GtCO_2eq$) with historical emissions, projected emissions in line with policies implemented until the end of 2020 (grey), and pathways consistent with temperature goals in colour (blue, purple, and brown, respectively). **Panel (a) (left)** shows pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1) and **Panel (b) (right)** shows pathways that limit warming to 2°C (>67%) (C3). **Bottom row: Panel (c)** shows median (vertical line), *likely* (bar) and *very likely* (thin lines) timing of reaching net zero GHG and CO_2 emissions for global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1) (left) or 2°C (>67%) (C3) (right). {*WGIII Figure SPM.5*}

3.3.3 Sectoral Contributions to Mitigation

All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve rapid and deep and in most cases immediate GHG emissions reductions in all sectors (see also 4.1, 4.5). Reductions in GHG emissions in industry, transport, buildings, and urban areas can be achieved through a combination of energy efficiency and conservation and a transition to low-GHG technologies and energy carriers (see also 4.5, Figure 4.4). Socio-cultural options and behavioural change can reduce global GHG emissions of end-use sectors, with most of the potential in developed countries, if combined with improved infrastructure design and access. (*high confidence*) {*WGIII SPM C.3, WGIII SPM C.5, WGIII SPM C.6, WGIII SPM C.7.3, WGIII SPM C.8, WGIII SPM C.10.2*}

Global modelled mitigation pathways reaching net zero CO_2 and GHG emissions include transitioning from fossil fuels without carbon capture and storage (CCS) to very low- or zero-carbon energy sources, such as renewables or fossil fuels with CCS, demand-side measures and improving efficiency, reducing non-CO_2 GHG emissions, and CDR[136]. In global modelled pathways that limit warming to 2°C or below, almost all electricity is supplied

[136] CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources provided geological storage is available. When CO_2 is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO_2 capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO_2 can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C to 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. *(high confidence)* {*WGIII SPM C.4.6*}

from zero or low-carbon sources in 2050, such as renewables or fossil fuels with CO_2 capture and storage, combined with increased electrification of energy demand. Such pathways meet energy service demand with relatively low energy use, through e.g., enhanced energy efficiency and behavioural changes and increased electrification of energy end use. Modelled global pathways limiting global warming to 1.5°C (>50%) with no or limited overshoot generally implement such changes faster than pathways limiting global warming to 2°C (>67%). (*high confidence*) {*WGIII SPM C.3, WGIII SPM C.3.2, WGIII SPM C.4, WGIII TS.4.2; SR1.5 SPM C.2.2*}

AFOLU mitigation options, when sustainably implemented, can deliver large-scale GHG emission reductions and enhanced CO_2 removal; however, barriers to implementation and trade-offs may result from the impacts of climate change, competing demands on land, conflicts with food security and livelihoods, the complexity of land ownership and management systems, and cultural aspects (see 3.4.1). All assessed modelled pathways that limit warming to 2°C (>67%) or lower by 2100 include land-based mitigation and land-use change, with most including different combinations of reforestation, afforestation, reduced deforestation, and bioenergy. However, accumulated carbon in vegetation and soils is at risk from future loss (or sink reversal) triggered by climate change and disturbances such as flood, drought, fire, or pest outbreaks, or future poor management. (*high confidence*) {*WGI SPM B.4.3; WGII SPM B.2.3, WGII SPM B.5.4; WGIII SPM C.9, WGIII SPM C.11.3, WGIII SPM D.2.3, WGIII TS.4.2, 3.4; SR1.5 SPM C.2.5; SRCCL SPM B.1.4, SRCCL SPM B.3, SRCCL SPM B.7*}

In addition to deep, rapid, and sustained emission reductions, CDR can fulfil three complementary roles: lowering net CO_2 or net GHG emissions in the near term; counterbalancing 'hard-to-abate' residual emissions (e.g., some emissions from agriculture, aviation, shipping, industrial processes) to help reach net zero CO_2 or GHG emissions, and achieving net negative CO_2 or GHG emissions if deployed at levels exceeding annual residual emissions (*high confidence*). CDR methods vary in terms of their maturity, removal process, time scale of carbon storage, storage medium, mitigation potential, cost, co-benefits, impacts and risks, and governance requirements (*high confidence*). Specifically, maturity ranges from lower maturity (e.g., ocean alkalinisation) to higher maturity (e.g., reforestation); removal and storage potential ranges from lower potential (<1 Gt CO_2 yr^{-1}, e.g., blue carbon management) to higher potential (>3 Gt CO_2 yr^{-1}, e.g., agroforestry); costs range from lower cost (e.g., –45 to 100 USD tCO_2^{-1} for soil carbon sequestration) to higher cost (e.g., 100 to 300 USD tCO_2^{-1} for direct air carbon dioxide capture and storage) (*medium confidence*). Estimated storage timescales vary from decades to centuries for methods that store carbon in vegetation and through soil carbon management, to ten thousand years or more for methods that store carbon in geological formations (*high confidence*). Afforestation, reforestation, improved forest management, agroforestry and soil carbon sequestration are currently the only widely practiced CDR methods (*high confidence*). Methods and levels of CDR deployment in global modelled mitigation pathways vary depending on assumptions about costs, availability and constraints (*high confidence*). {*WGIII SPM C.3.5, WGIII SPM C.11.1, WGIII SPM C.11.4*}

3.3.4 Overshoot Pathways: Increased Risks and Other Implications

Exceeding a specific remaining carbon budget results in higher global warming. Achieving and sustaining net negative global CO_2 emissions could reverse the resulting temperature exceedance (*high confidence*). Continued reductions in emissions of short-lived climate forcers, particularly methane, after peak temperature has been reached, would also further reduce warming (*high confidence*). Only a small number of the most ambitious global modelled pathways limit global warming to 1.5°C (>50%) without overshoot. {*WGI SPM D.1.1, WGI SPM D.1.6, WGI SPM D.1.7; WGIII TS.4.2*}

Overshoot of a warming level results in more adverse impacts, some irreversible, and additional risks for human and natural systems compared to staying below that warming level, with risks growing with the magnitude and duration of overshoot (*high confidence*). Compared to pathways without overshoot, societies and ecosystems would be exposed to greater and more widespread changes in climatic impact-drivers, such as extreme heat and extreme precipitation, with increasing risks to infrastructure, low-lying coastal settlements, and associated livelihoods (*high confidence*). Overshooting 1.5°C will result in irreversible adverse impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet melt, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*). Overshoot increases the risks of severe impacts, such as increased wildfires, mass mortality of trees, drying of peatlands, thawing of permafrost and weakening natural land carbon sinks; such impacts could increase releases of GHGs making temperature reversal more challenging (*medium confidence*). {*WGI SPM C.2, WGI SPM C.2.1, WGI SPM C.2.3; WGII SPM B.6, WGII SPM B.6.1, WGII SPM B.6.2; SR1.5 3.6*}

The larger the overshoot, the more net negative CO_2 emissions needed to return to a given warming level (*high confidence*). Reducing global temperature by removing CO_2 would require net negative emissions of 220 $GtCO_2$ (best estimate, with a *likely* range of 160 to 370 $GtCO_2$) for every tenth of a degree (*medium confidence*). Modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot reach median values of cumulative net negative emissions of 220 $GtCO_2$ by 2100, pathways that return warming to 1.5°C (>50%) after high overshoot reach median values of 360 $GtCO_2$ (*high confidence*).[137] More rapid reduction in CO_2 and non-CO_2 emissions, particularly methane, limits peak warming levels and reduces the requirement for net negative CO_2 emissions and CDR, thereby reducing feasibility and sustainability concerns, and social and environmental risks (*high confidence*). {*WGI SPM D.1.1; WGIII SPM B.6.4, WGIII SPM C.2, WGIII SPM C.2.2, WGIII Table SPM.2*}

[137] Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C, high overshoot by 0.1°C to 0.3°C, in both cases for up to several decades. {*WGIII Box SPM.1*}

3.4 Long-Term Interactions Between Adaptation, Mitigation and Sustainable Development

Mitigation and adaptation can lead to synergies and trade-offs with sustainable development (*high confidence*). Accelerated and equitable mitigation and adaptation bring benefits from avoiding damages from climate change and are critical to achieving sustainable development (*high confidence*). Climate resilient development[138] pathways are progressively constrained by every increment of further warming (*very high confidence*). There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all (*very high confidence*).

3.4.1 Synergies and trade-offs, costs and benefits

Mitigation and adaptation options can lead to synergies and trade-offs with other aspects of sustainable development (see also Section 4.6, Figure 4.4). Synergies and trade-offs depend on the pace and magnitude of changes and the development context including inequalities, with consideration of climate justice. The potential or effectiveness of some adaptation and mitigation options decreases as climate change intensifies (see also Sections 3.2, 3.3.3, 4.5). (*high confidence*) {*WGII SPM C.2, WGII Figure SPM.4b; WGIII SPM D.1, WGIII SPM D.1.2, WGIII TS.5.1, WGIII Figure SPM.8; SR1.5 SPM D.3, SR1.5 SPM D.4; SRCCL SPM B.2, SRCCL SPM B.3, SRCCL SPM D.3.2, SRCCL Figure SPM.3*}

In the energy sector, transitions to low-emission systems will have multiple co-benefits, including improvements in air quality and health. There are potential synergies between sustainable development and, for instance, energy efficiency and renewable energy. (*high confidence*) {*WGIII SPM C.4.2, WGIII SPM D.1.3*}

For agriculture, land, and food systems, many land management options and demand-side response options (e.g., dietary choices, reduced post-harvest losses, reduced food waste) can contribute to eradicating poverty and eliminating hunger while promoting good health and well-being, clean water and sanitation, and life on land (*medium confidence)*. In contrast, certain adaptation options that promote intensification of production, such as irrigation, may have negative effects on sustainability (e.g., for biodiversity, ecosystem services, groundwater depletion, and water quality) (*high confidence*). {*WGII TS.D.5.5; WGIII SPM D.10; SRCCL SPM B.2.3*}

Reforestation, improved forest management, soil carbon sequestration, peatland restoration and coastal blue carbon management are examples of CDR methods that can enhance biodiversity and ecosystem functions, employment and local livelihoods, depending on context[139]. However, afforestation or production of biomass crops for bioenergy with carbon dioxide capture and storage or biochar can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure. (*high confidence*) {*WGII SPM B.5.4, WGII SPM C.2.4; WGIII SPM C.11.2; SR1.5 SPM C.3.4, SR1.5 SPM C.3.5; SRCCL SPM B.3, SRCCL SPM B.7.3, SRCCL Figure SPM.3*}

Modelled pathways that assume using resources more efficiently or shift global development towards sustainability include fewer challenges, such as dependence on CDR and pressure on land and biodiversity, and have the most pronounced synergies with respect to sustainable development (*high confidence*). {*WGIII SPM C.3.6; SR1.5 SPM D.4.2*}

Strengthening climate change mitigation action entails more rapid transitions and higher up-front investments, but brings benefits from avoiding damages from climate change and reduced adaptation costs. The aggregate effects of climate change mitigation on global GDP (excluding damages from climate change and adaptation costs) are small compared to global projected GDP growth. Projected estimates of global aggregate net economic damages and the costs of adaptation generally increase with global warming level. (*high confidence*) {*WGII SPM B.4.6, WGII TS.C.10; WGIII SPM C.12.2, WGIII SPM C.12.3*}

Cost-benefit analysis remains limited in its ability to represent all damages from climate change, including non-monetary damages, or to capture the heterogeneous nature of damages and the risk of catastrophic damages (*high confidence*). Even without accounting for these factors or for the co-benefits of mitigation, the global benefits of limiting warming to 2°C exceed the cost of mitigation (*medium confidence*). This finding is robust against a wide range of assumptions about social preferences on inequalities and discounting over time (*medium confidence*). Limiting global warming to 1.5°C instead of 2°C would increase the costs of mitigation, but also increase the benefits in terms of reduced impacts and related risks (see 3.1.1, 3.1.2) and reduced adaptation needs (*high confidence*)[140]. {*WGII SPM B.4, WGII SPM B.6; WGIII SPM C.12, WGIII SPM C.12.2, WGIII SPM C.12.3 WGIII Box TS.7; SR1.5 SPM B.3, SR1.5 SPM B.5, SR1.5 SPM B.6*}

Considering other sustainable development dimensions, such as the potentially strong economic benefits on human health from air quality improvement, may enhance the estimated benefits of mitigation (*medium confidence*). The economic effects of strengthened mitigation action vary across regions and countries, depending notably on economic structure, regional emissions reductions, policy design and level of international cooperation (*high confidence*). Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with implications for near-term actions (Section 4.2), equity (Section 4.4), sustainability (Section 4.6), and finance (Section 4.8) (*high confidence*). {*WGIII SPM C.12.2, WGIII SPM D.3.2, WGIII TS.4.2*}

[138] See Annex I: Glossary.

[139] The impacts, risks, and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale (*high confidence*). {*WGIII SPM C.11.2*}

[140] The evidence is too limited to make a similar robust conclusion for limiting warming to 1.5°C. {*WGIII SPM footnote 68*}

3.4.2 Advancing Integrated Climate Action for Sustainable Development

An inclusive, equitable approach to integrating adaptation, mitigation and development can advance sustainable development in the long term (*high confidence*). Integrated responses can harness synergies for sustainable development and reduce trade-offs (*high confidence*). Shifting development pathways towards sustainability and advancing climate resilient development is enabled when governments, civil society and the private sector make development choices that prioritise risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors and timeframes (*very high confidence*) (see also Figure 4.2). Inclusive processes involving local knowledge and Indigenous Knowledge increase these prospects (*high confidence*). However, opportunities for action differ substantially among and within regions, driven by historical and ongoing patterns of development (*very high confidence*). Accelerated financial support for developing countries is critical to enhance mitigation and adaptation action (*high confidence*). {*WGII SPM C.5.4, WGII SPM D.1, WGII SPM D.1.1, WGII SPM D.1.2, WGII SPM D.2, WGII SPM D.3, WGII SPM D.5, WGII SPM D.5.1, WGII SPM D.5.2; WGIII SPM D.1, WGIII SPM D.2, WGIII SPM D.2.4, WGIII SPM E.2.2, WGIII SPM E.2.3, WGIII SPM E.5.3, WGIII Cross-Chapter Box 5*}

Policies that shift development pathways towards sustainability can broaden the portfolio of available mitigation and adaptation responses (*medium confidence*). Combining mitigation with action to shift development pathways, such as broader sectoral policies, approaches that induce lifestyle or behaviour changes, financial regulation, or macroeconomic policies can overcome barriers and open up a broader range of mitigation options (*high confidence*). Integrated, inclusive planning and investment in everyday decision-making about urban infrastructure can significantly increase the adaptive capacity of urban and rural settlements. Coastal cities and settlements play an important role in advancing climate resilient development due to the high number of people living in the Low Elevation Coastal Zone, the escalating and climate compounded risk that they face, and their vital role in national economies and beyond (*high confidence*). {*WGII SPM.D.3, WGII SPM D.3.3; WGIII SPM E.2, WGIII SPM E.2.2; SR1.5 SPM D.6*}

Observed adverse impacts and related losses and damages, projected risks, trends in vulnerability, and adaptation limits demonstrate that transformation for sustainability and climate resilient development action is more urgent than previously assessed (*very high confidence*). Climate resilient development integrates adaptation and GHG mitigation to advance sustainable development for all. Climate resilient development pathways have been constrained by past development, emissions and climate change and are progressively constrained by every increment of warming, in particular beyond 1.5°C (*very high confidence*). Climate resilient development will not be possible in some regions and sub-regions if global warming exceeds 2°C (*medium confidence*). Safeguarding biodiversity and ecosystems is fundamental to climate resilient development, but biodiversity and ecosystem services have limited capacity to adapt to increasing global warming levels, making climate resilient development progressively harder to achieve beyond 1.5°C warming (*very high confidence*). {*WGII SPM D.1, WGII SPM D.1.1, WGII SPM D.4, WGII SPM D.4.3, WGII SPM D.5.1; WGIII SPM D.1.1*}

The cumulative scientific evidence is unequivocal: climate change is a threat to human well-being and planetary health (*very high confidence*). Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all (*very high confidence*). Opportunities for near-term action are assessed in the following section. {*WGII SPM D.5.3; WGIII SPM D.1.1*}

Section 4
Near-Term Responses in a Changing Climate

Section 4 : Near-Term Responses in a Changing Climate

4.1 The Timing and Urgency of Climate Action

Deep, rapid, and sustained mitigation and accelerated implementation of adaptation reduces the risks of climate change for humans and ecosystems. In modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%) and assume immediate action, global GHG emissions are projected to peak in the early 2020s followed by rapid and deep reductions. As adaptation options often have long implementation times, accelerated implementation of adaptation, particularly in this decade, is important to close adaptation gaps. (*high confidence*)

The magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions (*very high confidence*). Global warming is *more likely than not* to reach 1.5°C between 2021 and 2040 even under the very low GHG emission scenarios (SSP1-1.9), and *likely* or *very likely* to exceed 1.5°C under higher emissions scenarios[141]. Many adaptation options have medium or high feasibility up to 1.5°C (*medium* to *high confidence*, depending on option), but hard limits to adaptation have already been reached in some ecosystems and the effectiveness of adaptation to reduce climate risk will decrease with increasing warming (*high confidence*). Societal choices and actions implemented in this decade determine the extent to which medium- and long-term pathways will deliver higher or lower climate resilient development (*high confidence*). Climate resilient development prospects are increasingly limited if current greenhouse gas emissions do not rapidly decline, especially if 1.5°C global warming is exceeded in the near term (*high confidence*). Without urgent, effective and equitable adaptation and mitigation actions, climate change increasingly threatens the health and livelihoods of people around the globe, ecosystem health, and biodiversity, with severe adverse consequences for current and future generations (*high confidence*). {*WGI SPM B.1.3, WGI SPM B.5.1, WGI SPM B.5.2; WGII SPM A, WGII SPM B.4, WGII SPM C.2, WGII SPM C.3.3, WGII Figure SPM.4, WGII SPM D.1, WGII SPM D.5, WGIII SPM D.1.1 SR1.5 SPM D.2.2*}. (*Cross-Section Box.2, Figure 2.1, Figure 2.3*)

In modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%), assuming immediate actions, global GHG emissions are projected to peak in the early 2020s followed by rapid and deep GHG emissions reductions (*high confidence*) [142]. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, net global GHG emissions are projected to fall by 43 [34 to 60]%[143] below 2019 levels by 2030, 60 [49 to 77]% by 2035, 69 [58 to 90]% by 2040 and 84 [73 to 98]% by 2050 (*high confidence*) (Section 2.3.1, Table 2.2, Figure 2.5, Table 3.1)[144]. Global modelled pathways that limit warming to 2°C (>67%) have reductions in GHG emissions below 2019 levels of 21 [1 to 42]% by 2030, 35 [22 to 55] % by 2035, 46 [34 to 63] % by 2040 and 64 [53 to 77]% by 2050[145] (*high confidence*). Global GHG emissions associated with NDCs announced prior to COP26 would make it *likely* that warming would exceed 1.5°C (*high confidence*) and limiting warming to 2°C (>67%) would then imply a rapid acceleration of emission reductions during 2030–2050, around 70% faster than in pathways where immediate action is taken to limit warming to 2°C (>67%) (*medium confidence*) (Section 2.3.1) Continued investments in unabated high-emitting infrastructure[146] and limited development and deployment of low-emitting alternatives prior to 2030 would act as barriers to this acceleration and increase feasibility risks (*high confidence*). {*WGIII SPM B.6.3, WGIII 3.5.2, WGIII SPM B.6, WGIII SPM B.6., WGIII SPM C.1, WGIII SPM C1.1, WGIII Table SPM.2*} (*Cross-Section Box.2*)

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141 In the near term (2021–2040), the 1.5°C global warming level is very *likely* to be exceeded under the very high GHG emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high GHG emissions scenarios (SSP2-4.5, SSP3-7.0), *more likely than not* to be exceeded under the low GHG emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low GHG emissions scenario (SSP1-1.9). The best estimates [and *very likely* ranges] of global warming for the different scenarios in the near term are: 1.5 [1.2 to 1.7]°C (SSP1-1.9); 1.5 [1.2 to 1.8]°C (SSP1-2.6); 1.5 [1.2 to 1.8]°C (SSP2-4.5); 1.5 [1.2 to 1.8]°C (SSP3-7.0); and 1.6[1.3 to 1.9]°C (SSP5-8.5). {*WGI SPM B.1.3, WGI Table SPM.1*} (*Cross-Section Box.2*)

142 Values in parentheses indicate the likelihood of limiting warming to the level specified (see Cross-Section Box.2).

143 Median and very *likely* range [5th to 95th percentile]. {*WGIII SPM footnote 30*}

144 These numbers for CO_2 are 48 [36 to 69]% in 2030, 65 [50 to 96] % in 2035, 80 [61 to109] % in 2040 and 99 [79 to 119]% in 2050.

145 These numbers for CO_2 are 22 [1 to 44]% in 2030, 37 [21 to 59] % in 2035, 51 [36 to 70] % in 2040 and 73 [55 to 90]% in 2050.

146 In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more CO_2 from power plants, or 50 to 80% of fugitive methane emissions from energy supply. {*WGIII SPM footnote 54*}

All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve reductions in both net CO_2 emissions and non-CO_2 emissions (see Figure 3.6) (*high confidence*). For example, in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global CH_4 (methane) emissions are reduced by 34 [21 to 57]% below 2019 levels by 2030 and by 44 [31 to 63]% in 2040 (*high confidence*). Global CH_4 emissions are reduced by 24 [9 to 53]% below 2019 levels by 2030 and by 37 [20 to 60]% in 2040 in modelled pathways that limit warming to 2°C with action starting in 2020 (>67%) (*high confidence*). {*WGIII SPM C1.2, WGIII Table SPM.2, WGIII 3.3; SR1.5 SPM C.1, SR1.5 SPM C.1.2*} (*Cross-Section Box.2*)

All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve GHG emission reductions in all sectors (*high confidence*). The contributions of different sectors vary across modelled mitigation pathways. In most global modelled mitigation pathways, emissions from land-use, land-use change and forestry, via reforestation and reduced deforestation, and from the energy supply sector reach net zero CO_2 emissions earlier than the buildings, industry and transport sectors (Figure 4.1). Strategies can rely on combinations of different options (Figure 4.1, Section 4.5), but doing less in one sector needs to be compensated by further reductions in other sectors if warming is to be limited. (*high confidence*) {*WGIII SPM C.3, WGIII SPM C.3.1, WGIII SPM 3.2, WGIII SPM C.3.3*} (*Cross-Section Box.2*)

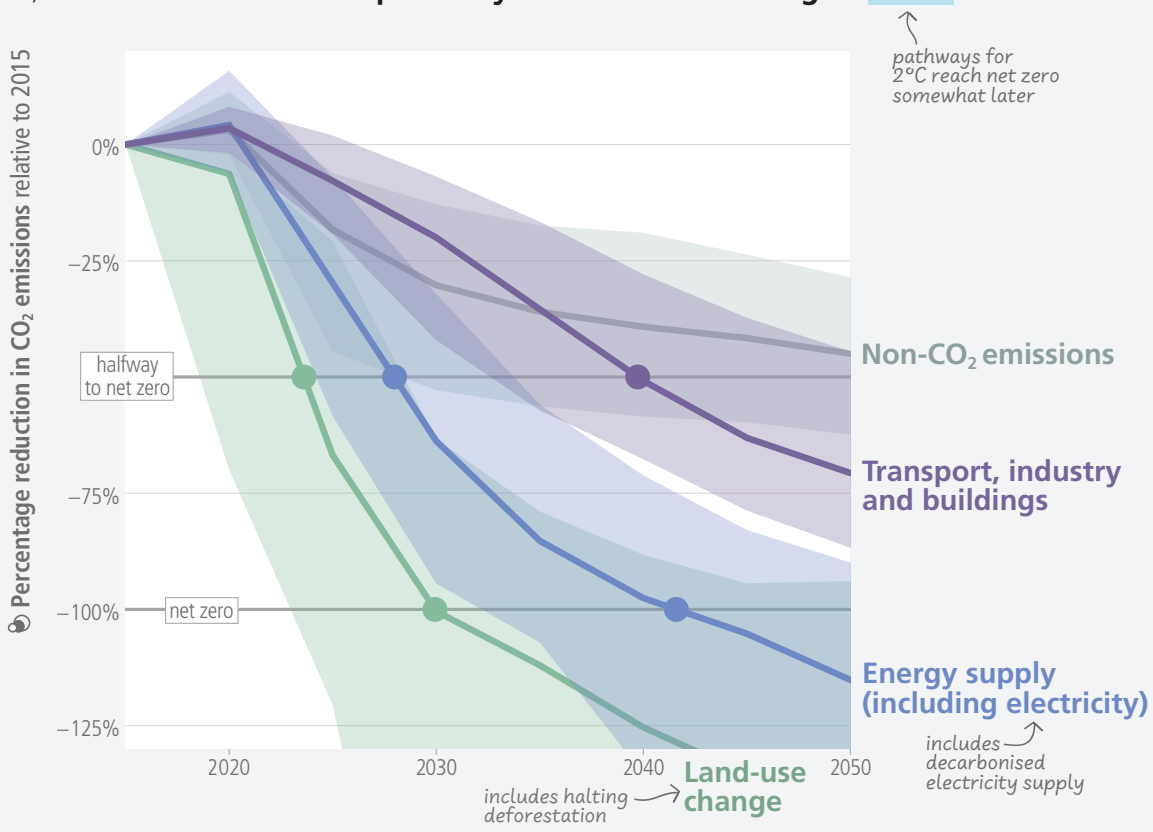
Without rapid, deep and sustained mitigation and accelerated adaptation actions, losses and damages will continue to increase, including projected adverse impacts in Africa, LDCs, SIDS, Central and South America[147], Asia and the Arctic, and will disproportionately affect the most vulnerable populations (*high confidence*). {*WGII SPM C.3.5, WGII SPM B.2.4, WGII 12.2, WGII 10. Box 10.6, WGII TS D.7.5, WGII Cross-Chapter Box 6 ES, WGII Global to Regional Atlas Annex A1.15, WGII Global to Regional Atlas Annex A1.27; SR1.5 SPM B.5.3, SR 1.5 SPM B.5.7; SRCCL A.5.6*} (*Figure 3.2; Figure 3.3*)

