10 New Insights in Climate Science 2021

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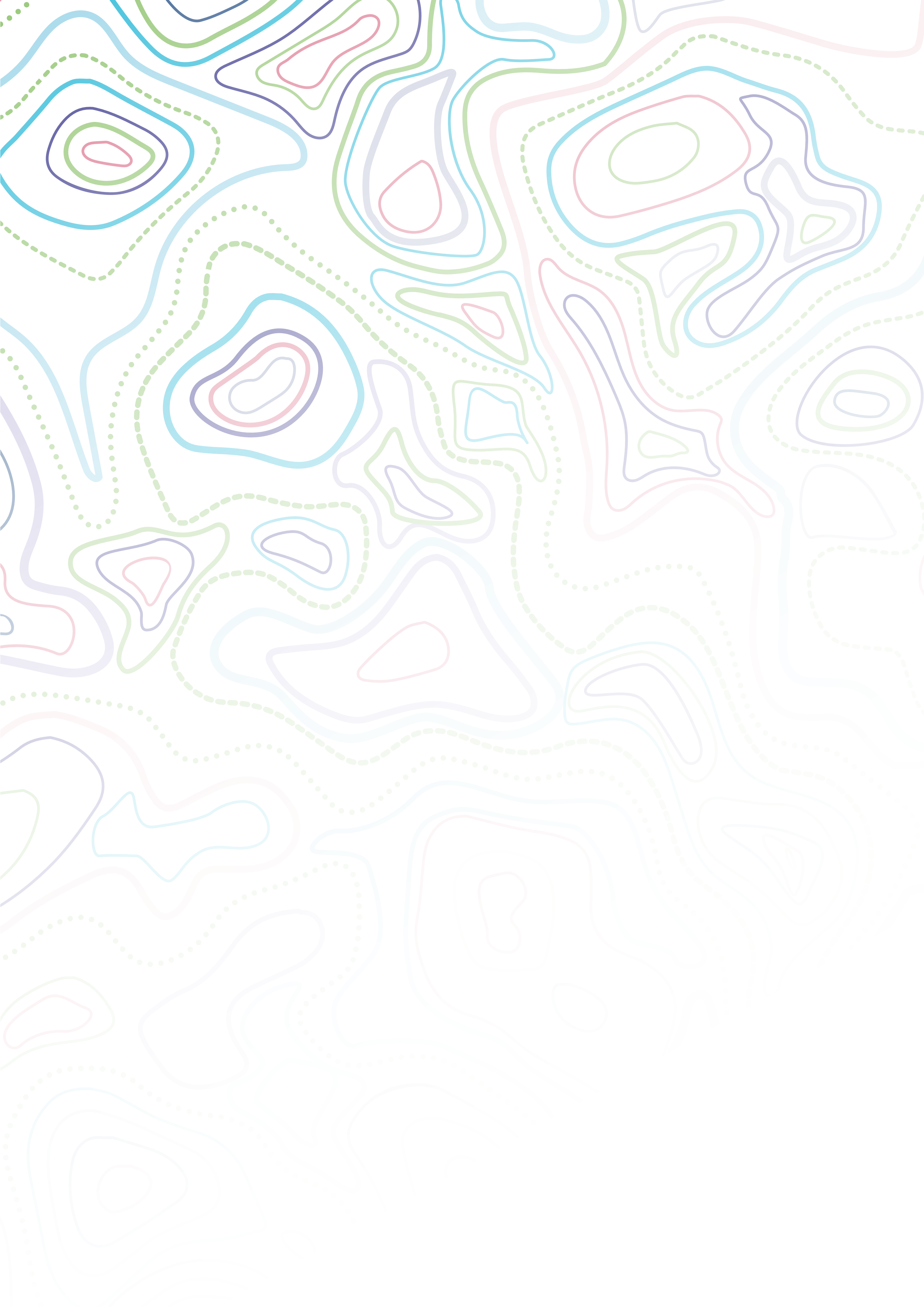

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Introduction

"To put it simply, the state of the planet is broken," as United Nations (UN) Secretary-General António Guterres said in the 2021 State of the Planet address.[1] Over the course of this past year and while the COVID-19 pandemic continues to ravage the world, massive wildfires wreaked havoc in places such as Siberia, western USA and Greece; cyclones devastated parts of South East Asia and the South Pacific; unprecedented and severe winter storms caused an extended power outage in the southern US state of Texas; and many parts of Europe experienced catastrophic flooding. The latest Intergovernmental Panel on Climate Change (IPCC) report should have put to rest any remaining doubts about the sources or impacts of climate change, and the 2018 IPCC Special Report covered how climate change strongly intersects with and amplifies threats to human and ecosystem health. The present study of the past year's climate change research parses the complexity of earth's systems in this context by highlighting 10 pertinent aspects, each of which is intrinsically linked to all others.

As this summary report shows, achieving the Paris Agreement target of a maximum of 1.5°C global temperature warming above pre-industrial levels is still possible. However, this will require transformations across all sectors, including deep decarbonization, and drastic coordinated global action to support lower-income countries in making climate-smart transitions as well as holding the highest emitters to account