[147] The southern part of Mexico is included in the climatic subregion South Central America (SCA) for WGI. Mexico is assessed as part of North America for WGII. The climate change literature for the SCA region occasionally includes Mexico, and in those cases WGII assessment makes reference to Latin America. Mexico is considered part of Latin America and the Caribbean for WGIII. {*WGII 12.1.1, WGIII AII.1.1*}

The transition towards net zero CO_2 will have different pace across different sectors

CO_2 emissions from the electricity/fossil fuel industries sector and land-use change generally reach net zero earlier than other sectors

a) **Sectoral emissions in pathways that limit warming to 1.5°C**



b) **Greenhouse gas emissions by sector at the time of net zero CO_2, compared to 2019**

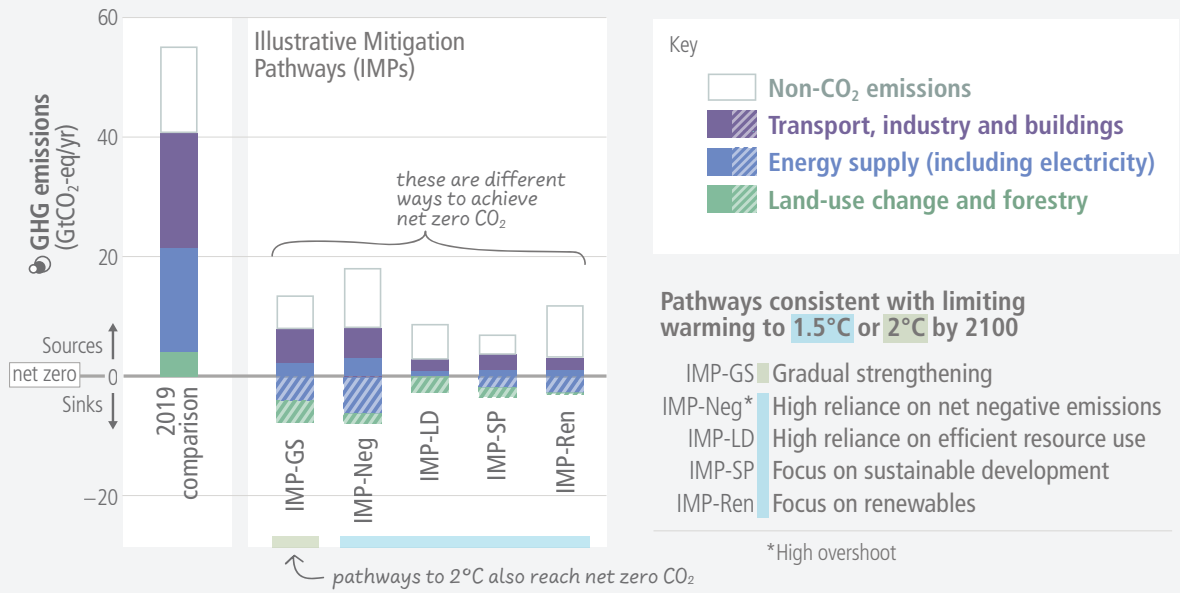


Figure 4.1: Sectoral emissions in pathways that limit warming to 1.5°C. Panel (a) shows sectoral CO_2 and non-CO_2 emissions in global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. The horizontal lines illustrate halving 2015 emissions (base year of the pathways) (dashed) and reaching net zero emissions (solid line). The range shows the 5–95th percentile of the emissions across the pathways. The timing strongly differs by sector, with the CO_2 emissions from the electricity/fossil fuel industries sector and land-use change generally reaching net zero earlier. Non-CO_2 emissions from agriculture are also substantially reduced compared to pathways without climate policy but do not typically reach zero. **Panel (b)** Although all pathways include strongly reduced emissions, there are different pathways as indicated by the illustrative mitigation pathways used in IPCC WGIII. The pathways emphasise routes consistent with limiting warming to 1.5°C with a high reliance on net negative emissions (IMP-Neg), high resource efficiency (IMP-LD), a focus on sustainable development (IMP-SP) or renewables (IMP-Ren) and consistent with 2°C based on a less rapid introduction of mitigation measures followed by a subsequent gradual strengthening (IMP-GS). Positive (solid filled bars) and negative emissions (hatched bars) for different illustrative mitigation pathways are compared to GHG emissions from the year 2019. The category "energy supply (including electricity)" includes bioenergy with carbon capture and storage and direct air carbon capture and storage. {*WGIII Box TS.5, WGIII 3.3, WGIII 3.4, WGIII 6.6, WGIII 10.3, WGIII 11.3*} (*Cross-Section Box.2*)

4.2 Benefits of Strengthening Near-Term Action

Accelerated implementation of adaptation will improve well-being by reducing losses and damages, especially for vulnerable populations. Deep, rapid, and sustained mitigation actions would reduce future adaptation costs and losses and damages, enhance sustainable development co-benefits, avoid locking-in emission sources, and reduce stranded assets and irreversible climate changes. These near-term actions involve higher up-front investments and disruptive changes, which can be moderated by a range of enabling conditions and removal or reduction of barriers to feasibility. (*high confidence*)

Accelerated implementation of adaptation responses will bring benefits to human well-being (*high confidence*) (Section 4.3). As adaptation options often have long implementation times, long-term planning and accelerated implementation, particularly in this decade, is important to close adaptation gaps, recognising that constraints remain for some regions. The benefits to vulnerable populations would be high (see Section 4.4). *(high confidence)* {*WGI SPM B.1, WGI SPM B.1.3, WGI SPM B.2.2, WGI SPM B.3; WGII SPM C.1.1, WGII SPM C.1.2, WGII SPM C.2, WGII SPM C.3.1, WGII Figure SPM.4b; SROCC SPM C.3.4, SROCC Figure 3.4, SROCC Figure SPM.5*}

Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). The magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions, and projected adverse impacts and related losses and damages escalate with every increment of global warming (*very high confidence*). Delayed mitigation action will further increase global warming which will decrease the effectiveness of many adaptation options, including Ecosystem-based Adaptation and many water-related options, as well as increasing mitigation feasibility risks, such as for options based on ecosystems (*high confidence*). Comprehensive, effective, and innovative responses integrating adaptation and mitigation can harness synergies and reduce trade-offs between adaptation and mitigation, as well as in meeting requirements for financing (*very high confidence*) (see Section 4.5, 4.6, 4.8 and 4.9). {*WGII SPM B.3, WGII SPM B.4, WGII SPM B.6.2, WGII SPM C.2, WGII SPM C.3, WGII SPM D.1, WGII SPM D.4.3, WGII SPM D.5, WG II TS D.1.4, WG II TS.D.5, WGII TS D.7.5; WGIII SPM B.6.3, WGIII SPM B.6.4, WGIII SPM C.9, WGIII SPM D.2, WGIII SPM E.13; SR1.5 SPM C.2.7, SR1.5 D.1.3, SR1.5 D.5.2*}

Mitigation actions will have other sustainable development co-benefits (*high confidence*). Mitigation will improve air quality and human health in the near term notably because many air pollutants are co-emitted by GHG emitting sectors and because methane emissions leads to surface ozone formation (*high confidence*). The benefits from air quality improvement include prevention of air pollution-related premature deaths, chronic diseases and damages to ecosystems and crops. The economic benefits for human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*). As methane has a short lifetime but is a potent GHG, strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*). {*WGI SPM D.1.7, WGI SPM D.2.2, WGI 6.7, WGI TS Box TS.7, WGI 6 Box 6.2, WGI Figure 6.3, WGI Figure 6.16, WGI Figure 6.17; WGII TS.D.8.3, WGII Cross-Chapter Box HEALTH, WGII 5 ES, WGII 7 ES; WGII 7.3.1.2; WGIII Figure SPM.8, WGIII SPM C.2.3, WGIII SPM C.4.2, WGIII TS.4.2*}

Challenges from delayed adaptation and mitigation actions include the risk of cost escalation, lock-in of infrastructure, stranded assets, and reduced feasibility and effectiveness of adaptation and mitigation options (*high confidence*). The continued installation of unabated fossil fuel[148] infrastructure will 'lock-in' GHG emissions (*high confidence*). Limiting global warming to 2°C or below will leave a substantial amount of fossil fuels unburned and could strand considerable fossil fuel infrastructure (*high confidence*), with globally discounted value projected to be around USD 1 to 4 trillion from 2015 to 2050 (*medium confidence*). Early actions would limit the size of these stranded assets, whereas delayed actions with continued investments in unabated high-emitting infrastructure and limited development and deployment of low-emitting alternatives prior to 2030 would raise future stranded assets to the higher end of the range – thereby acting as barriers and increasing political economy feasibility risks that may jeopardise efforts to limit global warming. (*high confidence*). {*WGIII SPM B.6.3, WGIII SPM C.4, WGIII Box TS.8*}

[148] In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more CO_2 from power plants, or 50 to 80% of fugitive methane emissions from energy supply. {*WGIII SPM footnote 54*}

Scaling-up near-term climate actions (Section 4.1) will mobilise a mix of low-cost and high-cost options. High-cost options, as in energy and infrastructure, are needed to avoid future lock-ins, foster innovation and initiate transformational changes (Figure 4.4). Climate resilient development pathways in support of sustainable development for all are shaped by equity, and social and climate justice (*very high confidence*). Embedding effective and equitable adaptation and mitigation in development planning can reduce vulnerability, conserve and restore ecosystems, and enable climate resilient development. This is especially challenging in localities with persistent development gaps and limited resources. (*high confidence*) {*WGII SPM C.5, WGII SPM D1; WGIII TS.5.2, WGIII 8.3.1, WGIII 8.3.4, WGIII 8.4.1, WGIII 8.6*}

Scaling-up climate action may generate disruptive changes in economic structure with distributional consequences and need to reconcile divergent interests, values and worldviews, within and between countries. Deeper fiscal, financial, institutional and regulatory reforms can offset such adverse effects and unlock mitigation potentials. Societal choices and actions implemented in this decade will determine the extent to which medium and long-term development pathways will deliver higher or lower climate resilient development outcomes. (*high confidence*) {*WGII SPM D.2, WGII SPM D.5, WGII Box TS.8; WGIII SPM D.3, WGIII SPM E.2, WGIII SPM E.3, WGIII SPM E.4, WGIII TS.2, WGIII TS.4.1, WGIII TS.6.4, WGIII 15.2, WGIII 15.6*}

Enabling conditions would need to be strengthened in the near-term and barriers reduced or removed to realise opportunities for deep and rapid adaptation and mitigation actions and climate resilient development (*high confidence*) (Figure 4.2). These enabling conditions are differentiated by national, regional and local circumstances and geographies, according to capabilities, and include: equity and inclusion in climate action (see Section 4.4), rapid and far-reaching transitions in sectors and system (see Section 4.5), measures to achieve synergies and reduce trade-offs with sustainable development goals (see Section 4.6), governance and policy improvements (see Section 4.7), access to finance, improved international cooperation and technology improvements (see Section 4.8), and integration of near-term actions across sectors, systems and regions (see Section 4.9). {*WGII SPM D.2; WGIII SPM E.1, WGIII SPM E.2*}

Barriers to feasibility would need to be reduced or removed to deploy mitigation and adaptation options at scale. Many limits to feasibility and effectiveness of responses can be overcome by addressing a range of barriers, including economic, technological, institutional, social, environmental and geophysical barriers. The feasibility and effectiveness of options increase with integrated, multi-sectoral solutions that differentiate responses based on climate risk, cut across systems and address social inequities. Strengthened near-term actions in modelled cost-effective pathways that limit global warming to 2°C or lower, reduce the overall risk to the feasibility of the system transitions, compared to modelled pathways with delayed or uncoordinated action. (*high confidence*) {*WGII SPM C.2, WGII SPM C.3, WGII SPM C.5; WGIII SPM E.1, WGIII SPM E.1.3*}

Integrating ambitious climate actions with macroeconomic policies under global uncertainty would provide benefits (*high confidence*). This encompasses three main directions: (a) economy-wide mainstreaming packages supporting options to improved sustainable low-emission economic recovery, development and job creation programs (Sections 4.4, 4.5, 4.6, 4.8, 4.9) (b) safety nets and social protection in the transition (Section 4.4, 4.7); and (c) broadened access to finance, technology and capacity-building and coordinated support to low-emission infrastructure ('leap-frog' potential), especially in developing regions, and under debt stress (*high confidence*). (Section 4.8) {*WGII SPM C.2, WGII SPM C.4.1, WGII SPM D.1.3, WGII SPM D.2, WGII SPM D.3.2, WGII SPM E.2.2, WGII SPM E.4, WGII SPM TS.2, WGII SPM TS.5.2, WGII TS.6.4, WGII TS.15, WGII TS Box TS.3; WGIII SPM B.4.2, WGIII SPM C.5.4, WGIII SPM C.6.2, WGIII SPM C.12.2, WGIII SPM D.3.4, WGIII SPM E.4.2, WGIII SPM E.4.5, WGIII SPM E.5.2, WGIII SPM E.5.3, WGIII TS.1, WGIII Box TS.15, WGIII 15.2, WGIII Cross-Chapter Box 1 on COVID in Chapter 1*}

There is a rapidly narrowing window of opportunity to enable climate resilient development

Multiple interacting choices and actions can shift development pathways towards sustainability

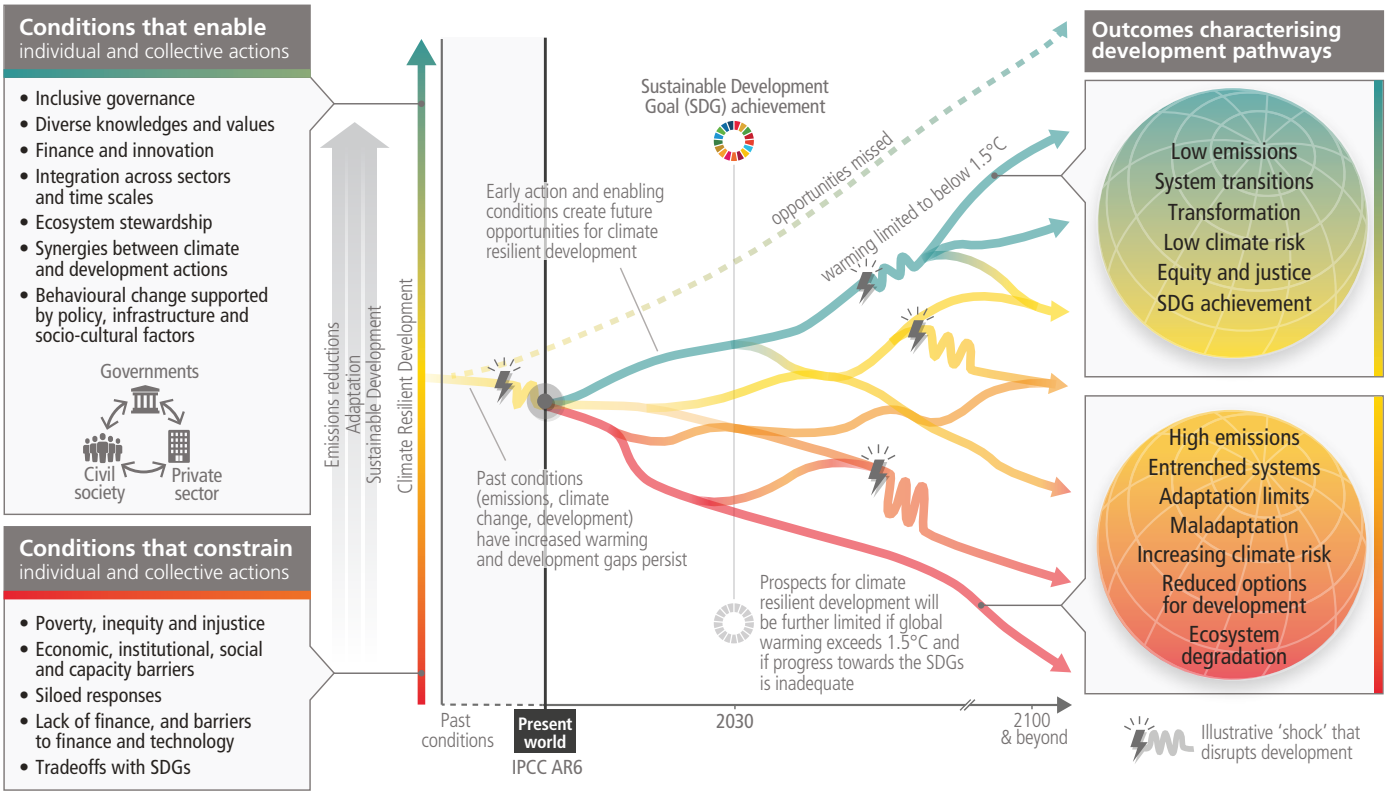


Figure 4.2: The illustrative development pathways (red to green) and associated outcomes (right panel) show that there is a rapidly narrowing window of opportunity to secure a liveable and sustainable future for all. Climate resilient development is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development. Diverging pathways illustrate that interacting choices and actions made by diverse government, private sector and civil society actors can advance climate resilient development, shift pathways towards sustainability, and enable lower emissions and adaptation. Diverse knowledges and values include cultural values, Indigenous Knowledge, local knowledge, and scientific knowledge. Climatic and non-climatic events, such as droughts, floods or pandemics, pose more severe shocks to pathways with lower climate resilient development (red to yellow) than to pathways with higher climate resilient development (green). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, and with every increment of warming, losses and damages will increase. The development pathways taken by countries at all stages of economic development impact GHG emissions and hence shape mitigation challenges and opportunities, which vary across countries and regions. Pathways and opportunities for action are shaped by previous actions (or inactions and opportunities missed, dashed pathway), and enabling and constraining conditions (left panel), and take place in the context of climate risks, adaptation limits and development gaps. The longer emissions reductions are delayed, the fewer effective adaptation options. {*WGI SPM B.1; WGII SPM B.1 to B.5, WGII SPM C.2 to 5, WGII SPM D.1 to 5, WGII Figure SPM.3, WGII Figure SPM.4, WGII Figure SPM.5, WGII TS.D.5, WGII 3.1, WGII 3.2, WGII 3.4, WGII 4.2, WGII Figure 4.4, WGII 4.5, WGII 4.6, WGII 4.9; WGIII SPM A, WGIII SPM B1, WGIII SPM B.3, WGIII SPM B.6, WGIII SPM C.4, WGIII SPM D1 to 3, WGIII SPM E.1, WGIII SPM E.2, WGIII SPM E.4, WGIII SPM E.5, WGIII Figure TS.1, WGIII Figure TS.7, WGIII Box TS.3, WGIII Box TS.8, Cross-Working Group Box 1 in Chapter 3, WGII Cross-Chapter Box 5 in Chapter 4; SR1.5 SPM D.1 to 6; SRCCL SPM D.3*}

4.3 Near-Term Risks

Many changes in the climate system, including extreme events, will become larger in the near term with increasing global warming (*high confidence*). Multiple climatic and non-climatic risks will interact, resulting in increased compounding and cascading impacts becoming more difficult to manage (*high confidence*). Losses and damages will increase with increasing global warming (*very high confidence*), while strongly concentrated among the poorest vulnerable populations (*high confidence*). Continuing with current unsustainable development patterns would increase exposure and vulnerability of ecosystems and people to climate hazards (*high confidence*).

Global warming will continue to increase in the near term (2021–2040) mainly due to increased cumulative CO_2 emissions in nearly all considered scenarios and pathways. In the near term, every region in the world is projected to face further increases in climate hazards (*medium* to *high confidence*, depending on region and hazard), increasing multiple risks to ecosystems and humans (*very high confidence*). In the near term, natural variability[149] will modulate human-caused changes, either attenuating or amplifying projected changes, especially at regional scales, with little effect on centennial global warming. Those modulations are important to consider in adaptation planning. Global surface temperature in any single year can vary above or below the long-term human-induced trend, due to natural variability. By 2030, global surface temperature in any individual year could exceed 1.5°C relative to 1850–1900 with a probability between 40% and 60%, across the five scenarios assessed in WGI (*medium confidence*). The occurrence of individual years with global surface temperature change above a certain level does not imply that this global warming level has been reached. If a large explosive volcanic eruption were to occur in the near term[150] , it would temporarily and partially mask human-caused climate change by reducing global surface temperature and precipitation, especially over land, for one to three years (*medium confidence*). {*WGI SPM B.1.3, WGI SPM B.1.4, WGI SPM C.1, WGI SPM C.2, WGI Cross-Section Box TS.1, WGI Cross-Chapter Box 4.1; WGII SPM B.3, WGII SPM B.3.1; WGIII Box SPM.1 Figure 1*}

The level of risk for humans and ecosystems will depend on near-term trends in vulnerability, exposure, level of socio-economic development and adaptation (*high confidence*). In the near term, many climate-associated risks to natural and human systems depend more strongly on changes in these systems' vulnerability and exposure than on differences in climate hazards between emissions scenarios (*high confidence*). Future exposure to climatic hazards is increasing globally due to socio-economic development trends including growing inequality, and when urbanisation or migration increase exposure (*high confidence*). Urbanisation increases hot extremes (*very high confidence*) and precipitation runoff intensity (*high confidence*). Increasing urbanisation in low-lying and coastal zones will be a major driver of increasing exposure to extreme riverflow events and sea level rise hazards, increasing risks (*high confidence*) (Figure 4.3). Vulnerability will also rise rapidly in low-lying Small Island Developing States and atolls in the context of sea level rise (*high confidence*) (see Figure 3.4 and Figure 4.3). Human vulnerability will concentrate in informal settlements and rapidly growing smaller settlements; and vulnerability in rural areas will be heightened by reduced habitability and high reliance on climate-sensitive livelihoods (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Vulnerability to climate change for ecosystems will be strongly influenced by past, present, and future patterns of human development, including from unsustainable consumption and production, increasing demographic pressures, and persistent unsustainable use and management of land, ocean, and water (*high confidence*). Several near-term risks can be moderated with adaptation (*high confidence*). {*WGI SPM C.2.6; WGII SPM B.2, WGII SPM B.2.3, WGII SPM B.2.5, WGII SPM B.3, WGII SPM B.3.2, WGII TS.C.5.2*} (*Section 4.5 and 3.2*)

Principal hazards and associated risks expected in the near term (at 1.5°C global warming) are:

- Increased intensity and frequency of hot extremes and dangerous heat-humidity conditions, with increased human mortality, morbidity, and labour productivity loss (*high confidence*). {*WGI SPM B.2.2, WGI TS Figure TS.6; WGII SPM B.1.4, WGII SPM B.4.4, WGII Figure SPM.2*}

- Increasing frequency of marine heatwaves will increase risks of biodiversity loss in the oceans, including from mass mortality events (*high confidence*). {*WGI SPM B.2.3; WGII SPM B.1.2, WGII Figure SPM.2; SROCC SPM B.5.1*}

- Near-term risks for biodiversity loss are moderate to high in forest ecosystems (*medium confidence*) and kelp and seagrass ecosystems (*high* to *very high confidence*) and are high to very high in Arctic sea-ice and terrestrial ecosystems (*high confidence*) and warm-water coral reefs (*very high confidence*). {*WGII SPM B.3.1*}

- More intense and frequent extreme rainfall and associated flooding in many regions including coastal and other low-lying cities (*medium* to *high confidence*), and increased proportion of and peak wind speeds of intense tropical cyclones (*high confidence*). {*WGI SPM B.2.4, WGI SPM C.2.2, WGI SPM C.2.6, WGI 11.7*}

- High risks from dryland water scarcity, wildfire damage, and permafrost degradation (*medium confidence*). {*SRCCL SPM A.5.3.*}

- Continued sea level rise and increased frequency and magnitude of extreme sea level events encroaching on coastal human settlements and damaging coastal infrastructure *(high confidence)*, committing low-lying coastal ecosystems to submergence and loss (*medium confidence*), expanding land salinization (*very high confidence*), with cascading to risks to livelihoods, health, well-being, cultural values, food and water security (*high confidence*). {*WGI SPM C.2.5, WGI SPM C.2.6; WGII SPM B.3.1, WGII SPM B.5.2; SRCCL SPM A.5.6; SROCC SPM B.3.4, SROCC SPM 3.6, SROCC SPM B.9.1*} (*Figure 3.4, 4.3*)

- Climate change will significantly increase ill health and premature deaths from the near to long term (*high confidence*). Further warming will increase climate-sensitive food-borne, water-borne, and vector-borne disease risks (*high confidence*), and mental health challenges including anxiety and stress (*very high confidence*). {*WGII SPM B.4.4*}

[149] See Annex I: Glossary. The main internal variability phenomena include El Niño–Southern Oscillation, Pacific Decadal Variability and Atlantic Multi-decadal Variability through their regional influence. The internal variability of global surface temperature in any single year is estimated to be about ±0.25°C (5 to 95% range, *high confidence*). {*WGI SPM footnote 29, WGI SPM footnote 37*}

[150] Based on 2500-year reconstructions, eruptions with a radiative forcing more negative than –1 Wm^{-2}, related to the radiative effect of volcanic stratospheric aerosols in the literature assessed in this report, occur on average twice per century. {*WGI SPM footnote 38*}

- Cryosphere-related changes in floods, landslides, and water availability have the potential to lead to severe consequences for people, infrastructure and the economy in most mountain regions (*high confidence*). {*WGII TS C.4.2*}

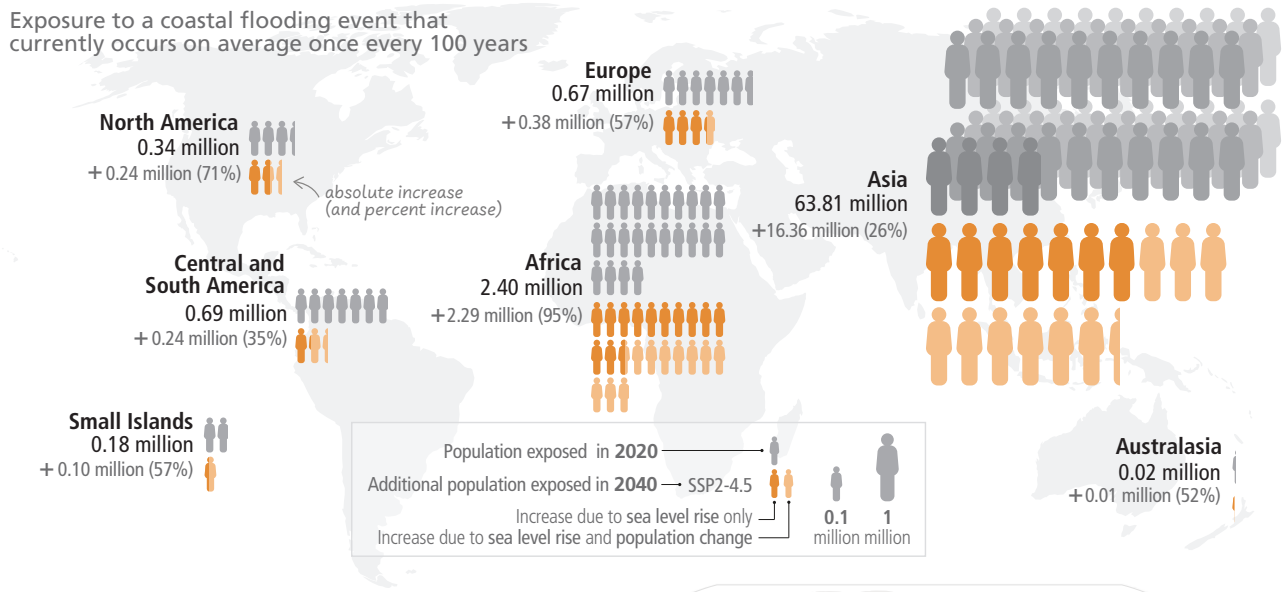
- The projected increase in frequency and intensity of heavy precipitation (*high confidence*) will increase rain-generated local flooding (*medium confidence*). {*WGI Figure SPM.6, WGI SPM B.2.2; WGII TS C.4.5*}

Multiple climate change risks will increasingly compound and cascade in the near term (*high confidence*). Many regions are projected to experience an increase in the probability of compound events with higher global warming (*high confidence*) including concurrent heatwaves and drought. Risks to health and food production will be made more severe from the interaction of sudden food production losses from heat and drought, exacerbated by heat-induced labour productivity losses (*high confidence*) (Figure 4.3). These interacting impacts will increase food prices, reduce household incomes, and lead to health risks of malnutrition and climate-related mortality with no or low levels of adaptation, especially in tropical regions (*high confidence*). Concurrent and cascading risks from climate change to food systems, human settlements, infrastructure and health will make these risks more severe and more difficult to manage, including when interacting with non-climatic risk drivers such as competition for land between urban expansion and food production, and pandemics (*high confidence*). Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems, to meet basic needs (*high confidence*). Increasing transboundary risks are projected across the food, energy and water sectors as impacts from weather and climate extremes propagate through supply-chains, markets, and natural resource flows (*high confidence*) and may interact with impacts from other crises such as pandemics. Risks also arise from some responses intended to reduce the risks of climate change, including risks from maladaptation and adverse side effects of some emissions reduction and carbon dioxide removal measures, such as afforestation of naturally unforested land or poorly implemented bioenergy compounding climate-related risks to biodiversity, food and water security, and livelihoods (*high confidence*) (see Section 3.4.1 and 4.5). {*WGI SPM.2.7; WGII SPM B.2.1, WGII SPM B.5, WGII SPM B.5.1, WGII SPM B.5.2, WGII SPM B.5.3, WGII SPM B.5.4, WGII Cross-Chapter Box COVID in Chapter 7; WGIII SPM C.11.2; SRCCL SPM A.5, SRCCL SPM A.6.5*} (*Figure 4.3*)

With every increment of global warming losses and damages will increase (*very high confidence*), become increasingly difficult to avoid and be strongly concentrated among the poorest vulnerable populations (*high confidence*). Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages will be unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries. (*high confidence*). {*WGII SPM B.4, WGII SPM C.3, WGII SPM C.3.5*}

Every region faces more severe and/or frequent compound and cascading climate risks

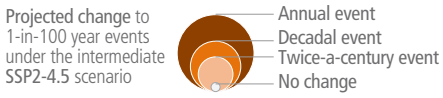
a) Increase in the population exposed to sea level rise from 2020 to 2040

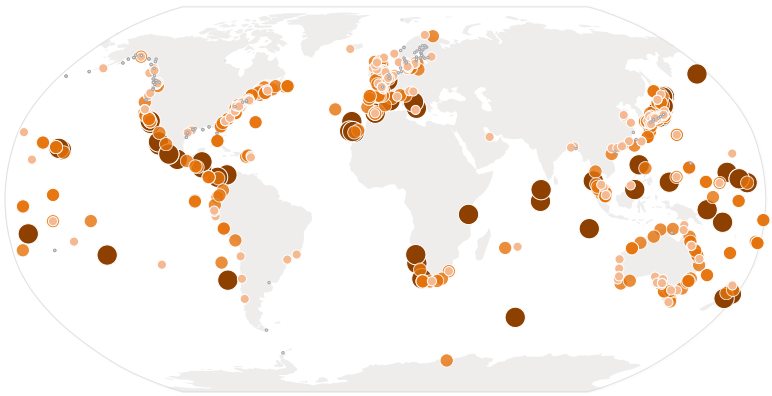


b) Increased frequency of extreme sea level events by 2040

Frequency of events that currently occur on average once every 100 years

The absence of a circle indicates an inability to perform an assessment due to a lack of data.





c) Example of complex risk, where impacts from climate extreme events have cascading effects on food, nutrition, livelihoods and well-being of smallholder farmers

Multiple climate change risks will increasingly compound and cascade in the near term

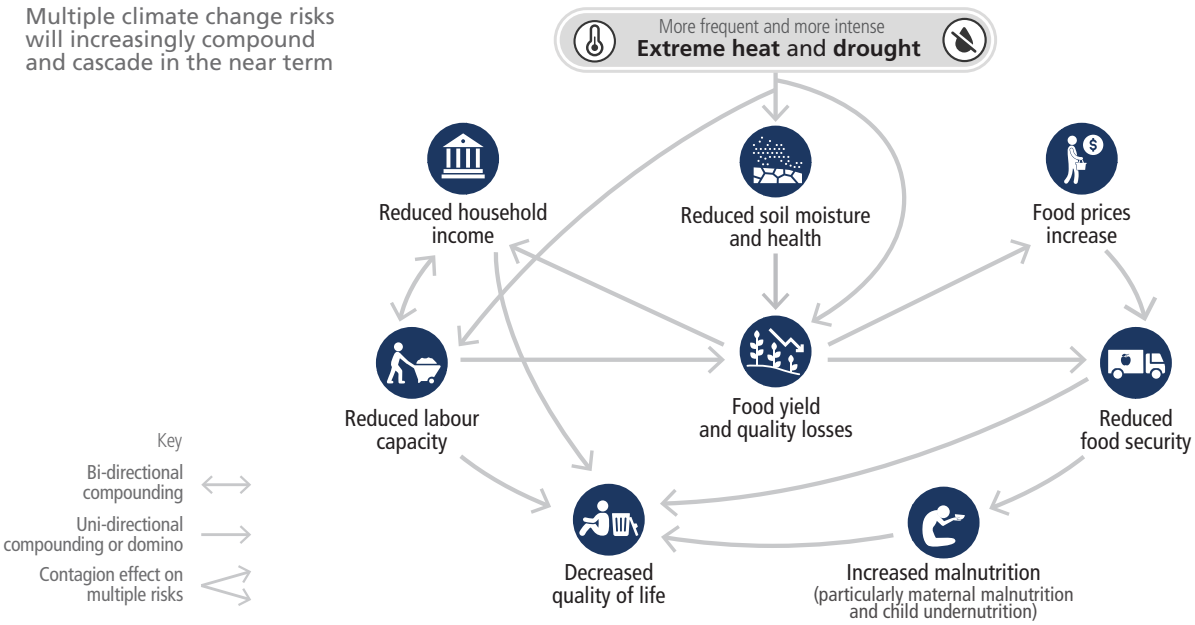


Figure 4.3: Every region faces more severe or frequent compound and/or cascading climate risks in the near term. Changes in risk result from changes in the degree of the hazard, the population exposed, and the degree of vulnerability of people, assets, or ecosystems. **Panel (a)** Coastal flooding events affect many of the highly populated regions of the world where large percentages of the population are exposed. The panel shows near-term projected increase of population exposed to 100-year flooding events depicted as the increase from the year 2020 to 2040 (due to sea level rise and population change), based on the intermediate GHG emissions scenario (SSP2-4.5) and current adaptation measures. Out-migration from coastal areas due to future sea level rise is not considered in the scenario. **Panel (b)** projected median probability in the year 2040 for extreme water levels resulting from a combination of mean sea level rise, tides and storm surges, which have a historical 1% average annual probability. A peak-over-threshold (99.7%) method was applied to the historical tide gauge observations available in the Global Extreme Sea Level Analysis version 2 database, which is the same information as WGI Figure 9.32, except here the panel uses relative sea level projections under SSP2-4.5 for the year 2040 instead of 2050 The absence of a circle indicates an inability to perform an assessment due to a lack of data, but does not indicate absence of increasing frequencies. **Panel (c)** Climate hazards can initiate risk cascades that affect multiple sectors and propagate across regions following complex natural and societal connections. This example of a compound heat wave and a drought event striking an agricultural region shows how multiple risks are interconnected and lead to cascading biophysical, economic, and societal impacts even in distant regions, with vulnerable groups such as smallholder farmers, children and pregnant women particularly impacted. {*WGI Figure 9.32; WGII SPM B4.3, WGII SPM B1.3, WGII SPM B.5.1, WGII TS Figure TS.9, WGII TS Figure TS.10 (c), WGII Fig 5.2, WGII TS.B.2.3, WGII TS.B.2.3, WGII TS.B.3.3, WGII 9.11.1.2*}

4.4 Equity and Inclusion in Climate Change Action

Actions that prioritise equity, climate justice, social justice and inclusion lead to more sustainable outcomes, co-benefits, reduce trade-offs, support transformative change and advance climate resilient development. Adaptation responses are immediately needed to reduce rising climate risks, especially for the most vulnerable. Equity, inclusion and just transitions are key to progress on adaptation and deeper societal ambitions for accelerated mitigation. (*high confidence*)

Adaptation and mitigation actions, across scales, sectors and regions, that prioritise equity, climate justice, rights-based approaches, social justice and inclusivity, lead to more sustainable outcomes, reduce trade-offs, support transformative change and advance climate resilient development (*high confidence*). Redistributive policies across sectors and regions that shield the poor and vulnerable, social safety nets, equity, inclusion and just transitions, at all scales can enable deeper societal ambitions and resolve trade-offs with sustainable development goals.(SDGs), particularly education, hunger, poverty, gender and energy access (*high confidence*). Mitigation efforts embedded within the wider development context can increase the pace, depth and breadth of emission reductions (*medium confidence*). Equity, inclusion and just transitions at all scales enable deeper societal ambitions for accelerated mitigation, and climate action more broadly (*high confidence*). The complexity in risk of rising food prices, reduced household incomes, and health and climate-related malnutrition (particularly maternal malnutrition and child undernutrition) and mortality increases with little or low levels of adaptation (*high confidence*). {*WGII SPM B.5.1, WGII SPM C.2.9, WGII SPM D.2.1, WGII TS Box TS.4; WGIII SPM D.3, WGIII SPM D.3.3, WGIII SPM WGIII SPM E.3, SR1.5 SPM D.4.5*} (*Figure 4.3c*)

Regions and people with considerable development constraints have high vulnerability to climatic hazards. Adaptation outcomes for the most vulnerable within and across countries and regions are enhanced through approaches focusing on equity, inclusivity, and rights-based approaches, including 3.3 to 3.6 billion people living in contexts that are highly vulnerable to climate change (*high confidence*). Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (*high confidence*). Several risks can be moderated with adaptation (*high confidence*). The largest adaptation gaps exist among lower income population groups (*high confidence*) and adaptation progress is unevenly distributed with observed adaptation gaps (*high confidence*). Present development challenges causing high vulnerability are influenced by historical and ongoing patterns of inequity such as colonialism, especially for many Indigenous Peoples and local communities (*high confidence*). Vulnerability is exacerbated by inequity and marginalisation linked to gender, ethnicity, low income or combinations thereof, especially for many Indigenous Peoples and local communities (*high confidence*). {*WGII SPM B.2, WGII SPM B.2.4, WGII SPM B.3.2, WGII SPM B.3.3, WGII SPM C.1, WGII SPM C.1.2, WGII SPM C.2.9*}

Meaningful participation and inclusive planning, informed by cultural values, Indigenous Knowledge, local knowledge, and scientific knowledge can help address adaptation gaps and avoid maladaptation (*high confidence*). Such actions with flexible pathways may encourage low-regret and timely actions (*very high confidence*). Integrating climate adaptation into social protection programmes, including cash transfers and public works programmes, would increase resilience to climate change, especially when supported by basic services and infrastructure *(high confidence).* {*WGII SPM C.2.3, WGII SPM C.4.3, WGII SPM C.4.4, WGII SPM C.2.9, WGII WPM D.3*}

Equity, inclusion, just transitions, broad and meaningful participation of all relevant actors in decision making at all scales enable deeper societal ambitions for accelerated mitigation, and climate action more broadly, and build social trust, support transformative changes and an equitable sharing of benefits and burdens (*high confidence*). Equity remains a central element in the UN climate regime, notwithstanding shifts in differentiation between states over time and challenges in assessing fair shares. Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries, including shifting of income and employment during the transition from high to low emissions activities (*high confidence*). While some jobs may be lost, low-emissions development can also open up opportunities to enhance skills and create jobs (*high confidence*). Broadening equitable access to finance, technologies and governance that facilitate mitigation, and consideration of climate justice can help equitable sharing of benefits

and burdens, especially for vulnerable countries and communities. {*WGIII SPM D.3, WGIII SPM D.3.2, WGIII SPM D.3.3, WGIII SPM D.3.4, WGIII TS Box TS.4*}

Development priorities among countries also reflect different starting points and contexts, and enabling conditions for shifting development pathways towards increased sustainability will therefore differ, giving rise to different needs (*high confidence*). Implementing just transition principles through collective and participatory decision-making processes is an effective way of integrating equity principles into policies at all scales depending on national circumstances, while in several countries just transition commissions, task forces and national policies have been established (*medium confidence*). {*WGIII SPM D.3.1, WGIII SPM D.3.3*}

Many economic and regulatory instruments have been effective in reducing emissions and practical experience has informed instrument design to improve them while addressing distributional goals and social acceptance (*high confidence*). The design of behavioural interventions, including the way that choices are presented to consumers work synergistically with price signals, making the combination more effective (*medium confidence*). Individuals with high socio-economic status contribute disproportionately to emissions, and have the highest potential for emissions reductions, e.g., as citizens, investors, consumers, role models, and professionals (*high confidence*). There are options on design of instruments such as taxes, subsidies, prices, and consumption-based approaches, complemented by regulatory instruments to reduce high-emissions consumption while improving equity and societal well-being (*high confidence*). Behaviour and lifestyle changes to help end-users adopt low-GHG-intensive options can be supported by policies, infrastructure and technology with multiple co-benefits for societal well-being (*high confidence*). Broadening equitable access to domestic and international finance, technologies and capacity can also act as a catalyst for accelerating mitigation and shifting development pathways in low-income contexts (*high confidence*). Eradicating extreme poverty, energy poverty, and providing decent living standards to all in these regions in the context of achieving sustainable development objectives, in the near term, can be achieved without significant global emissions growth (*high confidence*). Technology development, transfer, capacity building and financing can support developing countries/ regions leapfrogging or transitioning to low-emissions transport systems thereby providing multiple co-benefits (*high confidence*). Climate resilient development is advanced when actors work in equitable, just and enabling ways to reconcile divergent interests, values and worldviews, toward equitable and just outcomes (*high confidence*). {*WGII D.2.1, WGIII SPM B.3.3, WGIII SPM.C.8.5, WGIII SPM C.10.2, WGIII SPM C.10.4, WGIII SPM D.3.4, WGIII SPM E.4.2, WGIII TS.5.1, WGIII 5.4, WGIII 5.8, WGIII 15.2*}

4.5 Near-Term Mitigation and Adaptation Actions

Rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep and sustained emissions reductions and secure a liveable and sustainable future for all. These system transitions involve a significant upscaling of a wide portfolio of mitigation and adaptation options. Feasible, effective and low-cost options for mitigation and adaptation are already available, with differences across systems and regions. (*high confidence*)

Rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep emissions reductions and secure a liveable and sustainable future for all (*high confidence*). System transitions[151] consistent with pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are more rapid and pronounced in the near-term than in those that limit warming to 2°C (>67%) (*high confidence*). Such a systemic change is unprecedented in terms of scale, but not necessarily in terms of speed (*medium confidence*). The system transitions make possible the transformative adaptation required for high levels of human health and well-being, economic and social resilience, ecosystem health, and planetary health. {*WGII SPM A, WGII Figure SPM.1; WGIII SPM C.3; SR1.5 SPM C.2, SR1.5 SPM C.2.1, SR1.5 SPM C.2, SR1.5 SPM C.5*}

Feasible, effective and low-cost options for mitigation and adaptation are already available (*high confidence*) (Figure 4.4). Mitigation options costing USD 100 tCO_2-eq^{-1} or less could reduce global GHG emissions by at least half the 2019 level by 2030 (options costing less than USD 20 tCO_2-eq^{-1} are estimated to make up more than half of this potential) (*high confidence*) (Figure 4.4). The availability, feasibility[152] and potential of mitigation or effectiveness of adaptation options in the near term differ across systems and regions (*very high confidence*). {*WGII SPM C.2; WGIII SPM C.12, WGIII SPM E.1.1; SR1.5 SPM B.6*}

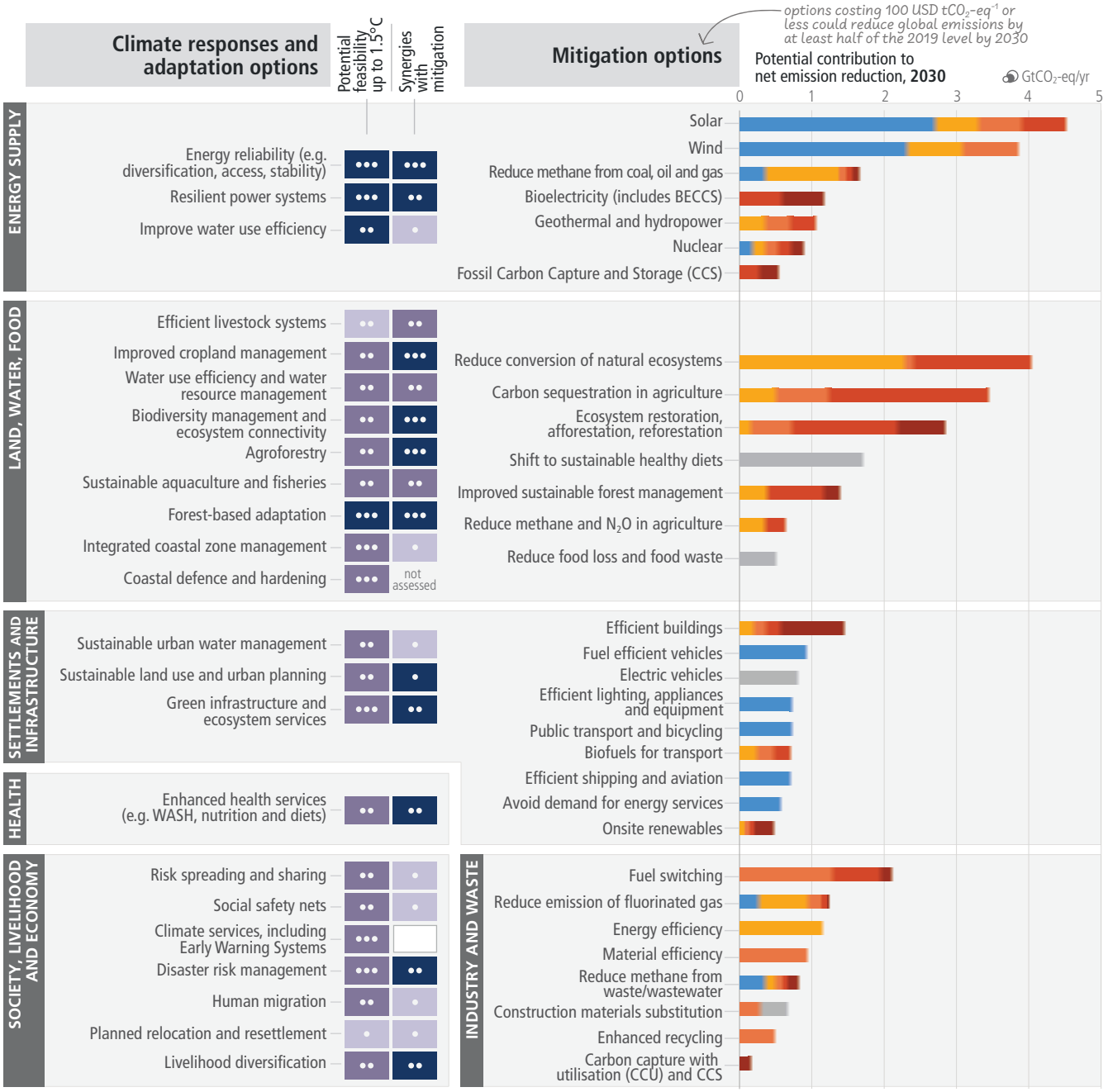
Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end-use sectors by 40 to 70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. Demand-side mitigation encompasses changes in infrastructure use, end-use technology adoption, and socio-cultural and behavioural change. (*high confidence*) (Figure 4.4). {*WGIII SPM C.10*}

[151] System transitions involve a wide portfolio of mitigation and adaptation options that enable deep emissions reductions and transformative adaptation in all sectors. This report has a particular focus on the following system transitions: energy; industry; cities, settlements and infrastructure; land, ocean, food and water; health and nutrition; and society, livelihood and economies. {*WGII SPM A, WGII Figure SPM.1, WGII Figure SPM.4; SR1.5 SPM C.2*}

[152] See Annex I: Glossary.

There are multiple opportunities for scaling up climate action

a) Feasibility of climate responses and adaptation, and potential of mitigation options in the near term



b) Potential of demand-side mitigation options by 2050

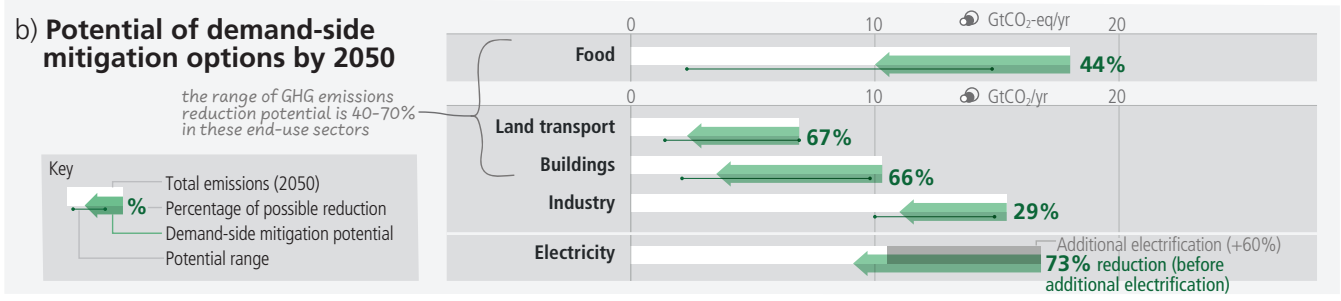


Figure 4.4: Multiple Opportunities for scaling up climate action. Panel (a) presents selected mitigation and adaptation options across different systems. The left hand side of panel (a) shows climate responses and adaptation options assessed for their multidimensional feasibility at global scale, in the near term and up to 1.5°C global warming. As literature above 1.5°C is limited, feasibility at higher levels of warming may change, which is currently not possible to assess robustly. The term response is used here in addition to adaptation because some responses, such as migration, relocation and resettlement may or may not be considered to be adaptation. Migration, when voluntary, safe and orderly, allows reduction of risks to climatic and non-climatic stressors. Forest based adaptation includes sustainable forest management, forest conservation and restoration, reforestation and afforestation. WASH refers to water, sanitation and hygiene. Six feasibility dimensions (economic, technological, institutional, social, environmental and geophysical) were used to calculate the potential feasibility of climate responses and adaptation options, along with their synergies with mitigation. For potential feasibility and feasibility dimensions, the figure shows high, medium, or low feasibility. Synergies with mitigation are identified as high, medium, and low. The right-hand side of panel (a) provides an overview of selected mitigation options and their estimated costs and potentials in 2030. Relative potentials and costs will vary by place, context and time and in the longer term compared to 2030. Costs are net lifetime discounted monetary costs of avoided greenhouse gas emissions calculated relative to a reference technology. The potential (horizontal axis) is the quantity of net GHG emission reduction that can be achieved by a given mitigation option relative to a specified emission baseline. Net GHG emission reductions are the sum of reduced emissions and/or enhanced sinks. The baseline used consists of current policy (around 2019) reference scenarios from the AR6 scenarios database (25–75 percentile values). The mitigation potentials are assessed independently for each option and are not necessarily additive. Health system mitigation options are included mostly in settlement and infrastructure (e.g., efficient healthcare buildings) and cannot be identified separately. Fuel switching in industry refers to switching to electricity, hydrogen, bioenergy and natural gas. The length of the solid bars represents the mitigation potential of an option. Potentials are broken down into cost categories, indicated by different colours (see legend). Only discounted lifetime monetary costs are considered. Where a gradual colour transition is shown, the breakdown of the potential into cost categories is not well known or depends heavily on factors such as geographical location, resource availability, and regional circumstances, and the colours indicate the range of estimates. The uncertainty in the total potential is typically 25–50%. When interpreting this figure, the following should be taken into account: (1) The mitigation potential is uncertain, as it will depend on the reference technology (and emissions) being displaced, the rate of new technology adoption, and several other factors; (2) Different options have different feasibilities beyond the cost aspects, which are not reflected in the figure; and (3) Costs for accommodating the integration of variable renewable energy sources in electricity systems are expected to be modest until 2030, and are not included. **Panel (b)** displays the indicative potential of demand-side mitigation options for 2050. Potentials are estimated based on approximately 500 bottom-up studies representing all global regions. The baseline (white bar) is provided by the sectoral mean GHG emissions in 2050 of the two scenarios (IEA-STEPS and IP_ModAct) consistent with policies announced by national governments until 2020. The green arrow represents the demand-side emissions reductions potentials. The range in potential is shown by a line connecting dots displaying the highest and the lowest potentials reported in the literature. Food shows demand-side potential of socio-cultural factors and infrastructure use, and changes in land-use patterns enabled by change in food demand. Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end-use sectors (buildings, land transport, food) by 40–70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. The last row shows how demand-side mitigation options in other sectors can influence overall electricity demand. The dark grey bar shows the projected increase in electricity demand above the 2050 baseline due to increasing electrification in the other sectors. Based on a bottom-up assessment, this projected increase in electricity demand can be avoided through demand-side mitigation options in the domains of infrastructure use and socio-cultural factors that influence electricity usage in industry, land transport, and buildings (green arrow). {*WGII Figure SPM.4, WGII Cross-Chapter Box FEASIB in Chapter 18; WGIII SPM C.10, WGIII 12.2.1, WGIII 12.2.2, WGIII Figure SPM.6, WGIII Figure SPM.7*}

4.5.1. Energy Systems

Rapid and deep reductions in GHG emissions require major energy system transitions (*high confidence*). Adaptation options can help reduce climate-related risks to the energy system (*very high confidence*). Net zero CO_2 energy systems entail: a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels[153], and use of Carbon Capture and Storage in the remaining fossil fuel systems; electricity systems that emit no net CO_2; widespread electrification; alternative energy carriers in applications less amenable to electrification; energy conservation and efficiency; and greater integration across the energy system *(high confidence).* Large contributions to emissions reductions can come from options costing less than USD 20 tCO_2-eq^{-1}, including solar and wind energy, energy efficiency improvements, and CH_4 (methane) emissions reductions (from coal mining, oil and gas, and waste) (*medium confidence*).[154] Many of these response options are technically viable and are supported by the public (*high confidence*). Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems (*high confidence*). {*WGII SPM C.2.10; WGIII SPM C.4.1, WGIII SPM C.4.2, WGIII SPM C.12.1, WGIII SPM E.1.1, WGIII TS.5.1*}

Climate change and related extreme events will affect future energy systems, including hydropower production, bioenergy yields, thermal power plant efficiencies, and demands for heating and cooling (*high confidence*). The most feasible energy system adaptation options support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (*very high confidence*). Adaptations for hydropower and thermo-electric power generation are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming (*medium confidence*). Energy generation diversification (e.g., wind, solar, small-scale hydroelectric) and demand side management (e.g., storage and energy efficiency improvements) can increase energy reliability and reduce vulnerabilities to climate change, especially in rural populations (*high confidence*). Climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits have high feasibility in the medium- to long-term, with mitigation co-benefits (*very high confidence*). {*WGII SPM B.5.3, WGII SPM C.2.10; WGIII TS.5.1*}

4.5.2. Industry

There are several options to reduce industrial emissions that differ by type of industry; many industries are disrupted by climate change, especially from extreme events (*high confidence*). Reducing industry emissions will entail coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and

[153] In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more CO_2 from power plants, or 50–80% of fugitive methane emissions from energy supply. {*WGIII SPM footnote 54*}

[154] The mitigation potentials and mitigation costs of individual technologies in a specific context or region may differ greatly from the provided estimates (*medium confidence*). {*WGIII SPM C.12.1*}

transformational changes in production processes (*high confidence*). Light industry and manufacturing can be largely decarbonized through available abatement technologies (e.g., material efficiency, circularity), electrification (e.g., electrothermal heating, heat pumps), and switching to low- and zero-GHG emitting fuels (e.g., hydrogen, ammonia, and bio-based and other synthetic fuels) (*high confidence*), while deep reduction of cement process emissions will rely on cementitious material substitution and the availability of Carbon Capture and Storage (CCS) until new chemistries are mastered (*high confidence*). Reducing emissions from the production and use of chemicals would need to rely on a life cycle approach, including increased plastics recycling, fuel and feedstock switching, and carbon sourced through biogenic sources, and, depending on availability, Carbon Capture and Utilisation (CCU), direct air CO_2 capture, as well as CCS (*high confidence*). Action to reduce industry sector emissions may change the location of GHG-intensive industries and the organisation of value chains, with distributional effects on employment and economic structure (*medium confidence*). {*WGII TS.B.9.1, WGII 16.5.2; WGIII SPM C.5, WGIII SPM C.5.2, WGIII SPM C.5.3, WGIII TS.5.5*}

Many industrial and service sectors are negatively affected by climate change through supply and operational disruptions, especially from extreme events (*high confidence*), and will require adaptation efforts. Water intensive industries (e.g., mining) can undertake measures to reduce water stress, such as water recycling and reuse, using brackish or saline sources, working to improve water use efficiency. However, residual risks will remain, especially at higher levels of warming (*medium confidence*). {*WGII TS.B.9.1, WGII 16.5.2, WGII 4.6.3*} (*Section 3.2*)

4.5.3. Cities, Settlements and Infrastructure

Urban systems are critical for achieving deep emissions reductions and advancing climate resilient development, particularly when this involves integrated planning that incorporates physical, natural and social infrastructure (*high confidence*). Deep emissions reductions and integrated adaptation actions are advanced by: integrated, inclusive land use planning and decision-making; compact urban form by co-locating jobs and housing; reducing or changing urban energy and material consumption; electrification in combination with low emissions sources; improved water and waste management infrastructure; and enhancing carbon uptake and storage in the urban environment (e.g. bio-based building materials, permeable surfaces and urban green and blue infrastructure). Cities can achieve net zero emissions if emissions are reduced within and outside of their administrative boundaries through supply chains, creating beneficial cascading effects across other sectors. (*high confidence*) {*WGII SPM C.5.6, WGII SPM D.1.3, WGII SPM D.3; WGIII SPM C.6, WGIII SPM C.6.2, WGIII TS 5.4, SR1.5 SPM C.2.4*}

Considering climate change impacts and risks (e.g., through climate services) in the design and planning of urban and rural settlements and infrastructure is critical for resilience and enhancing human well-being. Effective mitigation can be advanced at each of the design, construction, retrofit, use and disposal stages for buildings. Mitigation interventions for buildings include: at the construction phase, low-emission construction materials, highly efficient building envelope and the integration of renewable energy solutions; at the use phase, highly efficient appliances/equipment, the optimisation of the use of buildings and their supply with low-emission energy sources; and at the disposal phase, recycling and re-using construction materials. Sufficiency[155] measures can limit the demand for energy and materials over the lifecycle of buildings and appliances. (*high confidence*) {*WGII SPM C.2.5; WGIII SPM C.7.2*}

Transport-related GHG emissions can be reduced by demand-side options and low-GHG emissions technologies. Changes in urban form, reallocation of street space for cycling and walking, digitalisation (e.g., teleworking) and programs that encourage changes in consumer behaviour (e.g. transport, pricing) can reduce demand for transport services and support the shift to more energy efficient transport modes (*high confidence*). Electric vehicles powered by low-emissions electricity offer the largest decarbonisation potential for land-based transport, on a life cycle basis (*high confidence*). Costs of electrified vehicles are decreasing and their adoption is accelerating, but they require continued investments in supporting infrastructure to increase scale of deployment (*high confidence*). The environmental footprint of battery production and growing concerns about critical minerals can be addressed by material and supply diversification strategies, energy and material efficiency improvements, and circular material flows (*medium confidence*). Advances in battery technologies could facilitate the electrification of heavy-duty trucks and compliment conventional electric rail systems (*medium confidence*). Sustainable biofuels can offer additional mitigation benefits in land-based transport in the short and medium term (*medium confidence*). Sustainable biofuels, low-emissions hydrogen, and derivatives (including synthetic fuels) can support mitigation of CO_2 emissions from shipping, aviation, and heavy-duty land transport but require production process improvements and cost reductions (*medium confidence*). Key infrastructure systems including sanitation, water, health, transport, communications and energy will be increasingly vulnerable if design standards do not account for changing climate conditions (*high confidence*). {*WGII SPM B.2.5; WGIII SPM C.6.2, WGIII SPM C.8, WGIII SPM C.8.1, WGIII SPM C.8.2, WGIII SPM C.10.2, WGIII SPM C.10.3, WGIII SPM C.10.4*}

Green/natural and blue infrastructure such as urban forestry, green roofs, ponds and lakes, and river restoration can mitigate climate change through carbon uptake and storage, avoided emissions, and reduced energy use while reducing risk from extreme events such as heatwaves, heavy precipitation and droughts, and advancing co-benefits for health, well-being and livelihoods (*medium confidence*). Urban greening can provide local cooling (*very high confidence*). Combining green/natural and grey/physical infrastructure adaptation responses has potential to reduce adaptation costs and contribute to flood control, sanitation, water resources management, landslide prevention and coastal protection (*medium confidence*). Globally, more financing is directed at grey/physical infrastructure than green/natural infrastructure and social infrastructure (*medium confidence*), and there is limited evidence of investment in informal settlements (*medium* to *high confidence*). The greatest gains in well-being in urban areas can be achieved by prioritising finance to reduce climate risk for low-income

[155] A set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries. {*WGIII Annex I*}

and marginalised communities including people living in informal settlements (*high confidence*). {*WGII SPM C.2.5, WGII SPM C.2.6, WGII SPM C.2.7, WGII SPM D.3.2, WGII TS.E.1.4, WGII Cross-Chapter Box FEAS; WGIII SPM C.6, WGIII SPM C.6.2, WGIII SPM D.1.3, WGIII SPM D.2.1*}

Responses to ongoing sea level rise and land subsidence in low-lying coastal cities and settlements and small islands include protection, accommodation, advance and planned relocation. These responses are more effective if combined and/or sequenced, planned well ahead, aligned with sociocultural values and development priorities, and underpinned by inclusive community engagement processes. (*high confidence*) {*WGII SPM C.2.8*}

4.5.4. Land, Ocean, Food, and Water

There is substantial mitigation and adaptation potential from options in agriculture, forestry and other land use, and in the oceans, that could be upscaled in the near term across most regions (*high confidence*) (Figure 4.5). Conservation, improved management, and restoration of forests and other ecosystems offer the largest share of economic mitigation potential, with reduced deforestation in tropical regions having the highest total mitigation potential. Ecosystem restoration, reforestation, and afforestation can lead to trade-offs due to competing demands on land. Minimizing trade-offs requires integrated approaches to meet multiple objectives including food security. Demand-side measures (shifting to sustainable healthy diets and reducing food loss/waste) and sustainable agricultural intensification can reduce ecosystem conversion and CH_4 and N_2O emissions, and free up land for reforestation and ecosystem restoration. Sustainably sourced agriculture and forest products, including long-lived wood products, can be used instead of more GHG-intensive products in other sectors. Effective adaptation options include cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture. These AFOLU response options require integration of biophysical, socioeconomic and other enabling factors. The effectiveness of ecosystem-based adaptation and most water-related adaptation options declines with increasing warming (see 3.2). (*high confidence*) {*WGII SPM C.2.1, WGII SPM C.2.2, WGII SPM C.2.5; WGIII SPM C.9.1; SRCCL SPM B.1.1, SRCCL SPM B.5.4, SRCCL SPM D.1; SROCC SPM C*}

Some options, such as conservation of high-carbon ecosystems (e.g., peatlands, wetlands, rangelands, mangroves and forests), have immediate impacts while others, such as restoration of high-carbon ecosystems, reclamation of degraded soils or afforestation, take decades to deliver measurable results (*high confidence*). Many sustainable land management technologies and practices are financially profitable in three to ten years (*medium confidence*). {*SRCCL SPM B.1.2, SRCCL SPM D.2.2*}

Maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30–50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (*high confidence*). The services and options provided by terrestrial, freshwater, coastal and ocean ecosystems can be supported by protection, restoration, precautionary ecosystem-based management of renewable resource use, and the reduction of pollution and other stressors (*high confidence*). {*WGII SPM C.2.4, WGII SPM D.4; SROCC SPM C.2*}

Large-scale land conversion for bioenergy, biochar, or afforestation can increase risks to biodiversity, water and food security. In contrast, restoring natural forests and drained peatlands, and improving sustainability of managed forests enhances the resilience of carbon stocks and sinks and reduces ecosystem vulnerability to climate change. Cooperation, and inclusive decision making, with local communities and Indigenous Peoples, as well as recognition of inherent rights of Indigenous Peoples, is integral to successful adaptation across forests and other ecosystems. (*high confidence*) {*WGII SPM B.5.4, WGII SPM C.2.3, WGII SPM C.2.4; WGIII SPM D.2.3; SRCCL B.7.3, SRCCL SPM C.4.3, SRCCL TS.7*}

Natural rivers, wetlands and upstream forests reduce flood risk in most circumstances (*high confidence*). Enhancing natural water retention such as by restoring wetlands and rivers, land use planning such as no build zones or upstream forest management, can further reduce flood risk (*medium confidence*). For inland flooding, combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives (*medium confidence*), but hard defences against flooding or sea level rise can also be maladaptive (*high confidence*). {*WGII SPM C.2.1, WGII SPM C.4.1, WGII SPM C.4.2, WGII SPM C.2.5*}

Protection and restoration of coastal 'blue carbon' ecosystems (e.g., mangroves, tidal marshes and seagrass meadows) could reduce emissions and/or increase carbon uptake and storage (*medium confidence*). Coastal wetlands protect against coastal erosion and flooding (*very high confidence*). Strengthening precautionary approaches, such as rebuilding overexploited or depleted fisheries, and responsiveness of existing fisheries management strategies reduces negative climate change impacts on fisheries, with benefits for regional economies and livelihoods (*medium confidence*). Ecosystem-based management in fisheries and aquaculture supports food security, biodiversity, human health and well-being (*high confidence*). {*WGII SPM C.2.2, WGII SPM C.2; SROCC SPM C2.3, SROCC SPM C.2.4*}

4.5.5. Health and Nutrition

Human health will benefit from integrated mitigation and adaptation options that mainstream health into food, infrastructure, social protection, and water policies (*very high confidence*). Balanced and sustainable healthy diets[156] and reduced food loss and waste present important opportunities for adaptation and mitigation while generating significant co-benefits in terms of biodiversity and human health *(high confidence*). Public health policies to improve nutrition, such as increasing the diversity of food sources in public procurement, health insurance, financial incentives, and awareness-raising campaigns, can potentially influence food demand, reduce food waste, reduce healthcare costs, contribute to lower GHG emissions and enhance adaptive capacity (*high confidence*).

[156] Balanced diets refer to diets that feature plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, as described in SRCCL.

Improved access to clean energy sources and technologies, and shifts to active mobility (e.g., walking and cycling) and public transport can deliver socioeconomic, air quality and health benefits, especially for women and children (*high confidence*). {*WGII SPM C.2.2, WGII SPM C.2.11, WGII Cross-Chapter Box HEALTH; WGIII SPM C.2.2, WGIII SPM C.4.2, WGIII SPM C.9.1, WGIII SPM C.10.4, WGIII SPM D.1.3, WGIII Figure SPM.6, WGIII Figure SPM.8; SRCCL SPM B.6.2, SRCCL SPM B.6.3, SRCCL B.4.6, SRCCL SPM C.2.4*}

Effective adaptation options exist to help protect human health and well-being (*high confidence*). Health Action Plans that include early warning and response systems are effective for extreme heat (*high confidence*). Effective options for water-borne and food-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to flooding and extreme weather events, and improved early warning systems (*very high confidence*). For vector-borne diseases, effective adaptation options include surveillance, early warning systems, and vaccine development (*very high confidence*). Effective adaptation options for reducing mental health risks under climate change include improving surveillance and access to mental health care, and monitoring of psychosocial impacts from extreme weather events (*high confidence*). A key pathway to climate resilience in the health sector is universal access to healthcare (*high confidence*). {*WGII SPM C.2.11, WGII 7.4.6*}

4.5.6 Society, Livelihoods, and Economies

Enhancing knowledge on risks and available adaptation options promotes societal responses, and behaviour and lifestyle changes supported by policies, infrastructure and technology can help reduce global GHG emissions (*high confidence*). Climate literacy and information provided through climate services and community approaches, including those that are informed by Indigenous Knowledge and local knowledge, can accelerate behavioural changes and planning (*high confidence*). Educational and information programmes, using the arts, participatory modelling and citizen science can facilitate awareness, heighten risk perception, and influence behaviours (*high confidence*). The way choices are presented can enable adoption of low GHG intensive socio-cultural options, such as shifts to balanced, sustainable healthy diets, reduced food waste, and active mobility (*high confidence*). Judicious labelling, framing, and communication of social norms can increase the effect of mandates, subsidies, or taxes (*medium confidence*). {*WGII SPM C.5.3, WGII TS.D.10.1; WGIII SPM C.10, WGIII SPM C.10.2, WGIII SPM C.10.3, WGIII SPM E.2.2, WGIII Figure SPM.6, WGIII TS.6.1, 5.4; SR1.5 SPM D.5.6; SROCC SPM C.4*}

A range of adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing approaches, have broad applicability across sectors and provide greater risk reduction benefits when combined (*high confidence*). Climate services that are demand-driven and inclusive of different users and providers can improve agricultural practices, inform better water use and efficiency, and enable resilient infrastructure planning (*high confidence*). Policy mixes that include weather and health insurance, social protection and adaptive safety nets, contingent finance and reserve funds, and universal access to early warning systems combined with effective contingency plans, can reduce vulnerability and exposure of human systems (*high confidence*). Integrating climate adaptation into social protection programs, including cash transfers and public works programs, is highly feasible and increases resilience to climate change, especially when supported by basic services and infrastructure (*high confidence*). Social safety nets can build adaptive capacities, reduce socioeconomic vulnerability, and reduce risk linked to hazards *(robust evidence, medium agreement).* {*WGII SPM C.2.9, WGII SPM C.2.13, WGII Cross-Chapter Box FEASIB in Chapter 18; SRCCL SPM C.1.4, SRCCL SPM D.1.2*}

Reducing future risks of involuntary migration and displacement due to climate change is possible through cooperative, international efforts to enhance institutional adaptive capacity and sustainable development (*high confidence*). Increasing adaptive capacity minimises risk associated with involuntary migration and immobility and improves the degree of choice under which migration decisions are made, while policy interventions can remove barriers and expand the alternatives for safe, orderly and regular migration that allows vulnerable people to adapt to climate change (*high confidence*). {*WGII SPM C.2.12, WGII TS.D.8.6, WGII Cross-Chapter Box MIGRATE in Chapter 7*}

Accelerating commitment and follow-through by the private sector is promoted for instance by building business cases for adaptation, accountability and transparency mechanisms, and monitoring and evaluation of adaptation progress (*medium confidence*). Integrated pathways for managing climate risks will be most suitable when so-called 'low-regret' anticipatory options are established jointly across sectors in a timely manner and are feasible and effective in their local context, and when path dependencies and maladaptations across sectors are avoided (*high confidence*). Sustained adaptation actions are strengthened by mainstreaming adaptation into institutional budget and policy planning cycles, statutory planning, monitoring and evaluation frameworks and into recovery efforts from disaster events (*high confidence*). Instruments that incorporate adaptation such as policy and legal frameworks, behavioural incentives, and economic instruments that address market failures, such as climate risk disclosure, inclusive and deliberative processes strengthen adaptation actions by public and private actors (*medium confidence*). {*WGII SPM C.5.1, WGII SPM C.5.2, WGII TS.D.10.4*}

4.6 Co-Benefits of Adaptation and Mitigation for Sustainable Development Goals

Mitigation and adaptation actions have more synergies than trade-offs with Sustainable Development Goals (SDGs). Synergies and trade-offs depend on context and scale of implementation. Potential trade-offs can be compensated or avoided with additional policies, investments and financial partnerships. (*high confidence*)

Many mitigation and adaptation actions have multiple synergies with Sustainable Development Goals (SDGs), but some actions can also have trade-offs. Potential synergies with SDGs exceed potential trade-offs. Synergies and trade-offs are context specific and depend on: means and scale of implementation, intra- and inter-sectoral interactions, cooperation between countries and regions, the sequencing, timing and stringency of actions, governance, and policy design. Eradicating extreme poverty, energy poverty, and providing decent living standards to all, consistent with near-term sustainable development objectives, can be achieved without significant global emissions growth. (*high confidence*) {*WGII SPM C.2.3, WGII Figure SPM.4b; WGIII SPM B.3.3, WGIII SPM C.9.2, WGIII SPM D.1.2, WGIII SPM D.1.4, WGIII Figure SPM.8*} (*Figure 4.5*)

Several mitigation and adaptation options can harness near-term synergies and reduce trade-offs to advance sustainable development in energy, urban and land systems (Figure 4.5) (*high confidence*). Clean energy supply systems have multiple co-benefits, including improvements in air quality and health. Heat Health Action Plans that include early warning and response systems, approaches that mainstream health into food, livelihoods, social protection, water and sanitation benefit health and well-being. There are potential synergies between multiple Sustainable Development Goals and sustainable land use and urban planning with more green spaces, reduced air pollution, and demand-side mitigation including shifts to balanced, sustainable healthy diets. Electrification combined with low-GHG energy, and shifts to public transport can enhance health, employment, and can contribute to energy security and deliver equity. Conservation, protection and restoration of terrestrial, freshwater, coastal and ocean ecosystems, together with targeted management to adapt to unavoidable impacts of climate change can generate multiple additional benefits, such as agricultural productivity, food security, and biodiversity conservation. (*high confidence*) {*WGII SPM C.1.1, WGII C.2.4, WGII SPM D.1, WGII Figure SPM.4, WGII Cross-Chapter Box HEALTH in Chapter 17, WGII Cross-Chapter Box FEASIB in Chapter 18; WGIII SPM C.4.2, WGIII SPM D.1.3, WGIII SPM D.2, WGIII Figure SPM.8; SRCCL SPM B.4.6*}

When implementing mitigation and adaptation together, and taking trade-offs into account, multiple co-benefits and synergies for human well-being as well as ecosystem and planetary health can be realised (*high confidence*). There is a strong link between sustainable development, vulnerability and climate risks. Social safety nets that support climate change adaptation have strong co-benefits with development goals such as education, poverty alleviation, gender inclusion and food security. Land restoration contributes to mitigation and adaptation with synergies via enhanced ecosystem services and with economically positive returns and co-benefits for poverty reduction and improved livelihoods. Trade-offs can be evaluated and minimised by giving emphasis to capacity building, finance, technology transfer, investments; governance, development, context specific gender-based and other social equity considerations with meaningful participation of Indigenous Peoples, local communities and vulnerable populations. (*high confidence*). {*WGII SPM C.2.9, WGII SPM C.5.6, WGII SPM D.5.2, WGII Cross-Chapter Box on Gender in Chapter 18; WGIII SPM C.9.2, WGIII SPM D.1.2, WGIII SPM D.1.4, WGIII SPM D.2; SRCCL SPM D.2.2, SRCCL TS.4*}

Context relevant design and implementation requires considering people's needs, biodiversity, and other sustainable development dimensions (*very high confidence*). Countries at all stages of economic development seek to improve the well-being of people, and their development priorities reflect different starting points and contexts. Different contexts include but are not limited to social, economic, environmental, cultural, or political circumstances, resource endowment, capabilities, international environment, and prior development. n regions with high dependency on fossil fuels for, among other things, revenue and employment generation, mitigating risks for sustainable development requires policies that promote economic and energy sector diversification and considerations of just transitions principles, processes and practices (*high confidence*). For individuals and households in low-lying coastal areas, in Small Islands, and smallholder farmers transitioning from incremental to transformational adaptation can help overcome soft adaptation limits (*high confidence*). Effective governance is needed to limit trade-offs of some mitigation options such as large scale afforestation and bioenergy options due to risks from their deployment for food systems, biodiversity, other ecosystem functions and services, and livelihoods (*high confidence*). Effective governance requires adequate institutional capacity at all levels (*high confidence*). {*WGII SPM B.5.4, WGII SPM C.3.1, WGII SPM C.3.4; WGIII SPM D.1.3, WGIII SPM E.4.2; SR1.5 SPM C.3.4, SR1.5 SPM C.3.5, SR1.5 SPM Figure SPM.4, SR1.5 SPM D.4.3, SR1.5 SPM D.4.4*}

Near-term adaptation and mitigation actions have more synergies than trade-offs with Sustainable Development Goals (SDGs)

Synergies and trade-offs depend on context and scale

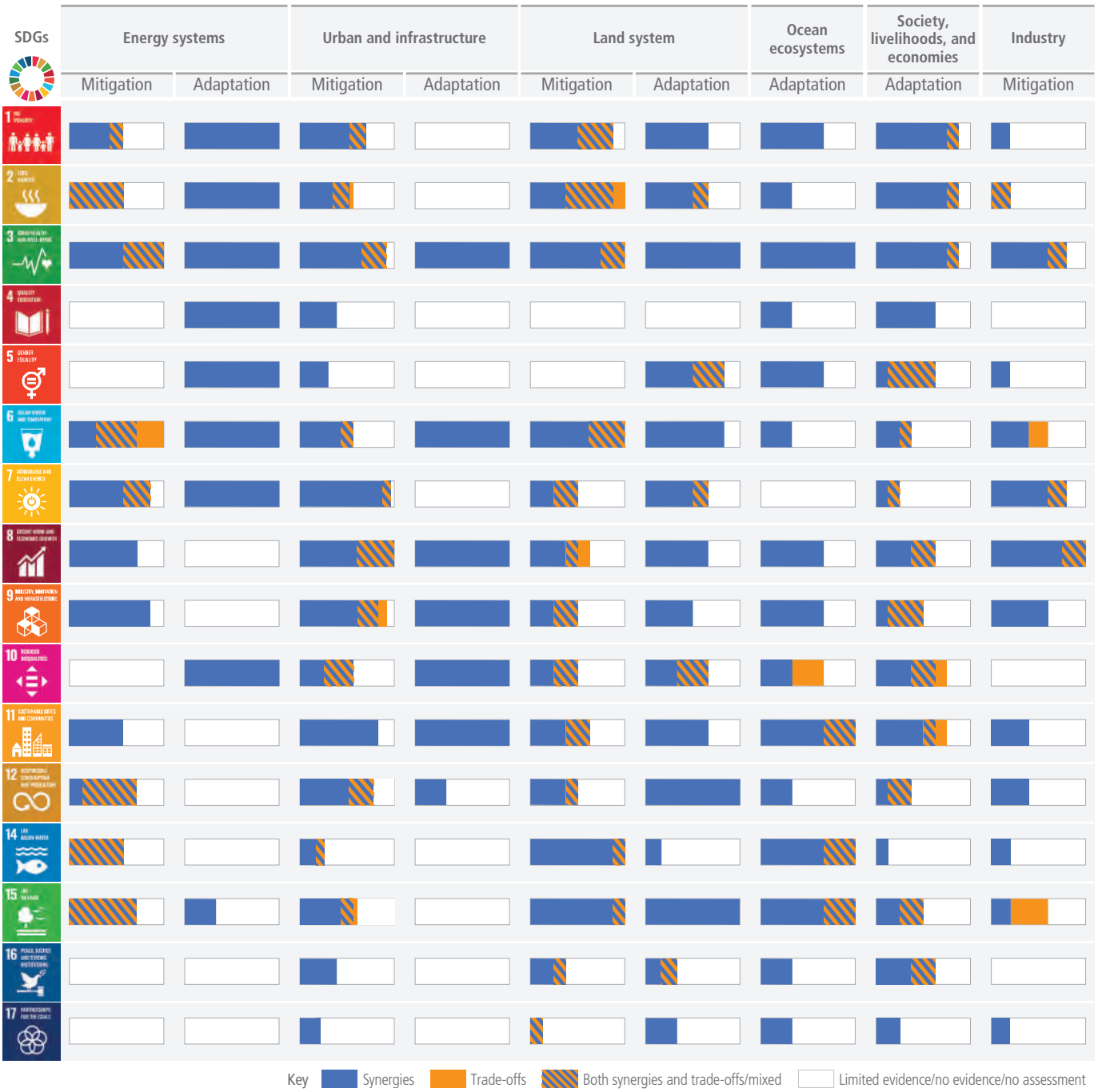


Figure 4.5: Potential synergies and trade-offs between the portfolio of climate change mitigation and adaptation options and the Sustainable Development Goals (SDGs). This figure presents a high-level summary of potential synergies and trade-offs assessed in WGII Figure SPM.4b and WGIII Figure SPM.8, based on the qualitative and quantitative assessment of each individual mitigation or option. The SDGs serve as an analytical framework for the assessment of different sustainable development dimensions, which extend beyond the time frame of 2030 SDG targets. Synergies and trade-offs across all individual options within a sector/system are aggregated into sector/system potentials for the whole mitigation or adaptation portfolio. The length of each bar represents the total number of mitigation or adaptation options under each system/sector. The number of adaptation and mitigation options vary across system/sector, and have been normalised to 100% so that bars are comparable across mitigation, adaptation, system/sector, and SDGs. Positive links shown in WGII Figure SPM.4b and WGIII Figure SPM.8 are counted and aggregated to generate the percentage share of synergies, represented here by the blue proportion within the bars. Negative links shown in WGII Figure SPM.4b and WGIII Figure SPM.8 are counted and aggregated to generate the percentage share of trade-offs and is represented by orange proportion within the bars. 'Both synergies and trade-offs' shown in WGII Figure SPM.4b WGIII Figure SPM.8 are counted and aggregated to generate the percentage share of 'both synergies and trade-off', represented by the striped proportion within the bars. The 'white' proportion within the bar indicates limited evidence/ no evidence/ not assessed. Energy systems comprise all mitigation options listed in WGIII Figure SPM.8 and WGII Figure SPM.4b for adaptation. Urban and infrastructure comprises all mitigation options listed

in WGIII Figure SPM.8 under Urban systems, under Buildings and under Transport and adaptation options listed in WGII Figure SPM.4b under Urban and infrastructure systems. Land system comprises mitigation options listed in WGIII Figure SPM.8 under AFOLU and adaptation options listed in WGII Figure SPM.4b under Land and ocean systems: forest-based adaptation, agroforestry, biodiversity management and ecosystem connectivity, improved cropland management, efficient livestock management, water use efficiency and water resource management. Ocean ecosystems comprises adaptation options listed in WGII Figure SPM.4b under Land and ocean systems: coastal defence and hardening, integrated coastal zone management and sustainable aquaculture and fisheries. Society, livelihood and economies comprises adaptation options listed in WGII Figure SPM.4b under Cross-sectoral; Industry comprises all those mitigation options listed in WGIII Figure SPM.8 under Industry. SDG 13 (Climate Action) is not listed because mitigation/ adaptation is being considered in terms of interaction with SDGs and not vice versa (SPM SR1.5 Figure SPM.4 caption). The bars denote the strength of the connection and do not consider the strength of the impact on the SDGs. The synergies and trade-offs differ depending on the context and the scale of implementation. Scale of implementation particularly matters when there is competition for scarce resources. For the sake of uniformity, we are not reporting the confidence levels because there is knowledge gap in adaptation option wise relation with SDGs and their confidence level which is evident from WGII fig SPM.4b. {*WGII Figure SPM.4b; WGIII Figure SPM.8*}

4.7 Governance and Policy for Near-Term Climate Change Action

Effective climate action requires political commitment, well-aligned multi-level governance and institutional frameworks, laws, policies and strategies. It needs clear goals, adequate finance and financing tools, coordination across multiple policy domains, and inclusive governance processes. Many mitigation and adaptation policy instruments have been deployed successfully, and could support deep emissions reductions and climate resilience if scaled up and applied widely, depending on national circumstances. Adaptation and mitigation action benefits from drawing on diverse knowledge. (*high confidence*)

Effective climate governance enables mitigation and adaptation by providing overall direction based on national circumstances, setting targets and priorities, mainstreaming climate action across policy domains and levels, based on national circumstances and in the context of international cooperation. Effective governance enhances monitoring and evaluation and regulatory certainty, prioritising inclusive, transparent and equitable decision-making, and improves access to finance and technology (*high confidence*). These functions can be promoted by climate-relevant laws and plans, which are growing in number across sectors and regions, advancing mitigation outcomes and adaptation benefits (*high confidence*). Climate laws have been growing in number and have helped deliver mitigation and adaptation outcomes (*medium confidence*). {*WGII SPM C.5, WGII SPM C.5.1, WGII SPM C5.4, WGII SPM C.5.6; WGIII SPM B.5.2, WGIII SPM E.3.1*}

Effective municipal, national and sub-national climate institutions, such as expert and co-ordinating bodies, enable co-produced, multi-scale decision-processes, build consensus for action among diverse interests, and inform strategy settings (*high confidence*). This requires adequate institutional capacity at all levels (*high confidence*). Vulnerabilities and climate risks are often reduced through carefully designed and implemented laws, policies, participatory processes, and interventions that address context specific inequities such as based on gender, ethnicity, disability, age, location and income (*high confidence*). Policy support is influenced by Indigenous Peoples, businesses, and actors in civil society, including, youth, labour, media, and local communities, and effectiveness is enhanced by partnerships between many different groups in society (*high confidence*). Climate-related litigation is growing, with a large number of cases in some developed countries and with a much smaller number in some developing countries, and in some cases has influenced the outcome and ambition of climate governance (*medium confidence*). {*WGII SPM C2.6, WGII SPM C.5.2, WGII SPM C.5.5, WGII SPM C.5.6, WGII SPM D.3.1; WGIII SPM E3.2, WGIII SPM E.3.3*}

Effective climate governance is enabled by inclusive decision processes, allocation of appropriate resources, and institutional review, monitoring and evaluation (*high confidence*). Multi-level, hybrid and cross-sector governance facilitates appropriate consideration for co-benefits and trade-offs, particularly in land sectors where decision processes range from farm level to national scale (*high confidence*). Consideration of climate justice can help to facilitate shifting development pathways towards sustainability. {*WGII SPM C.5.5, WGII SPM C.5.6, WGII SPM D.1.1, WGII SPM D.2, WGII SPM D.3.2; SRCCL SPM C.3, SRCCL TS.1*}

Drawing on diverse knowledge and partnerships, including with women, youth, Indigenous Peoples, local communities, and ethnic minorities can facilitate climate resilient development and has allowed locally appropriate and socially acceptable solutions (*high confidence*). {*WGII SPM D.2, D.2.1*}

Many regulatory and economic instruments have already been deployed successfully. These instruments could support deep emissions reductions if scaled up and applied more widely. Practical experience has informed instrument design and helped to improve predictability, environmental effectiveness, economic efficiency, and equity. (*high confidence*) {*WGII SPM E.4; WGIII SPM E.4.2*}

Scaling up and enhancing the use of regulatory instruments, consistent with national circumstances, can improve mitigation outcomes in sectoral applications (*high confidence*), and regulatory instruments that include flexibility mechanisms can reduce costs of cutting emissions (*medium confidence*). {*WGII SPM C.5.4; WGIII SPM E.4.1*}

Where implemented, carbon pricing instruments have incentivized low-cost emissions reduction measures, but have been less effective, on their own and at prevailing prices during the assessment period, to promote higher-cost measures necessary for further reductions (*medium confidence*). Revenue from carbon taxes or emissions trading can be used for equity and distributional goals, for example to support low-income households, among other

approaches (*high confidence*). There is no consistent evidence that current emission trading systems have led to significant emissions leakage (*medium confidence*). {*WGIII SPM E4.2, WGIII SPM E.4.6*}

Removing fossil fuel subsidies would reduce emissions, improve public revenue and macroeconomic performance, and yield other environmental and sustainable development benefits such as improved public revenue, macroeconomic and sustainability performance; subsidy removal can have adverse distributional impacts especially on the most economically vulnerable groups which, in some cases, can be mitigated by measures such as re-distributing revenue saved, and depend on national circumstances (*high confidence*). Fossil fuel subsidy removal is projected by various studies to reduce global CO_2 emissions by 1–4%, and GHG emissions by up to 10% by 2030, varying across regions (*medium confidence*). {*WGIII SPM E.4.2*}

National policies to support technology development, and participation in international markets for emission reduction, can bring positive spillover effects for other countries (*medium confidence*), although reduced demand for fossil fuels as a result of climate policy could result in costs to exporting countries (*high confidence*). Economy-wide packages can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). Examples are public spending commitments; pricing reforms; and investment in education and training, R&D and infrastructure (*high confidence*). Effective policy packages would be comprehensive in coverage, harnessed to a clear vision for change, balanced across objectives, aligned with specific technology and system needs, consistent in terms of design and tailored to national circumstances (*high confidence*). {*WGIII SPM E4.4, WGIII SPM 4.5, WGIII SPM 4.6*}

4.8 Strengthening the Response: Finance, International Cooperation and Technology

Finance, international cooperation and technology are critical enablers for accelerated climate action. If climate goals are to be achieved, both adaptation and mitigation financing would have to increase many-fold. There is sufficient global capital to close the global investment gaps but there are barriers to redirect capital to climate action. Barriers include institutional, regulatory and market access barriers, which can be reduced to address the needs and opportunities, economic vulnerability and indebtedness in many developing countries. Enhancing international cooperation is possible through multiple channels. Enhancing technology innovation systems is key to accelerate the widespread adoption of technologies and practices. (*high confidence*)

4.8.1. Finance for Mitigation and Adaptation Actions

Improved availability and access to finance[157] will enable accelerated climate action (*very high confidence*). Addressing needs and gaps and broadening equitable access to domestic and international finance, when combined with other supportive actions, can act as a catalyst for accelerating mitigation and shifting development pathways (*high confidence*). Climate resilient development is enabled by increased international cooperation including improved access to financial resources, particularly for vulnerable regions, sectors and groups, and inclusive governance and coordinated policies (*high confidence*). Accelerated international financial cooperation is a critical enabler of low-GHG and just transitions, and can address inequities in access to finance and the costs of, and vulnerability to, the impacts of climate change (*high confidence*). {*WGII SPM C.1.2, WGII SPM C.3.2, WGII SPM C.5, WGII SPM C.5.4, WGII SPM D.2, WGII SPM D.3.2, WGII SPM D.5, WGII SPM D.5.2; WGIII SPM B.4.2,WGIII SPM B.5, WGIII SPM B.5.4, WGIII SPM C.4.2, WGIII SPM C.7.3, WGIII SPM C.8.5, WGIII SPM D.1.2, WGIII SPM D.2.4, WGIII SPM D.3.4, WGIII SPM E.2.3, WGIII SPM E.3.1, WGIII SPM E.5, WGIII SPM E.5.1, WGIII SPM E.5.2, WGIII SPM E.5.3, WGIII SPM E.5.4, WGIII SPM E.6.2*}

Both adaptation and mitigation finance need to increase many-fold, to address rising climate risks and to accelerate investments in emissions reduction (*high confidence*). Increased finance would address soft limits to adaptation and rising climate risks while also averting some related losses and damages, particularly in vulnerable developing countries (*high confidence*). Enhanced mobilisation of and access to finance, together with building capacity, are essential for implementation of adaptation actions and to reduce adaptation gaps given rising risks and costs, especially for the most vulnerable groups, regions and sectors (*high confidence*). Public finance is an important enabler of adaptation and mitigation, and can also leverage private finance (*high confidence*). Adaptation funding predominately comes from public sources, and public mechanisms and finance can leverage private sector finance by addressing real and perceived regulatory, cost and market barriers, for instance via public-private partnerships (*high confidence*). Financial and technological resources enable effective and ongoing implementation of adaptation, especially when supported by institutions with a strong understanding of adaptation needs and capacity (*high confidence*). Average annual modelled mitigation investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels, and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Even if extensive global mitigation efforts are implemented, there will be a large need for financial, technical, and human resources for adaptation (*high confidence*). {*WGII SPM C.1.2, WGII SPM C2.11, WGII SPM C.3, WGII SPM C.3.2, WGII SPM C3.5, WGII SPM C.5, WGII SPM C.5.4, WGII SPM D.1, WGII SPM D.1.1, WGII SPM D.1.2, WGII SPM C.5.4; WGIII SPM D.2.4, WGIII SPM E.5, WGIII SPM E.5.1, WGIII 15.2*} *(Section 2.3.2, 2.3.3, 4.4, Figure 4.6)*

[157] Finance can originate from diverse sources, singly or in combination: public or private, local, national or international, bilateral or multilateral, and alternative sources (e.g., philanthropic, carbon offsets). It can be in the form of grants, technical assistance, loans (concessional and non-concessional), bonds, equity, risk insurance and financial guarantees (of various types).

There is sufficient global capital and liquidity to close global investment gaps, given the size of the global financial system, but there are barriers to redirect capital to climate action both within and outside the global financial sector and in the context of economic vulnerabilities and indebtedness facing many developing countries (*high confidence*). For shifts in private finance, options include better assessment of climate-related risks and investment opportunities within the financial system, reducing sectoral and regional mismatches between available capital and investment needs, improving the risk-return profiles of climate investments, and developing institutional capacities and local capital markets. Macroeconomic barriers include, amongst others, indebtedness and economic vulnerability of developing regions. (*high confidence*) {*WGII SPM C.5.4; WGIII SPM E.4.2, WGIII SPM E.5, WGIII SPM E.5.2, WGIII SPM E.5.3*}

Scaling up financial flows requires clear signalling from governments and the international community (*high confidence*). Tracked financial flows fall short of the levels needed for adaptation and to achieve mitigation goals across all sectors and regions (*high confidence*). These gaps create many opportunities and the challenge of closing gaps is largest in developing countries (*high confidence*). This includes a stronger alignment of public finance, lowering real and perceived regulatory, cost and market barriers, and higher levels of public finance to lower the risks associated with low-emission investments. Up-front risks deter economically sound low carbon projects, and developing local capital markets are an option. Investors, financial intermediaries, central banks and financial regulators can shift the systemic underpricing of climate-related risks. A robust labelling of bonds and transparency is needed to attract savers. (*high confidence*) {*WGII SPM C.5.4; WGIII SPM B.5.4, WGIII SPM E.4, WGIII SPM E.5.4, WGIII 15.2, WGIII 15.6.1, WGIII 15.6.2, WGIII 15.6.7*}

The largest climate finance gaps and opportunities are in developing countries (*high confidence*). Accelerated support from developed countries and multilateral institutions is a critical enabler to enhance mitigation and adaptation action and can address inequities in finance, including its costs, terms and conditions, and economic vulnerability to climate change. Scaled-up public grants for mitigation and adaptation funding for vulnerable regions, e.g., in Sub-Saharan Africa, would be cost-effective and have high social returns in terms of access to basic energy. Options for scaling up mitigation and adaptation in developing regions include: increased levels of public finance and publicly mobilised private finance flows from developed to developing countries in the context of the USD 100 billion-a-year goal of the Paris Agreement; increase the use of public guarantees to reduce risks and leverage private flows at lower cost; local capital markets development; and building greater trust in international cooperation processes. A coordinated effort to make the post-pandemic recovery sustainable over the long term through increased flows of financing over this decade can accelerate climate action, including in developing regions facing high debt costs, debt distress and macroeconomic uncertainty. (*high confidence*) {*WGII SPM C.5.2, WGII SPM C.5.4, WGII SPM C.6.5, WGII SPM D.2, WGII TS.D.10.2; WGIII SPM E.5, WGIII SPM E.5.3, WGIII TS.6.4, WGIII Box TS.1, WGIII 15.2, WGIII 15.6*}

4.8.2. International Cooperation and Coordination

International cooperation is a critical enabler for achieving ambitious climate change mitigation goals and climate resilient development (*high confidence*). Climate resilient development is enabled by increased international cooperation including mobilising and enhancing access to finance, particularly for developing countries, vulnerable regions, sectors and groups and aligning finance flows for climate action to be consistent with ambition levels and funding needs (*high confidence*). While agreed processes and goals, such as those in the UNFCCC, Kyoto Protocol and Paris Agreement, are helping (Section 2.2.1), international financial, technology and capacity building support to developing countries will enable greater implementation and more ambitious actions (*medium confidence*). By integrating equity and climate justice, national and international policies can help to facilitate shifting development pathways towards sustainability, especially by mobilising and enhancing access to finance for vulnerable regions, sectors and communities (*high confidence*). International cooperation and coordination, including combined policy packages, may be particularly important for sustainability transitions in emissions-intensive and highly traded basic materials industries that are exposed to international competition (*high confidence*). The large majority of emission modelling studies assume significant international cooperation to secure financial flows and address inequality and poverty issues in pathways limiting global warming. There are large variations in the modelled effects of mitigation on GDP across regions, depending notably on economic structure, regional emissions reductions, policy design and level of international cooperation (*high confidence*). Delayed global cooperation increases policy costs across regions (*high confidence*). {*WGII SPM D.2, WGII SPM D.3.1, WGII SPM D.5.2; WGIII SPM D.3.4, WGIII SPM C5.4, WGIII SPM C.12.2, WGIII SPM E.6, WGIII SPM E.6.1, WGIII E.5.4, WGIII TS.4.2, WGIII TS.6.2; SR1.5 SPM D.6.3, SR1.5 SPM D.7, SR1.5 SPM D.7.3*}

The transboundary nature of many climate change risks (e.g., for supply chains, markets and natural resource flows in food, fisheries, energy and water, and potential for conflict) increases the need for climate-informed transboundary management, cooperation, responses and solutions through multi-national or regional governance processes (*high confidence*). Multilateral governance efforts can help reconcile contested interests, world views and values about how to address climate change. International environment and sectoral agreements, and initiatives in some cases, may help to stimulate low GHG investment and reduce emissions (such as ozone depletion, transboundary air pollution and atmospheric emissions of mercury). Improvements to national and international governance structures would further enable the decarbonisation of shipping and aviation through deployment of low-emissions fuels, for example through stricter efficiency and carbon intensity standards. Transnational partnerships can also stimulate policy development, low-emissions technology diffusion, emission reductions and adaptation, by linking sub-national and other actors, including cities, regions, non-governmental organisations and private sector entities, and by enhancing interactions between state and non-state actors, though uncertainties remain over their costs, feasibility, and effectiveness. International environmental and sectoral agreements, institutions, and initiatives are helping, and in some cases may help, to stimulate low GHG emissions investment and reduce emissions. (*medium confidence*) {*WGII SPM B.5.3, WGII SPM C.5.6, WGII TS.E.5.4, WGII TS.E.5.5; WGIII SPM C.8.4, WGIII SPM E.6.3, WGIII SPM E.6.4, WGIII SPM E.6.4, WGIII TS.5.3*}

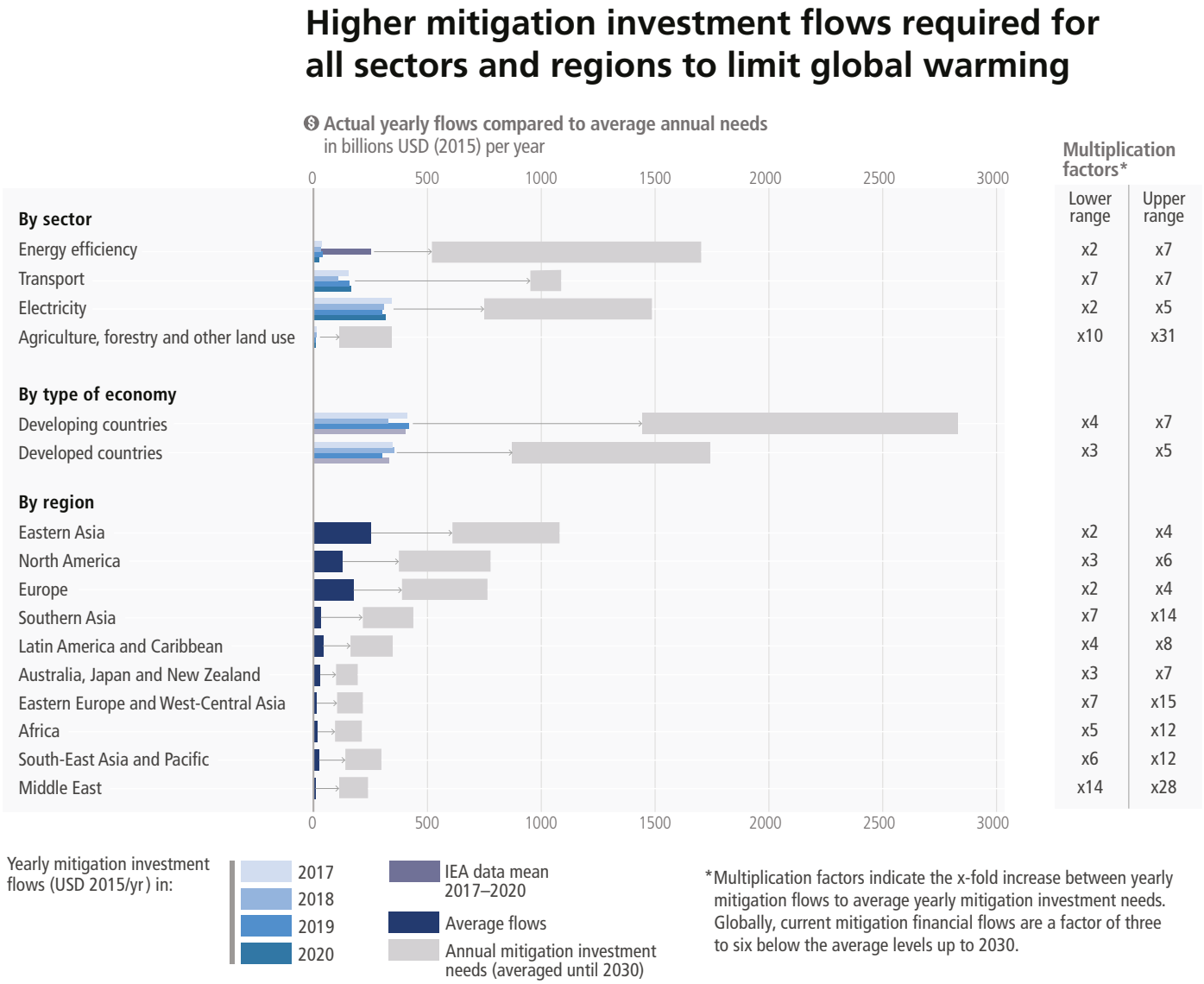


Figure 4.6: Breakdown of average mitigation investment flows and investment needs until 2030 (USD billion). Mitigation investment flows and investment needs by sector (energy efficiency, transport, electricity, and agriculture, forestry and other land use), by type of economy, and by region (see WGIII Annex II Part I Section 1 for the classification schemes for countries and areas). The blue bars display data on mitigation investment flows for four years: 2017, 2018, 2019 and 2020 by sector and by type of economy. For the regional breakdown, the annual average mitigation investment flows for 2017–2019 are shown. The grey bars show the minimum and maximum level of global annual mitigation investment needs in the assessed scenarios. This has been averaged until 2030. The multiplication factors show the ratio of global average early mitigation investment needs (averaged until 2030) and current yearly mitigation flows (averaged for 2017/18–2020). The lower multiplication factor refers to the lower end of the range of investment needs. The upper multiplication factor refers to the upper range of investment needs. Given the multiple sources and lack of harmonised methodologies, the data can be considered only if indicative of the size and pattern of investment needs. {*WGIII Figure TS.25, WGIII 15.3, WGIII 15.4, WGIII 15.5, WGIII Table 15.2, WGIII Table 15.3, WGIII Table 15.4*}

4.8.3. Technology Innovation, Adoption, Diffusion and Transfer

Enhancing technology innovation systems can provide opportunities to lower emissions growth and create social and environmental co-benefits. Policy packages tailored to national contexts and technological characteristics have been effective in supporting low-emission innovation and technology diffusion. Support for successful low-carbon technological innovation includes public policies such as training and R&D, complemented by regulatory and market-based instruments that create incentives and market opportunities such as appliance performance standards and building codes. (*high confidence*) {*WGIII SPM B.4, WGIII SPM B.4.4, WGIII SPM E.4.3, WGIII SPM E4.4*}

International cooperation on innovation systems and technology development and transfer, accompanied by capacity building, knowledge sharing, and technical and financial support can accelerate the global diffusion of mitigation technologies, practices and policies and align these with other development objectives (*high confidence*). Choice architecture can help end-users adopt technology and low-GHG-intensive options (*high confidence*). Adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity building (*medium confidence*). {*WGIII SPM B.4.2, WGIII SPM E.6.2, WGIII SPM C.10.4, WGIII 16.5*}

International cooperation on innovation works best when tailored to and beneficial for local value chains, when partners collaborate on an equal footing, and when capacity building is an integral part of the effort (*medium confidence*). {*WGIII SPM E.4.4, WGIII SPM E.6.2*}

Technological innovation can have trade-offs that include externalities such as new and greater environmental impacts and social inequalities; rebound effects leading to lower net emission reductions or even emission increases; and overdependence on foreign knowledge and providers (*high confidence*). Appropriately designed policies and governance have helped address distributional impacts and rebound effects (*high confidence*). For example, digital technologies can promote large increases in energy efficiency through coordination and an economic shift to services (*high confidence*). However, societal digitalization can induce greater consumption of goods and energy and increased electronic waste as well as negatively impacting labour markets and worsening inequalities between and within countries (*medium confidence*). Digitalisation requires appropriate governance and policies in order to enhance mitigation potential (*high confidence*). Effective policy packages can help to realise synergies, avoid trade-offs and/or reduce rebound effects: these might include a mix of efficiency targets, performance standards, information provision, carbon pricing, finance and technical assistance (*high confidence*). {*WGIII SPM B.4.2, WGIII SPM B.4.3, WGIII SPM E.4.4, WGIII TS 6.5, WGIII Cross-Chapter Box 11 on Digitalization in Chapter 16*}

Technology transfer to expand use of digital technologies for land use monitoring, sustainable land management, and improved agricultural productivity supports reduced emissions from deforestation and land use change while also improving GHG accounting and standardisation (*medium confidence*). {*SRCCL SPM C.2.1, SRCCL SPM D.1.2, SRCCL SPM D.1.4, SRCCL 7.4.4, SRCCL 7.4.6*}

4.9 Integration of Near-Term Actions Across Sectors and Systems

The feasibility, effectiveness and benefits of mitigation and adaptation actions are increased when multi-sectoral solutions are undertaken that cut across systems. When such options are combined with broader sustainable development objectives, they can yield greater benefits for human well-being, social equity and justice, and ecosystem and planetary health. (*high confidence*)

Climate resilient development strategies that treat climate, ecosystems and biodiversity, and human society as parts of an integrated system are the most effective (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Climate resilient development is enabled when decision-making processes and actions are integrated across sectors (*very high confidence*). Synergies with and progress towards the Sustainable Development Goals enhance prospects for climate resilient development. Choices and actions that treat humans and ecosystems as an integrated system build on diverse knowledge about climate risk, equitable, just and inclusive approaches, and ecosystem stewardship. {*WGII SPM B.2, WGII Figure SPM.5, WGII SPM D.2, WGII SPM D2.1, WGII SPM 2.2, WGII SPM D4, WGII SPM D4.1, WGII SPM D4.2, WGII SPM D5.2, WGII Figure SPM.5*}

Approaches that align goals and actions across sectors provide opportunities for multiple and large-scale benefits and avoided damages in the near term. Such measures can also achieve greater benefits through cascading effects across sectors (*medium confidence*). For example, the feasibility of using land for both agriculture and centralised solar production can increase when such options are combined (*high confidence*). Similarly, integrated transport and energy infrastructure planning and operations can together reduce the environmental, social, and economic impacts of decarbonising the transport and energy sectors (*high confidence*). The implementation of packages of multiple city-scale mitigation strategies can have cascading effects across sectors and reduce GHG emissions both within and outside a city's administrative boundaries (*very high confidence*). Integrated design approaches to the construction and retrofit of buildings provide increasing examples of zero energy or zero carbon buildings in several regions. To minimise maladaptation, multi-sectoral, multi-actor and inclusive planning with flexible pathways encourages low-regret and timely actions that keep options open, ensure benefits in multiple sectors and systems and suggest the available solution space for adapting to long-term climate change (*very high confidence*). Trade-offs in terms of employment, water use, land-use competition and biodiversity, as well as access to, and the affordability of, energy, food, and water can be avoided by well-implemented land-based mitigation options, especially those that do not threaten existing sustainable land uses and land rights, with frameworks for integrated policy implementation (*high confidence*). {*WGII SPM C.2, WGII SPM C.4.4; WGIII SPM C.6.3, WGIII SPM C.6, WGIII SPM C.7.2, WGIII SPM C.8.5, WGIII SPM D.1.2, WGIII SPM D.1.5, WGIII SPM E.1.2*}

Mitigation and adaptation when implemented together, and combined with broader sustainable development objectives, would yield multiple benefits for human well-being as well as ecosystem and planetary health (*high confidence*). The range of such positive interactions is significant in the landscape of near-term climate policies across regions, sectors and systems. For example, AFOLU mitigation actions in land-use change and forestry, when sustainably implemented, can provide large-scale GHG emission reductions and removals that simultaneously benefit biodiversity, food security, wood supply and other ecosystem services but cannot fully compensate for delayed mitigation action in other sectors. Adaptation measures in land, ocean and ecosystems similarly can have widespread benefits for food security, nutrition, health and well-being, ecosystems and biodiversity. Equally, urban systems are critical, interconnected sites for climate resilient development; urban policies that implement multiple interventions can yield adaptation or mitigation gains with equity and human well-being. Integrated policy packages can improve the ability to integrate considerations of equity, gender equality and justice. Coordinated cross-sectoral policies and planning can maximise synergies and avoid or reduce trade-offs between mitigation

and adaptation. Effective action in all of the above areas will require near-term political commitment and follow-through, social cooperation, finance, and more integrated cross-sectoral policies and support and actions. (*high confidence*). {*WGII SPM C.1, WG II SPM C.2, WGII SPM C.2, WGII SPM C.5, WGII SPM D.2, WGII SPM D.3.2, WGII SPM D.3.3, WGII Figure SPM.4; WGIII SPM C.6.3, WGIII SPM C.8.2, WGIII SPM C.9, WGIII SPM C.9.1, WGIII SPM C.9.2, WGIII SPM D.2, WGIII SPM D.2.4, WGIII SPM D.3.2, WGIII SPM E.1, WGIII SPM E.2.4, WGIII Figure SPM.8, WGIII TS.7, WGIII TS Figure TS.29: SRCCL ES 7.4.8, SRCCL SPM B.6*} (*3.4, 4.4*)

Decision -/CP.26

Glasgow Climate Pact

The Conference of the Parties,

Recalling decisions 1/CP.19, 1/CP.20, 1/CP.21, 1/CP.22, 1/CP.23, 1/CP.24 and 1/CP.25,

Noting decisions 1/CMP.16 and 1/CMA.3,

Recognizing the role of multilateralism and the Convention, including its processes and principles, and the importance of international cooperation in addressing climate change and its impacts, in the context of sustainable development and efforts to eradicate poverty,

Acknowledging the devastating impacts of the coronavirus disease 2019 pandemic and the importance of ensuring a sustainable, resilient and inclusive global recovery, showing solidarity particularly with developing country Parties,

Recognizing the important advances made through the UNFCCC multilateral process since 1994, including in the context of the Convention, the Kyoto Protocol and the Paris Agreement,

Acknowledging that climate change is a common concern of humankind, Parties should, when taking action to address climate change, respect, promote and consider their respective obligations on human rights, the right to health, the rights of indigenous peoples, local communities, migrants, children, persons with disabilities and people in vulnerable situations and the right to development, as well as gender equality, empowerment of women and intergenerational equity,

Noting the importance of ensuring the integrity of all ecosystems, including in forests, the ocean and the cryosphere, and the protection of biodiversity, recognized by some cultures as Mother Earth, and *also noting* the importance for some of the concept of 'climate justice', when taking action to address climate change,

Expressing appreciation to the Heads of State and Government who participated in the World Leaders Summit in Glasgow and for the increased targets and actions announced and the commitments made to work together and with non-Party stakeholders to accelerate sectoral action by 2030,

Recognizing the important role of indigenous peoples, local communities and civil society, including youth and children, in addressing and responding to climate change, and *highlighting* the urgent need for multilevel and cooperative action,

Recognizing the interlinked global crises of climate change and biodiversity loss, and the critical role of protecting, conserving and restoring nature and ecosystems in delivering benefits for climate adaptation and mitigation, while ensuring social and environmental safeguards,

I. Science and urgency

1. *Recognizes* the importance of the best available science for effective climate action and policymaking;

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2. *Welcomes* the contribution of Working Group I to the Intergovernmental Panel on Climate Change Sixth Assessment Report[1] and the recent global and regional reports on the state of the climate from the World Meteorological Organization, and *invites* the Intergovernmental Panel on Climate Change to present its forthcoming reports to the Subsidiary Body for Scientific and Technological Advice in 2022;

3. *Expresses alarm and utmost concern* that human activities have caused around 1.1 °C of global warming to date and that impacts are already being felt in every region;

4. *Stresses* the urgency of enhancing ambition and action in relation to mitigation adaptation and finance in this critical decade to address gaps between current efforts and pathways in pursuit of the ultimate objective of the Convention and its long-term global goal;

II. Adaptation

5. *Notes with serious concern* the findings from the contribution of Working Group I to the Intergovernmental Panel on Climate Change Sixth Assessment Report, including that climate and weather extremes and their adverse impacts on people and nature will continue to increase with every additional increment of rising temperatures;

6. *Emphasizes* the urgency of scaling up action and support, including finance, capacity-building and technology transfer, to enhance adaptive capacity, strengthen resilience and reduce vulnerability to climate change in line with the best available science, taking into account the priorities and needs of developing country Parties;

7. *Welcomes* the national adaptation plans submitted to date, which enhance the understanding and implementation of adaptation actions and priorities;

8. *Urges* Parties to further integrate adaptation into local, national and regional planning;

9. *Invites* the Intergovernmental Panel on Climate Change to present to the Conference of the Parties at its twenty-seventh session (November 2022) the findings from the contribution of Working Group II to its Sixth Assessment Report, including those relevant to assessing adaptation needs, and *calls upon* the research community to further the understanding of global, regional and local impacts of climate change, response options and adaptation needs;

III. Adaptation finance

10. *Notes with concern* that the current provision of climate finance for adaptation remains insufficient to respond to worsening climate change impacts in developing country Parties;

11. *Urges* developed country Parties to urgently and significantly scale up their provision of climate finance, technology transfer and capacity-building for adaptation so as to respond to the needs of developing country Parties as part of a global effort, including for the formulation and implementation of national adaptation plans;

12. *Recognizes* the importance of the adequacy and predictability of adaptation finance, including the value of the Adaptation Fund in delivering dedicated support for adaptation;

13. *Welcomes* the recent pledges made by many developed country Parties to increase their provision of climate finance to support adaptation in developing country Parties in

[1] Intergovernmental Panel on Climate Change. 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. V Masson-Delmotte, P Zhai, A Pirani, et al. (eds.). Cambridge: Cambridge University Press. Available at https://www.ipcc.ch/report/ar6/wg1/.

response to their growing needs, including contributions made to the Adaptation Fund and the Least Developed Countries Fund, which represent significant progress compared with previous efforts;

14. *Calls upon* multilateral development banks, other financial institutions and the private sector to enhance finance mobilization in order to deliver the scale of resources needed to achieve climate plans, particularly for adaptation, and *encourages* Parties to continue to explore innovative approaches and instruments for mobilizing finance for adaptation from private sources;

IV. Mitigation

15. *Reaffirms* the long-term global goal to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

16. *Recognizes* that the impacts of climate change will be much lower at the temperature increase of 1.5 °C compared with 2 °C, and *resolves* to pursue efforts to limit the temperature increase to 1.5 °C;

17. *Also recognizes* that limiting global warming to 1.5 °C requires rapid, deep and sustained reductions in global greenhouse gas emissions, including reducing global carbon dioxide emissions by 45 per cent by 2030 relative to the 2010 level and to net zero around mid-century, as well as deep reductions in other greenhouse gases;

18. *Further recognizes* that this requires accelerated action in this critical decade, on the basis of the best available scientific knowledge and equity, reflecting common but differentiated responsibilities and respective capabilities and in the context of sustainable development and efforts to eradicate poverty;

19. *Invites* Parties to consider further actions to reduce by 2030 non-carbon dioxide greenhouse gas emissions, including methane;

20. *Calls upon* Parties to accelerate the development, deployment and dissemination of technologies, and the adoption of policies, to transition towards low-emission energy systems, including by rapidly scaling up the deployment of clean power generation and energy efficiency measures, including accelerating efforts towards the phasedown of unabated coal power and phase-out of inefficient fossil fuel subsidies, while providing targeted support to the poorest and most vulnerable in line with national circumstances and recognizing the need for support towards a just transition;

21. *Emphasizes* the importance of protecting, conserving and restoring nature and ecosystems, including forests and other terrestrial and marine ecosystems, to achieve the long-term global goal of the Convention by acting as sinks and reservoirs of greenhouse gases and protecting biodiversity, while ensuring social and environmental safeguards;

V. Finance, technology transfer and capacity-building for mitigation and adaptation

22. *Urges* developed country Parties to provide enhanced support, including through financial resources, technology transfer and capacity-building, to assist developing country Parties with respect to both mitigation and adaptation, in continuation of their existing obligations under the Convention, and *encourages* other Parties to provide or continue to provide such support voluntarily;

23. *Notes with concern* the growing needs of developing country Parties, in particular due to the increasing impacts of climate change and increased indebtedness as a consequence of the coronavirus disease 2019 pandemic;

24. *Welcomes* the first report on the determination of the needs of developing country Parties related to implementing the Convention and the Paris Agreement[2] and the fourth Biennial Assessment and Overview of Climate Finance Flows[3] by the Standing Committee on Finance;

25. *Emphasizes* the need to mobilize climate finance from all sources to reach the level needed to achieve the goals of the Paris Agreement, including significantly increasing support for developing country Parties, beyond USD 100 billion per year;

26. *Notes with deep regret* that the goal of developed country Parties to mobilize jointly USD 100 billion per year by 2020 in the context of meaningful mitigation actions and transparency on implementation has not yet been met, and *welcomes* the increased pledges made by many developed country Parties and the *Climate Finance Delivery Plan: Meeting the US$100 Billion Goal*[4] and the collective actions contained therein;

27. *Urges* developed country Parties to fully deliver on the USD 100 billion goal urgently and through to 2025, and *emphasizes* the importance of transparency in the implementation of their pledges;

28. *Urges* the operating entities of the Financial Mechanism, multilateral development banks and other financial institutions to further scale up investments in climate action, and *calls for* a continued increase in the scale and effectiveness of climate finance from all sources globally, including grants and other highly concessional forms of finance;

29. *Re-emphasizes* the need for scaled-up financial resources to take into account the needs of those countries particularly vulnerable to the adverse effects of climate change, and in this regard *encourages* relevant multilateral institutions to consider how climate vulnerabilities should be reflected in the provision and mobilization of concessional financial resources and other forms of support, including special drawing rights;

30. *Emphasizes* the challenges faced by many developing country Parties in accessing finance and *encourages* further efforts to enhance access to finance, including by the operating entities of the Financial Mechanism;

31. *Notes* the specific concerns raised with regard to eligibility and ability to access concessional forms of climate finance, and *re-emphasizes* the importance of the provision of scaled-up financial resources, taking into account the needs of developing country Parties that are particularly vulnerable to the adverse effects of climate change;

32. *Encourages* relevant providers of financial support to consider how vulnerability to the adverse effects of climate change could be reflected in the provision and mobilization of concessional financial resources and how they could simplify and enhance access to finance;

33. *Acknowledges* the progress made on capacity-building, particularly in relation to enhancing the coherence and coordination of capacity-building activities towards the implementation of the Convention and the Paris Agreement;

34. *Recognizes* the need to continue supporting developing country Parties in identifying and addressing both current and emerging capacity-building gaps and needs, and to catalyse climate action and solutions to respond;

[2] See document FCCC/CP/2021/10/Add.2–FCCC/PA/CMA/2021/7/Add.2.
[3] See document FCCC/CP/2021/10/Add.1–FCCC/PA/CMA/2021/7/Add.1.
[4] Available at https://ukcop26.org/wp-content/uploads/2021/10/Climate-Finance-Delivery-Plan-1.pdf.

35. *Welcomes* the joint annual reports of the Technology Executive Committee and the Climate Technology Centre and Network for 2020 and 2021[5] and *invites* the two bodies to strengthen their collaboration;

36. *Emphasizes* the importance of strengthening cooperative action on technology development and transfer for the implementation of mitigation and adaptation action, including accelerating, encouraging and enabling innovation, and the importance of predictable, sustainable and adequate funding from diverse sources for the Technology Mechanism;

VI. Loss and damage

37. *Acknowledges* that climate change has already caused and will increasingly cause loss and damage and that, as temperatures rise, impacts from climate and weather extremes, as well as slow onset events, will pose an ever-greater social, economic and environmental threat;

38. *Also acknowledges* the important role of a broad range of stakeholders at the local, national and regional level, including indigenous peoples and local communities, in averting, minimizing and addressing loss and damage associated with the adverse effects of climate change;

39. *Reiterates* the urgency of scaling up action and support, as appropriate, including finance, technology transfer and capacity-building, for implementing approaches to averting, minimizing and addressing loss and damage associated with the adverse effects of climate change in developing country Parties that are particularly vulnerable to these effects;

40. *Urges* developed country Parties, the operating entities of the Financial Mechanism, United Nations entities and intergovernmental organizations and other bilateral and multilateral institutions, including non-governmental organizations and private sources, to provide enhanced and additional support for activities addressing loss and damage associated with the adverse effects of climate change;

41. *Recognizes* the importance of demand-driven technical assistance in building capacity to implement approaches to averting, minimizing and addressing loss and damage associated with the adverse effects of climate change;

42. *Welcomes* the further operationalization of the Santiago network for averting, minimizing and addressing loss and damage associated with the adverse effects of climate change, including the agreement on its functions and process for further developing its institutional arrangements;

43. *Endorses* paragraphs 67–70 and 73–74 of decision -/CMA.3;[6, 7]

44. *Acknowledges* the importance of coherent action to respond to the scale of needs caused by the adverse impacts of climate change;

45. *Resolves* to strengthen partnerships between developing and developed countries, funds, technical agencies, civil society and communities to enhance understanding of how approaches to averting, minimizing and addressing loss and damage can be improved;

[5] FCCC/SB/2020/4 and FCCC/SB/2021/5.

[6] Draft decision entitled “Glasgow Climate Pact” proposed under agenda item 2(c) of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement at its third session.

[7] It is noted that discussions related to the governance of the Warsaw International Mechanism on Loss and Damage associated with Climate Change Impacts did not produce an outcome: this is without prejudice to further consideration of this matter.

VII. Implementation

46. *Recalls* that the round tables among Parties and non-Party stakeholders on pre-2020 implementation and ambition held in 2018, 2019 and 2020 helped to highlight and enhance understanding of the efforts of and challenges faced by Parties in relation to action and support in the pre-2020 period, as well as of the work of the constituted bodies in that period;

47. *Strongly urges* all Parties that have not yet done so to meet any outstanding pledges under the Convention as soon as possible;

48. *Welcomes* the action taken to unlock the potential for sectoral action to contribute to fulfilling and implementing national targets, particularly in emission-intensive sectors;

49. *Recognizes* the need to take into consideration the concerns of Parties with economies most affected by the impacts of response measures, particularly developing country Parties, in line with Article 4, paragraphs 8 and 10, of the Convention;

50. *Also recognizes* the importance of protecting, conserving and restoring ecosystems to deliver crucial services, including acting as sinks and reservoirs of greenhouse gases, reducing vulnerability to climate change impacts and supporting sustainable livelihoods, including for indigenous peoples and local communities;

51. *Encourages* Parties to take an integrated approach to addressing the issues referred to in paragraph 50 above in national and local policy and planning decisions;

52. *Recognizes* the need to ensure just transitions that promote sustainable development and eradication of poverty, and the creation of decent work and quality jobs, including through making financial flows consistent with a pathway towards low greenhouse gas emission and climate-resilient development, including through deployment and transfer of technology, and provision of support to developing country Parties;

VIII. Collaboration

53. *Recognizes* the importance of international collaboration on innovative climate action, including technological advancement, across all actors of society, sectors and regions, in contributing to progress towards the objective of the Convention and the goals of the Paris Agreement;

54. *Recalls* Article 3, paragraph 5, of the Convention and the importance of cooperation to address climate change and support sustainable economic growth and development;

55. *Recognizes* the important role of non-Party stakeholders, including civil society, indigenous peoples, local communities, youth, children, local and regional governments and other stakeholders, in contributing to progress towards the objective of the Convention and the goals of the Paris Agreement;

56. *Welcomes* the improvement of the Marrakech Partnership for Global Climate Action[8] for enhancing ambition, the leadership and actions of the high-level champions, and the work of the secretariat on the Non-state Actor Zone for Climate Action platform to support accountability and track progress of voluntary initiatives;

57. *Also welcomes* the high-level communiqué[9] on the regional climate weeks and *encourages* the continuation of regional climate weeks where Parties and non-Party

[8] Available at https://unfccc.int/sites/default/files/resource/Improved%20Marrakech%20Partnership%202021-2025.pdf.

[9] Available at https://unfccc.int/regional-climate-weeks/rcw-2021-cop26-communique.

stakeholders can strengthen their credible and durable response to climate change at the regional level;

58. *Further welcomes* the informal summary reports by the Chair of the Subsidiary Body for Scientific and Technological Advice on the ocean and climate change dialogue to consider how to strengthen adaptation and mitigation action and on the dialogue on the relationship between land and climate change adaptation related matters;

59. *Invites* Parties to submit views on how to enhance climate action on land under the existing UNFCCC programmes and activities in paragraph 75 of the report on the dialogue on the relationship between land and climate change adaptation related matters referred to in paragraph 58 above, and *requests* the Chair of the Subsidiary Body for Scientific and Technological Advice to prepare an informal summary report thereon and make it available to the Conference of the Parties at its twenty-seventh session;

60. *Invites* the relevant work programmes and constituted bodies under the UNFCCC to consider how to integrate and strengthen ocean-based action in their existing mandates and workplans and to report on these activities within the existing reporting processes, as appropriate;

61. *Also invites* the Chair of the Subsidiary Body for Scientific and Technological Advice to hold an annual dialogue, starting at the fifty-sixth session of the Subsidiary Body for Scientific and Technological Advice (June 2022), to strengthen ocean-based action and to prepare an informal summary report thereon and make it available to the Conference of the Parties at its subsequent session;

62. *Urges* Parties to swiftly begin implementing the Glasgow work programme on Action for Climate Empowerment, respecting, promoting and considering their respective obligations on human rights, as well as gender equality and empowerment of women;

63. *Expresses appreciation* for the outcomes of the sixteenth Conference of Youth, organized by the constituency of children and youth non-governmental organizations and held in Glasgow in October 2021, and the "Youth4Climate2021: Driving Ambition" event hosted by Italy in Milan, Italy, in September 2021;

64. *Urges* Parties and stakeholders to ensure meaningful youth participation and representation in multilateral, national and local decision-making processes, including under the Convention and the Paris Agreement;

65. *Invites* future Presidencies of the Conference of the Parties, with the support of the secretariat, to facilitate the organization of an annual youth-led climate forum for dialogue between Parties and youth in collaboration with the UNFCCC children and youth constituency and other youth organizations with a view to contributing to the implementation of the Glasgow work programme on Action for Climate Empowerment;

66. *Emphasizes* the important role of indigenous peoples' and local communities' culture and knowledge in effective action on climate change, and *urges* Parties to actively involve indigenous peoples and local communities in designing and implementing climate action and to engage with the second three-year workplan for implementing the functions of the Local Communities and Indigenous Peoples Platform, for 2022–2024;

67. *Expresses its recognition* for the important role the observer organizations play, including the nine non-governmental organization constituencies, in sharing their knowledge, and their calls to see ambitious action to meet the objectives of the Convention and collaborating with Parties to that end;

68. *Encourages* Parties to increase the full, meaningful and equal participation of women in climate action and to ensure gender-responsive implementation and means of implementation, which are vital for raising ambition and achieving climate goals;

69. *Calls upon* Parties to strengthen their implementation of the enhanced Lima work programme on gender and its gender action plan;[10]

70. *Takes note* of the estimated budgetary implications of the activities to be undertaken by the secretariat referred to in this decision;

71. *Requests* that the actions of the secretariat called for in this decision be undertaken subject to the availability of financial resources.

[10] Decision 3/CP.25.

Jonathan Boston

Living Within Biophysical Limits

green growth versus degrowth

Abstract

Since the early 1970s there has been vigorous debate over whether global economic growth can continue more or less indefinitely on a finite planet. Central to the most recent version of this debate are the claims and counterclaims of those advocating 'green growth' and those advocating 'degrowth'. This article outlines and briefly assesses the main areas of agreement and disagreement between these contending schools of thought. It is argued that humanity must live within real, non-negotiable biophysical constraints. Failure to make the required transformation of the global economy soon will ultimately undermine social progress. But what level and form of global economic activity is ultimately compatible with ecological sustainability remains uncertain.

Keyword green growth, degrowth, decoupling, decarbonisation, environmental sustainability

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Vigorous debate continues over the feasibility and desirability of unending global economic growth, even at modest annual rates (e.g., 2–3%). At stake is whether economic growth, as measured by an increase in gross domestic product (GDP), is compatible with – and perhaps even necessary for – environmental sustainability and intergenerational wellbeing. In short, is global GDP growth (and higher per capita incomes) counterproductive and thus 'uneconomic', in the sense that the overall long-term costs will outweigh, and perhaps even dwarf, the overall long-term benefits? Further, even if global GDP growth is technically possible for much of the 21st century, is it feasible indefinitely, and what bearing should this have on current policymaking? Can there be an unlimited global economy on a finite Earth? Can humanity continue to increase the value of the goods and services it produces independent of resource throughput and damaging environmental impacts?

Central to the current debate are the contrasting assumptions, assertions and policy prescriptions of the advocates, respectively, of 'green growth' and 'degrowth'. Those championing 'green growth' (also referred to as 'sustainable economic growth' and 'ecomodernism') include major international organisations, such as the International Energy Agency (2009, 2021), the OECD (2011), the United Nations

Environment Programme (UNEP, 2011a, 2011b, 2017) and the World Bank (2012), along with numerous leading economists and policy experts.[1] Many green-oriented policy packages have been advanced over the past decade or so, such as the 'global green new deal', the 'European green new deal' and the US version. Significantly, however, not all proponents of the 'green economy' support continued, let alone indefinite, GDP growth.

For their part, the advocates of 'degrowth' (sometimes referred to as 'anti-growth' or 'post-growth') comprise researchers from multiple disciplines within the social and biophysical sciences, including many ecological economists.[2] While the global debate continues to evolve and new evidence is constantly emerging, the main fault lines are now well established.

This article identifies and briefly assesses the key claims and counterclaims at the heart of this debate. It proceeds as follows. First, it clarifies the meaning of several important terms and concepts. Second, it places the current debate in the context of earlier debates about the relationship between economic growth and environmental limits. Third, it summarises the main areas of agreement and disagreement between the contending schools of thought. Finally, it offers a brief assessment.

Several caveats

Several caveats deserve mention. First, doing justice to the scope and significance of the topic is impossible in a short article. The relevant academic literature on green growth and degrowth and their many variants is already vast and continues to expand rapidly. Moreover, it traverses an extraordinary range of issues – philosophical, ethical, political, technological, biophysical, behavioural, social, cultural and economic. Some of these issues are highly technical and inherently complex. There is also much disputed empirical evidence and numerous uncertainties. Accordingly, this brief analysis is limited to the main contours of the debate. It does not address, therefore, the wider societal and ethical issues raised by the green growth/degrowth debate, such as those relating to global governance, population limits, aid and development and intergenerational justice.

Second, several related schools of thought are ignored here. One of these is 'ungreen growth' or 'brown growth'; another is 'a-growth'. The former approach either rejects the need for the global economy to operate within biophysical limits or denies that such limits exist. Neither position is scientifically plausible. The latter approach involves being agnostic or neutral about GDP growth (see van den Bergh, 2009, 2011, 2017; van den Bergh and Kallis, 2012) and/or prioritising other policy goals (e.g., wellbeing, social welfare, etc.) (see, for instance, Jacob and Edenhofer, 2014). Such perspectives merit serious consideration. But while there are good reasons to deprioritise GDP as a performance measure, the suggestion that GDP growth is largely irrelevant or inconsequential from a policy perspective is less convincing. Politically, too, the proposition that governments should simply be indifferent to economic growth, and hence to changes in per capita incomes, is likely to be difficult to justify, not least in low-income countries.

> '… decoupling 'is reducing the amount of resources such as water or fossil fuels used to produce economic growth and delinking economic development from environmental deterioration'

Third, the relative merits of green growth and degrowth can be investigated at multiple scales (e.g., global, regional, national, sub-national) and over radically different time horizons (e.g., decades and centuries). Given the current serious ecological issues facing humanity at a planetary level – not least anthropogenic climate change, large-scale biodiversity loss, extensive pollution and rapid depletion of many non-renewable resources – the crucial analytical issues are global rather than local. In short, the fundamental question is whether continued (even modest) annual *global* GDP growth (both in aggregate and per capita) is a feasible and desirable policy objective over an extended time frame (e.g., the next 50–100 years) rather than, say, the next decade or two. Answering this question necessarily requires a global focus. Equally, the relevant timespan must be multi-decadal, not short term. What might be possible within individual countries (e.g., see Hatfield-Dodds et al., 2015) or over much shorter time horizons are separate issues and are not explored here.

Fourth, this analysis accepts the seriousness of the current global ecological challenges and hence the need for urgent and effective policy responses at the national and sub-national levels (e.g., see IPBES, 2019; IPCC, 2018, 2021; OECD, 2021). There is no suggestion, therefore, that the decisions of national policymakers, and especially those in the major economies (e.g., the US, China and the EU), are irrelevant to the green growth/degrowth debate. But it is beyond the scope of this analysis to consider national-level policy options, strategies and pathways, whether for major economies or much smaller ones such as Aotearoa New Zealand. That said, no country has fully embraced, let alone achieved, a genuinely sustainable pathway ecologically.

Defining key terms

Economic growth and gross domestic product (GDP)

Economic growth is typically measured by changes in GDP over a specified period (e.g., quarterly or annually). GDP is a monetary measure or indicator of economic value; it is not a measure of physical properties, such as natural resources or energy flows. It is generally defined as the market value of all the final goods and services produced in a country over a particular time frame. It can be expressed in various ways (e.g., as an aggregate or per capita measure), and changes can be measured in either real or nominal terms. Global GDP is simply the aggregate of the GDP of every nation (currently close to 200). In 2021 global GDP was approximately US$95 trillion. Significantly, the composition of GDP can, and does, change over time and it varies greatly between countries. For the purposes of this article, economic growth and GDP growth will be used interchangeably.

Green growth

The concept of green growth has various strands and definitions. In broad terms, it involves a commitment to continued GDP

growth, both globally and nationally, on the grounds that growth, at least of certain kinds, is beneficial in net terms – socially, politically and environmentally. The crucial caveat, however, is that future growth must be consistent with clearly identified biophysical limits at multiple scales (e.g., global, national and local). Accordingly, advocates of green growth support a raft of fiscal and regulatory policies to enhance the efficient use of resources (both renewable and non-renewable) and minimise waste (i.e., embrace a more circular economy), improve societal resilience, and minimise environmental pressures. To quote from a major OECD report, *Towards Green Growth*:

> A green growth strategy is centred on mutually reinforcing aspects of economic and environmental policy. It takes into account the full value of natural capital as a factor of production and its role in growth. It focuses on cost-effective ways of attenuating environmental pressures to effect a transition towards new patterns of growth that will avoid crossing critical local, regional and global environmental thresholds … It is about fostering economic growth and development while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies. (OECD, 2011, pp.10, 18)

Degrowth

As with 'green growth', the concept of 'degrowth' comprises multiple strands and definitions (see Hagens, 2020; Hickel and Kallis, 2020; Hickel and Hallegatte, 2021; IPCC, 2022; Ward et al., 2016). Indeed, those associated with the degrowth camp differ markedly in their philosophical, ideological and policy preferences. Hence, some degrowth proponents (for example, Jason Hickel and Juila Steinberger) have more affinity with green growth advocates, at least on certain matters, than with their more radical associates (e.g., see Seibert and Rees, 2021).

Be that as it may, degrowth advocates are united in rejecting economic growth as a legitimate policy goal and oppose using GDP as an indicator of societal progress or prosperity. Instead, much broader policy goals and progress indicators are favoured (Jackson, 2009 ; see also Stiglitz et al., 2009). Nonetheless, many advocates endorse (at least temporary) additional GDP growth per capita in low-income countries, if not also in emerging economies, to reduce poverty and enhance

> … there has been mounting evidence that humanity is harming vital biophysical systems, living beyond Earth's means … and exceeding 'safe' planetary boundaries …

human wellbeing. By contrast, continuing GDP growth in high-income (OECD) countries is rejected. There is no consensus, however, over whether average per capita incomes in high-income countries needs to fall, and, if so, by how much, over what specific time frame and by what means.

Second, degrowth advocates favour slowing and then reversing global resource consumption, commodity production and energy usage until they reach genuinely sustainable levels. This entails support for a raft of regenerative policies to reduce the aggregate use of natural resources (e.g., via comprehensive recycling, reusing, refurbishing, remaking, sharing, etc.), lower the physical throughput of the global economy, decrease overall energy consumption, and decarbonise global energy systems rapidly (i.e., within about three decades) to achieve net zero carbon dioxide (CO_2) emissions and large reductions in other greenhouse gas emissions.

Third, degrowth proponents generally favour stabilising the global population and ensuring a more egalitarian distribution of income and wealth, both globally (i.e., from North to South) and within individual nations. Some degrowth proponents believe a significant fall in the global population is essential.

Finally, degrowth proponents often emphasise that a failure to mitigate urgently the current global ecological challenges will inevitably slow, if not reverse, GDP growth, due to ever more disruptive and damaging impacts (e.g., more severe storms and droughts, sea level rise, massive crop failures, etc.) precipitating mass migration, increased conflict, economic shocks, financial instability and ineffective governance. In short, beyond a certain point, temperature increases will render further global growth impossible. This argument, while plausible, is not discussed here.

Decoupling

The concept of decoupling is pivotal to the debate between the advocates of green growth and degrowth (see Jackson, 2009; Hickel and Hallegatte, 2021; UNEP, 2011a; Ward et al., 2016). Put simply, decoupling 'is reducing the amount of resources such as water or fossil fuels used to produce economic growth and delinking economic development from environmental deterioration' (UNEP, 2011a, p.xi). Resources, in this context, embrace both renewable and non-renewable resources. The former include biotic resources, such as forests, animals and fish, along with renewable energy sources, such as solar, wind and geothermal.[3] Non-renewable resources include construction minerals, ores and industrial minerals, and fossil fuels.

Decoupling has various forms. First, there is a distinction between *resource* decoupling and *impact* decoupling. The former refers to delinking GDP from resource use, whether in aggregate or for specific material and energy resources (e.g., overall energy decoupling, fossil fuel decoupling, etc.); the latter refers to delinking GDP from environmental impacts (e.g., greenhouse gas emissions, ocean acidification, biodiversity loss, including the loss of insect pollinators, soil degradation and loss, air and water pollution, and ever-increasing waste), thereby reducing impacts per unit of output. Overall, the evidence points to a close correlation between aggregate resource use and environmental impacts, but actual impacts vary depending on the specific resource in question and the technologies employed (van der Voet, van Oers and Nikolic, 2004; Hickel and Kallis, 2020; Steinmann et al., 2017).

Second, there is a distinction between *relative* (or weak) and *absolute* (or strong). Relative decoupling implies that the growth in resource use and/or environmental impacts is slower than GDP growth (e.g., because of improved resource efficiency or substitution). For absolute decoupling, the rate of relative decoupling must exceed the rate of increase in GDP (i.e., resource use and/or environmental impacts must decline while GDP rises). As discussed later, while

some relative decoupling has occurred globally (and within many countries) over recent decades, absolute decoupling (whether resource or impact) has been limited. In other words, per capita GDP growth globally, coupled with ongoing population growth, has generally exceeded improvements in overall resource efficiency and efforts to reduce environmental impacts.

The context for the current debate

Debates about the potential for humanity to overshoot critical biophysical limits at a planetary scale are not new. In 1798 Thomas Malthus published *An Essay on the Principle of Population*, in which he argued that the size of the human population would ultimately be limited by scarce resources, not least food supplies. To quote: 'The power of population is indefinitely greater than the power in the earth to produce subsistence for man' (1798, p.13). To date, Malthus has been wrong.

Almost two centuries after Malthus, Meadows et al. (1972) argued in *The Limits to Growth*, and in various subsequent publications (Meadows, Meadows and Randers, 1992, 2004), that long-term exponential GDP growth is impossible, given Earth's limited natural resources and constrained absorptive capacity. Indeed, the MIT team claimed that even under the most optimistic assumptions concerning the nature and pace of technological innovation, continuing economic and population growth globally would eventually lead to overshoot and collapse. Such claims proved to be highly controversial and were the subject of many sustained and detailed rebuttals (e.g., Cole et al., 1973). Such critiques – which covered a range of methodological, empirical and normative issues – led many policymakers globally to dismiss the core arguments in *The Limits to Growth* (and related publications) as seriously flawed and misguided.

In recent decades, however, concerns about humanity's severe and widespread ecological impacts have intensified. In short, there has been mounting evidence that humanity is harming vital biophysical systems, living beyond Earth's means (i.e., consuming or damaging beyond what nature can regenerate), and exceeding 'safe' planetary boundaries (Rockström et al., 2009a, 2009b; Steffen et al., 2015, 2018). According to a recent OECD report, for instance:

> While global GDP per capita increased by more than 60% between 1992 and 2014, natural capital stocks per capita declined by nearly 40%, undermining future economic growth and well-being. One million plant and animal species now face extinction. (OECD, 2021, p.6; see also Managi and Kumar, 2018)

Green growth advocates believe that the fiscal and regulatory reforms needed for environmental sustainability will be unacceptable politically if citizens in high-income countries ... are confronted with a stark choice between ... environmental responsibility and ... continued improvements in living standards ...

Similar concerns have been raised by many other international organisations, along with scientific academies, governmental agencies and leading researchers.[4] There have also been various studies updating, and generally supporting, many of the assumptions and projections of Meadows et al. (e.g., Randers, 2008; Turner, 2008, 2019).

Broad areas of agreement

While the advocates of green growth and degrowth disagree about many things, there are also important areas of agreement (see, for instance, Hickel and Hallegatte, 2021; Hickel and Kallis, 2020; van den Bergh, 2017). These can be summarised as follows.

First, humanity faces many systemic complexities and multiple uncertainties – technological, ecological, social and political – with the potential for significant non-linear changes. Accordingly, the future cannot be fully known, the past may not provide a reliable guide to the future, and many surprises are likely, some positive, others negative. All this points to the need for a flexible and precautionary approach.

Second, there is a general acceptance that Earth, as a finite planet, exhibits various real, non-negotiable biophysical constraints. These include basic physical constraints. For instance, human settlements and related structures cannot get bigger indefinitely and non-renewable resources, if exploited continuously and not fully recycled or repurposed, will eventually be exhausted. Likewise, the (safe) absorptive capacities of Earth's biosphere are limited (e.g., the capacity to absorb greenhouse gas emissions and material waste), as are its regenerative capacities. These constraints must be respected if a modern industrial civilisation is to survive, let alone prosper. Against this, there is less agreement about where 'safe' boundaries should be drawn, what limits have already been exceeded, and the severity of the current biophysical risks. That said, few doubt the difficulties of forging a global path that is compatible with the full range of planetary and sub-planetary limits (Boston, 2011).

Third, there is broad agreement that the current global patterns of production and consumption are unsustainable ecologically. Moreover, supporting up to 10 billion people with an average per capita income of US citizens, and comparable per capita resource and energy use, is not feasible. Hence, significant changes are needed to investment flows, modes of production, transport and stationary energy systems, land management, and the use of material resources, both renewable and non-renewable. In particular, the global economy must be decarbonised (or 'defossilised') rapidly and a circular economy instigated, with minimal waste. These changes, it is generally accepted, will be impossible without globally coordinated, widely adopted and highly effective policy reforms and related behavioural changes. Current reform agendas fall far short.

Fourth, there is no dispute that significant and sustained absolute decoupling of resource

Table 1: Green growth versus degrowth: key issues, assumptions and claims

Issue	Green growth	Degrowth
Biophysical limits, including the absorptive and regenerative capacity of the biosphere	There are real, non-negotiable biophysical limits at multiple scales which is why global GDP growth must be 'green' if it is to continue indefinitely	There are real, non-negotiable biophysical limits at multiple scales which is why global GDP growth must discontinue, and sooner rather than later, in the interests of ecological sustainability and human wellbeing
Current ecological crises	There are multiple ecological crises; current global production and consumption patterns are not ecologically sustainable; significant policy changes are essential	There are multiple ecological crises; current global production and consumption patterns are not ecologically sustainable; radical policy changes are essential
Global population	The human population can be expected to stabilize at an ecologically sustainable level	Additional efforts are needed to stabilize the human population; some degrowth advocates favour a substantial fall in the human population by 2100
GDP per capita as a measure of economic progress	GDP per capita is a useful but inadequate measure; more comprehensive measures of progress and societal wellbeing are desirable	GDP per capita is neither a reliable measure of human wellbeing nor a proper focus for public policy; more comprehensive measures of progress and societal wellbeing are desirable
The desirability of further global GDP growth	Overall, GDP growth is welfare enhancing; prudent green growth strategies will accelerate the required technological transitions and generate higher long-term growth rates	Further GDP growth per capita is justified in low-income countries, but not in high-income countries. Continuing global GDP growth will make the required technological transitions harder by increasing aggregate demand for energy and natural resource, exacerbating harmful environmental impacts, and increasing the reliance on speculative negative emissions technologies
Constraints on global GDP growth	Assuming ecologically sound policies are adopted globally, the only long-term constraints on global GDP growth will be human creativity, technological innovation, and good governance; continued GDP growth can be expected in a fully circular, zero-carbon global economy	Fundamental biophysical constraints of various kinds will ultimately limit the capacity for further efficiency gains and resource substitution, thereby limiting further global GDP growth
Absolute decoupling	While the historical record provides no evidence of sustained absolute decoupling globally, the future can be different from the past. Rapid technological transitions are possible	The historical record provides no evidence to support the contention that long-term absolute decoupling is likely. Relative decoupling, however, has been occurring
Absolute resource decoupling	Absolute resource decoupling is technically feasible, but suitable policies will be needed to catalyse the required technological transitions	Absolute resource decoupling on the speed and scale required appears unlikely based on recent evidence. There are multiple behavioural, structural, institutional, and political barriers to rapid and sustained resource decoupling
Absolute impact decoupling	Absolute decoupling of global GDP growth and global GHG emissions is not only technically feasible, but with suitable policies can also be achieved at a rate sufficient to meet agreed global climate change targets and other important ecological goals	Absolute decoupling of global GDP growth and global GHG emissions appears unlikely based on recent evidence; rapid and sustained reductions in global GHG emissions to meet ambitious targets (e.g. a warming cap of 1.5°C) will require a significant decline in global GDP
Renewable energy technologies	Renewable energy technologies can power a modern industrial civilization	Some, but not all, degrowth proponents doubt whether renewable energy technologies can power a modern industrial civilization
Negative emissions pathways	Negative emissions pathways are technically viable and will become increasingly feasible economically	Both the technical and economic viability of negative emissions technologies are doubtful; some are highly speculative; it is too risky to rely on such technologies to achieve global GHG mitigation goals
Governance capacity and policy reform	Enough governments globally will design and implement sufficient 'green' policy reforms to enable sustained global GDP growth during the 21st century	The evidence to date raises serious doubts about the capacity and willingness of governments, whether democratic or otherwise, to implement the policy reforms needed for ecological sustainability
The damaging economic impacts of ecological problems	The negative impacts of climate change and other ecological problems have the potential to impede long-term global GDP growth which is why a green growth strategy is essential	The negative impacts of climate change and other ecological problems are likely to cause large-scale economic losses, damage critical infrastructure, and undermine existing social and political institutions

consumption and environmental impacts from global GDP growth is ecologically essential. Net zero greenhouse gas emissions globally, for instance, requires full decoupling, regardless of the level of economic activity. Plainly, this represents a demanding constraint. How best to respond remains hotly contested. Against this, there is no dispute that the pace of resource and impact decoupling can be changed and will, among other things, be influenced by the nature, scale and uptake of technological advances. That said, whether GDP growth can be rendered completely independent of environmental degradation remains uncertain.

Fifth, there is general agreement that the quest for ecological sustainability must not ignore other important goals (as reflected, for instance, in the Sustainable Development Goals), and especially the needs of the world's poorest citizens. This includes several billion people who currently lack access to electricity and proper sanitation, and nearly one billion people who experience regular or periodic hunger. It is recognised that ensuring an acceptable standard of living and universal access to basic services globally (e.g., education, health care, fresh water and energy) will require massive investment over a generation or more and almost certainly much higher GDP per capita in all low-income countries; achieving such outcomes will be challenging (see Millward-Hopkins et al., 2020). While degrowth advocates tend to be egalitarians and strongly support a just transition to a zero-emissions, circular and more inclusive economy, green growth advocates have widely divergent distributional preferences.

Finally, there is a partial consensus on the demand-side and supply-side policies required for greater sustainability. These include: better environmental governance, with improved goal setting, monitoring and reporting (see Petrie, 2021); 'green budgeting' (e.g., taxing/pricing environmental externalities such as greenhouse gas emissions, removing subsidies for the wasteful use of land, energy and natural resources, and robust resource rentals); a range of industry- and sector-specific measures; comprehensive regulatory measures to limit environmental harms, protect biodiversity and enhance the efficient use of resources (e.g., strict efficiency standards for all buildings and appliances, requirements for firms to recycle their products along their entire lifetimes, standardised requirements to lower the transaction costs of technology and network integration, etc.); and higher investment in environmentally relevant research and development. Many degrowth proponents go much further, arguing for comprehensive national planning, massive public investment (with long-term horizons) and vigorous 'technology-forcing' regulation, if not the fundamental rethinking of modern capitalist institutions and market-oriented policies (e.g., monetary and fiscal policies, the nature and role of property rights, the operation of major financial institutions, etc.).

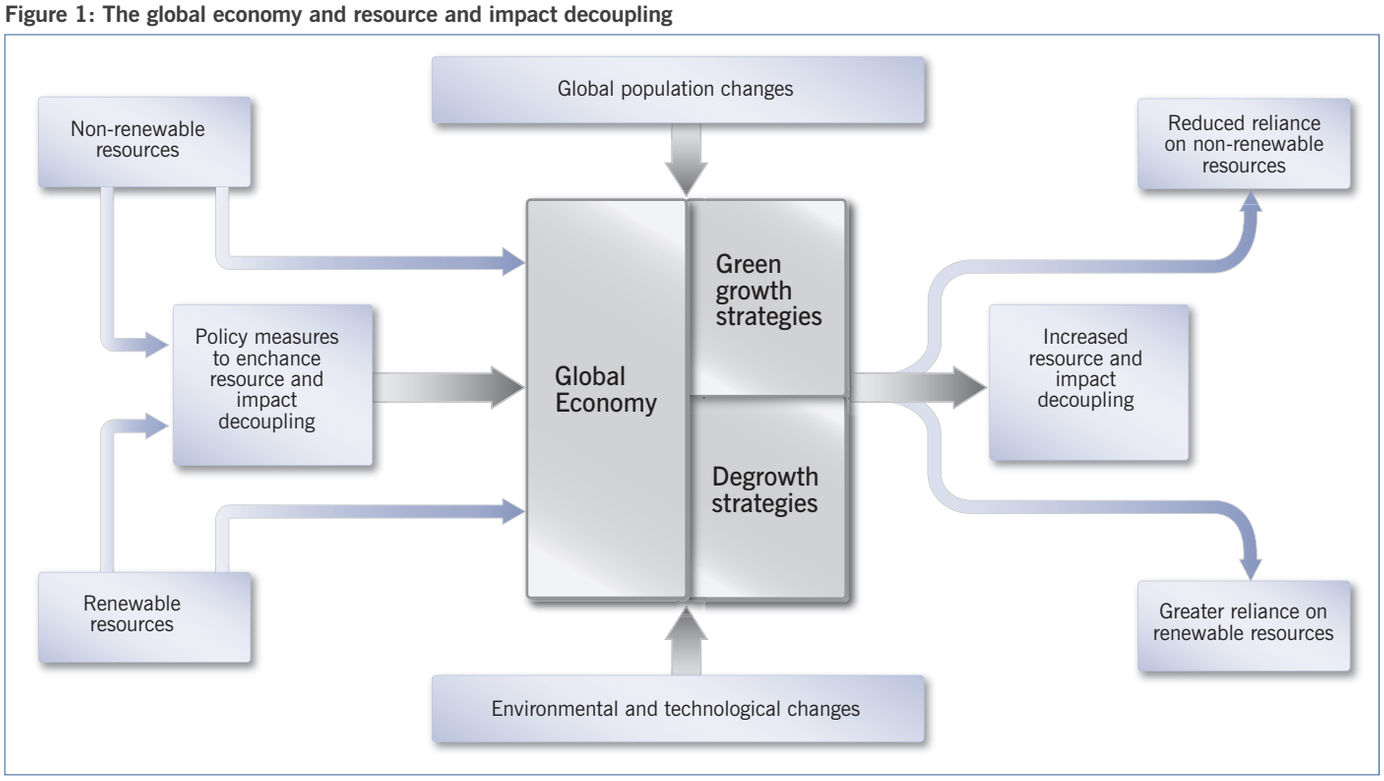
Key areas of disagreement

Turning now to the empirical and normative issues at the centre of the green growth–degrowth debate, these are summarised briefly below (see also Table 1), followed by a more detailed discussion of absolute decoupling.

The overall long-term desirability of GDP growth

While both schools of thought acknowledge the limitations of GDP as an indicator of societal progress and reject *unconditional* GDP growth, green growth advocates believe that GDP growth, at least of a particular kind, not only enhances overall human wellbeing and reduces poverty, but also facilitates improved environmental outcomes and more rapid technological and structural transitions. Indeed, if properly regulated, growth will both drive the required ecological transformation and trigger new sources of growth. By contrast, it is argued that a degrowth strategy – to the extent that a long-term contraction of GDP can be engineered, whether across the OECD or globally, perhaps by comprehensive planning and/or quantitative caps on resource use – will increase unemployment and inequality, reduce resource efficiency, undermine public finances, diminish the capacity to invest in resilient, climate-aligned infrastructure, and provoke deep political tensions. Accordingly, deliberately contracting GDP is neither necessary nor sufficient for ecological sustainability; economic growth should thus

Figure 1: The global economy and resource and impact decoupling



remain a core policy goal, including in high-income countries.

As noted earlier, degrowth proponents disagree on all these points. In particular, they reject the proposition that GDP growth will help catalyse the required technological transitions, including a radical recomposition of global consumption patterns; on the contrary, it will make such transitions harder by increasing the aggregate demand for resources and energy.

The speed, scale and scope of the required technological innovations

Overall, green growth advocates believe that current and likely future technologies, if supported by suitable policies, can enable both absolute resource and absolute impact decoupling to occur at a speed, scale and scope necessary to achieve crucial ecological goals (e.g., global decarbonisation at a rate sufficient to avoid warming of more than 1.5°C or 2.0°C). For various reasons, many degrowth advocates doubt such assumptions. These include the limits to resource substitutability, the constraints imposed by the laws of thermodynamics on efficiency, the challenges of path dependence (e.g., due to the long lifetime of most physical infrastructure, including carbon-intensive energy systems), and related barriers to socio-technical transitions (see Geels and Schot, 2007; Geels et al., 2017; also Chapman, 2019).

The political feasibility of the respective strategies

Green growth advocates believe that the fiscal and regulatory reforms needed for environmental sustainability will be unacceptable politically if citizens in high-income countries (and subsequently elsewhere) are confronted with a stark choice between, on the one hand, environmental responsibility and, on the other, continued improvements in living standards (e.g., as reflected in higher per capita incomes, comprehensive social services, adequate pensions, etc.). Moreover, a degrowth strategy is considered politically implausible: proactively engineering a long-term contraction of GDP while simultaneously transforming economic structures and energy systems and redistributing income and wealth to low-income citizens would require policy measures well beyond those possible in a democracy, certainly in peacetime.

Degrowth advocates dispute such claims, arguing that a completely new 'social contract' is imperative and, ultimately, unavoidable.

> ... questions arise over proposals to rely heavily on bioenergy with carbon capture and storage ... to assist with the energy transition and subsequently to secure negative net emissions globally ...

Prevarication will only increase the overall economic and other sacrifices required. Equally, some doubt the political viability of critical aspects of the green growth approach (e.g., because of the power of vested interests).

Psychological dispositions

Standing back from all the particulars of the debate, the respective schools of thought diverge in their psychological dispositions, or mental models. First, imagination: degrowth advocates find it hard to imagine a world where GDP growth continues more or less indefinitely, while green growth advocates find it equally hard to conceive of a world without ongoing GDP growth (e.g., some kind of stable or steady-state economy). Second, optimism: relative to many of their degrowth counterparts, (most) green growth advocates tend to be technological optimists, with a high confidence in human ingenuity. Also, to the extent that both camps include optimists, their hopes lie in different futures for humanity. That said, some degrowth advocates are undoubtedly pessimistic, if not fatalistic, about humanity's prospects.

Absolute decoupling

At the core of the debate over absolute decoupling are several crucial questions, none of which are amenable to a simple answer. First, what rates of resource and impact decoupling are needed to achieve various desired ecological outcomes (e.g., the key goals of the Paris Agreement and other relevant international instruments)? Clearly, answers will depend, among other things, on exactly how such goals are specified, including the level of acceptable risk. Second, what assumptions can reasonably be made about the speed, scope and scale of resource and impact decoupling by, say, 2050? And are the optimistic claims of many green growth advocates about both the potential and likely rates of decoupling justified? Third, and related, would global GDP growth, other things being equal, facilitate a significantly higher sustained rate of both resource and impact decoupling than would otherwise be possible (e.g., by increasing relevant public and private investment, encouraging more rapid shifts in consumption patterns, and enabling faster technological and structural transitions)? Alternatively, will any additional efficiency gains associated with GDP growth be overwhelmed by the tendency for such growth to increase overall environmental impacts (via the rebound effect or Jevons paradox)?[5] This section offers some brief reflections on the issues surrounding resource and impact decoupling. Figure 1 provides a simplified representation of the process of resource and impact decoupling at the global level.

Absolute resource decoupling

Natural resource use globally reached an estimated 100 billion metric tons annually in 2020. This is claimed to be about double the maximum sustainable boundary level (Bringezu, 2015; Bringezu et al., 2017; Hoekstra and Wiedmann, 2014; Hickel and Kallis, 2020; Hickel and Hallegatte, 2021). If so, a massive reduction in aggregate resource use will be necessary during the 21st century, as well as large shifts in consumption patterns to reflect the relative scarcity of different resources. Achieving such changes, even with much lower (or zero) GDP growth, will require dramatic gains in resource efficiency (well above average historical rates), large-scale substitution, and a huge increase in resource recycling. Realistically, from a technical perspective, how rapidly could such changes be achieved? And could the required transformation occur within the very limited time frame available if the global economy continued to grow at a moderate pace?

Degrowth advocates are pessimistic. First, it is acknowledged that a relative decoupling

of global GDP from total world material and energy consumption has occurred since the mid-20th century, with an expanding gap between GDP and resource use. But the pace of dematerialisation of GDP growth slowed in recent decades (Hickel and Kallis, 2020). More importantly, there is no evidence yet, despite the large shift in consumption towards services and away from manufacturing, that the world economy has experienced sustained absolute resource decoupling (Ward et al., 2016). At best, such decoupling has been limited to specific countries (e.g., Germany) and certain resources (e.g., via efficiency gains and/or substitution). For the future to be radically different, a massive upswing in the pace and diffusion of technological change and related material efficiency improvements would be needed, one sufficient and sustainable in the long term to negate the Jevons paradox and counteract the impact of continuing global population growth (see Schandl et al., 2016). Degrowth advocates doubt whether such outcomes are realistic.

Second, and related, it is argued that permanent decoupling, both absolute and relative, is 'impossible for essential, non-substitutable resources because the efficiency gains are ultimately governed by physical limits' (Ward et al., 2016). Such resources include land, fresh water, soil and a stable climate: they lack obvious substitutes (excluding other planets), yet are essential to meet basic human needs. Moreover, physiological constraints govern the efficiency of water use by crops and there are photosynthetic limits to plant productivity. Many non-renewable resources are, of course, substitutable, but their substitutes may also be non-renewable and thus limited in supply.

Third, some degrowth advocates highlight both the technical (e.g., thermodynamic) and societal limits to a largely circular economy. Currently, aside from biomass, less than 10% of all materials processed globally are recycled. Further, many materials cannot readily be recycled or reused, high levels of path dependence will slow the pace of recycling where it is technically viable, many countries and sectors are unlikely to follow best practice in efficient resource use, and in-use stocks of materials (e.g., physical infrastructure and buildings) continue to grow, thus constraining the scope for circularity. Yet without high levels of circularity, certain non-renewable resources – even gravel and sand – will eventually run out.

In brief, green growth advocates generally respond to these concerns as follows. They accept that some essential resources are non-substitutable and that, thus far at least, population growth and increased affluence globally have nullified (most of) the resource efficiency gains from technological innovation, but they maintain that the future can be different. For one thing, the current technical limits to improved efficiency and substitution are far from being reached; for another, breakthrough technologies (e.g., nuclear fusion) could extend these limits radically. Hence, hitherto unprecedented gains in resource efficiency (e.g., several times higher annually than the historical average) are technically possible, thereby making rapid absolute resource decoupling a realistic option (Hatfield-Dodds et al., 2015; Schandl et al., 2016; see also the reply to both from Lenzen et al., 2016). It is accepted, however, that this would require major policy reforms globally, massive investments in research and development, and the swift uptake and diffusion of many current and new technologies.

> Given the existing ecological crises, both green growth and degrowth advocates readily accept the need for radical technological changes, including rapid de-carbonisation and greatly enhanced energy and resource efficiency.

Of course, much the same requirements would apply under a degrowth scenario. Degrowth by itself is thus no substitute. Yet, as noted earlier, securing sustained political support for transformative policy reforms may well be much harder if governments are simultaneously pursuing a long-term strategy of economic contraction (or even zero GDP growth), let alone seeking to implement fundamental changes to the core institutions of modern capitalist economies.

Absolute impact decoupling

Any limits to absolute or relative resource decoupling will necessarily constrain the scope for absolute impact decoupling, even with a concerted shift to lower-impact resources and different consumption patterns. Equally important, absolute impact decoupling (e.g., to meet global greenhouse gas mitigation goals) will depend heavily on whether: a) global energy and transport systems can be rapidly and fully decarbonised (e.g., by 2050 or soon after); and b) there is a significant reduction in the energy intensity (the amount of energy used per unit of output) of the global economy (e.g., via improved energy-service efficiency and conservation). Degrowth advocates accept the possibility of absolute decoupling of greenhouse gas emissions from global GDP growth, but doubt whether the required magnitude and speed of such decoupling is technically possible and/or likely in practice even if technically possible (e.g., because of political resistance and inappropriate policy settings) (Hickel and Kallis, 2020).

First, questions arise over proposals to rely heavily on bioenergy with carbon capture and storage (BECCS) to assist with the energy transition and subsequently to secure negative net emissions globally (that is, later in the century to address the likely overshooting of global warming limits) (Anderson and Peters, 2016; McLaren and Markusson, 2020). BECCS involves sequestering CO_2 from the atmosphere via large plantation forests, harvesting the trees, burning them for energy, and then capturing and storing the released CO_2. Yet any significant reliance on BECCS would require massive forest plantations covering extensive areas of land, with likely negative implications for global food production and biodiversity loss. Success would also depend on large-scale, permanent and secure storage of CO_2. The technical challenges to such a strategy are likely to be daunting, yet even more essential to overcome under a scenario involving continuing global economic growth.

Second, degrowth advocates argue that aggressive mitigation strategies to achieve net

zero CO_2 emissions by around 2050 without BECCS (or other negative emissions technologies) will face formidable hurdles. If global GDP grows at an average annual rate of about 3% over coming decades, it is estimated that to have a roughly two-thirds chance of avoiding warming of more than 1.5°C, the rate of decoupling annually must be at least 10% – or around 7% to meet a 2.0°C warming cap (Hickel and Kallis, 2020). Even greater decoupling rates will be needed in high-income countries if such countries are to make a fair contribution to the global mitigation effort (and/or reduce the risks of overshooting the warming caps). With zero or very low annual global growth, the required decoupling rates would be somewhat lower. Even so, the required rates would exceed anything hitherto achieved globally by a large margin. Might this be possible?

There are various studies using different models and assumptions (including varied growth assumptions) exploring this question (IPCC, 2018). In short, any potentially plausible scenario involving the rapid absolute decoupling of greenhouse gas emissions from GDP growth requires most, if not all, of the following elements:

- a massive expansion of renewable energy technologies (RETs), especially solar and wind, and related energy storage capacity, with total renewable energy capacity needing to double every five to eight years by 2050 (depending on trends in aggregate energy demand);
- the complete decarbonisation of the world's transport fleets (including around one billion cars and 400 million trucks and vans) and key industrial processes (e.g., the production of steel and cement);
- large-scale afforestation and soil regeneration;
- a significant reduction in the energy intensity of the global economy;
- substantial efficiency improvements in the use of non energy-related resources;
- significant changes in food production (e.g., away from livestock agriculture);
- minimising any rebound effects; and
- various behavioural, social, cultural and institutional changes to enable systemic reforms and accelerate the diffusion of new technologies (see, for instance, Grubler et al., 2018; IPCC, 2018).

Degrowth advocates doubt whether many of these outcomes are achievable, particularly under scenarios involving significant economic growth. Take, for instance, a rapid transition to a 100% reliance on RETs and the related uptake of electric vehicle technologies (EVTs). According to many degrowth advocates, not only will such transitions require substantial additional overall electricity-generating capacity (even more so with economic growth), but they will also require hitherto unprecedented levels of investment in new energy systems. It is claimed that the scale, complexity, and cost of the energy transition, including likely information asymmetries, supply chain problems, bottlenecks and path dependencies, has been seriously underestimated by green growth advocates. Replicating the remarkably efficient energy storage function of fossil fuels, whether via electro-chemical batteries, pumped hydro storage or other means, will be massively challenging technically, as well as costly economically and in resource terms (Palmer and Floyd, 2020). In this respect, Aotearoa New Zealand is relatively fortunate given its substantial hydro storage capacity and the option to develop pumped hydro.

> Leaving technological uncertainties aside, our governance arrangements, both democratic and otherwise, remain deeply problematic.

Related to this, many degrowth proponents argue that various natural resources essential for RETs and EVTs, including many 'critical raw materials' (e.g., cobalt, lithium, rare earth elements, etc.), are relatively scarce, often environmentally and socially damaging to exploit, and sometimes located in areas of political instability (Michaux, 2021; Seibert and Rees, 2021; see also Sovacool et al., 2020). Another common claim is that RETs cannot power a modern industrial civilisation without some reliance on fossil fuels. This is because – or so it is argued – some RETs (e.g., corn ethanol, biodiesel and solar PV) have low energy returns on energy invested (EROEI or EROI), some raise energy storage issues (e.g., wind and solar), and some have limited lifespans and/or significant recycling costs (Ferroni and Hopkirk, 2016; Hall, 2017; Murphy and Hall, 2010). Aside from this, many degrowth advocates doubt that current market-based or neo-liberal policy approaches can achieve the non-marginal, disruptive, system-wide re-engineering of global energy systems by 2050.

Unsurprisingly, these claims have generated a large literature, with substantial debate over numerous technical, methodological and measurement issues (see, for instance, Fthenakis et al., 2021; Raugei et al., 2017). Assessing all the claims and counterclaims of energy economists and other experts is not possible here. Importantly, however, concerns about low EROI for RETs have been vigorously rebutted point by point (see Diesendorf, 2021; Diesendorf and Wiedmann, 2020; Raugei and Leccisi, 2016; Raugei et al., 2017). Much the same applies to other key objections to relying fully on RETs and EVTs (note that EVs have energy conversion efficiencies about three to five times those of internal combustion engines). It is accepted, however, that the projected demand by 2050 for some material resources may exceed currently known reserves (Bobba et al., 2020; Junne et al., 2020) and that much better environmental regulation of mining is vital. But technological innovations over the coming decades, including recycling and substitution, and efforts to diversify supply sources are expected to ease critical resource pressures.

Such rebuttals have given green growth advocates confidence that a growing global economy can be powered 100% by RETs for some time, if not indefinitely, and that the investment funds required for the massive energy transition can be mobilised, as long as governments implement supportive regulatory and pricing policies. Indeed, the transition is already well underway, albeit too slowly currently to meet ambitious global mitigation targets (International Energy Agency, 2021).

Whether, and to what extent, the global transition will accelerate during the 2020s depends heavily on policy settings in the major economies, especially the US, EU, China and India, and the investment decisions of large international corporations and financial institutions. Currently, the outlook is mixed. If the Biden administration fails to secure congressional support for significant federal decarbonisation measures

and/or if the US Supreme Court blocks vital regulatory initiatives, other major global players, particularly China, may be less inclined to take bold measures. In this scenario, the global transition will be much slower than desirable. Against this, Russia's invasion of Ukraine may spur investment in RETs and EVTs, contributing to significant technological innovations. Realistically, what Aotearoa New Zealand does on the climate mitigation front will have little global impact, except perhaps for livestock emissions. But this does not lessen the long-term economic wisdom of, let alone the moral case for, radical policy measures to enhance ecological sustainability.

Conclusion

There is increasing recognition that humanity must live within real, non-negotiable biophysical constraints at multiple scales. Failure to do so will eventually prevent, if not reverse, economic and social progress. But what level and form of global economic activity is ultimately compatible with ecological sustainability remains uncertain. That said, continued global GDP growth over an extended time horizon – and even maintaining current levels of economic activity – will only be possible under strict conditions. These include adequately protecting the resilience of vital ecosystem services and biophysical systems. Currently, these conditions are not being met.

Given the existing ecological crises, both green growth and degrowth advocates readily accept the need for radical technological changes, including rapid decarbonisation and greatly enhanced energy and resource efficiency. They differ, however, over whether ecological sustainability will also require significantly (and perhaps rapidly) slowing, if not reversing, global GDP growth and the political feasibility of their respective policy approaches.

Assessing the validity of these contrasting perspectives is difficult because of multiple deep uncertainties. Two such uncertainties are critical. The first concerns the speed with which current and future breakthrough technologies are developed and comprehensively applied, and hence the potential pace and scale of absolute resource and impact decoupling. The second concerns the capacity of current governance arrangements, both global and national, to design and implement policy frameworks sufficient to catalyse and accelerate the necessary energy and resource transitions, including widespread and substantial changes in consumer behaviour. In both cases, the judgements of experts appear to be influenced not only by evidential considerations, but also by philosophical, ideological and psychological dispositions. In short, technological optimists, neoclassical economists, and those who doubt the political viability of economic contractionism (whether in democracies or autocracies) are drawn more strongly to the green growth camp.

Leaving technological uncertainties aside, our governance arrangements, both democratic and otherwise, remain deeply problematic. Here the evidence points unequivocally to a fundamental mismatch between the scale of humanity's ecological challenges and the capacity and willingness of citizens and policymakers to respond (Hagens, 2020). If this mismatch persists for a decade or more – perhaps due to a combination of cognitive biases (including myopia and denial), ideological preferences, geo-political conflicts, short-term electoral pressures and powerful vested interests – then the required transitions may be too slow. In this scenario, the ecological crises will deepen and the negative impacts will increase, eventually causing large-scale damage to critical physical infrastructure and widespread supply disruptions. At that point, global degrowth may become inevitable (Keen, 2021). The resulting social and political tensions will be immense, and probably unmanageable. In short, modern civilisation could destroy itself. Such an outcome, while tragic, would not be totally unprecedented. Previous civilisations have mismanaged their environments and suffered dire consequences – the Sumerians, Babylonians and Mayans, to name but a few (Diamond, 2005).

But suppose enough governments respond swiftly and effectively and the required systemic, technological and behavioural changes occur within ecologically sustainable time frames: is indefinite GDP growth then a plausible scenario? Interestingly, some ardent supporters of green growth say no. To quote Nicholas Stern: 'Strong growth, of the right kind, will be both necessary and feasible for many decades … [But] This is not to claim that the world can continue to grow indefinitely … A picture of indefinite expansion is an implausible story of the future' (Stern, 2009, p.10).

Yet perhaps humility, in the face of deep uncertainty and complexity, requires a more equivocal answer.[6] As Hickel and Kallis (2020) acknowledge, 'as long as ultimate limits in efficiency and substitution have not been reached', the question cannot be answered definitively. That, in my view, constitutes a prudent response.

Nevertheless, to minimise the risk of a catastrophic ecological collapse globally, prudence also requires immediate, bold and transformative actions, at all levels of society and in every sphere of economic and social life. As a recent editorial in the authoritative journal *Nature* (2022, p.361) concluded, 'the world is running out of time'.

1 See, for instance, Carney, 2021; Fiorino, 2018; Hall, 2016; Pollin, 2018; Stern, 2007, 2009.

2 See, for instance, Brown et al., 2011; Costanza et al., 2014; Hagens, 2020; Hickel and Kallis, 2020; Hickel, 2021; Kallis, 2011; Jackson and Victor, 2019; Mastini et al., 2021; Murphy et al., 2021; Otero et al., 2020; Pollitt, 2022; Schröder and Strom, 2020; Vogel et al., 2021; Ward et al., 2016; Wilkins and Murphy, 2021.

3 But note that expanding the reliance of the global econoy on solar and wind energy requires the exploitation of many non-renewable, and hence finite, resources, as discussed later.

4 See, for instance, Arrow et al., 2004; Bradshaw et al., 2021; Dasgupta, 2021; Folke et al., 2021; IPCC, 2018, 2021, 2022; IPBES, 2019; Stern, 2007; UNEP, 2011a, 2011b.

5 The Jevons paradox or rebound effect involves the tendency for cheaper and more energy-efficient services, whether arising from technological progress or policy changes, to increase the demand for energy and other resources, thus resulting in smaller reductions in overall energy consumption than otherwise expected.

6 On the need for and virtues of humility in the public sphere, see Annala et al., 2021.

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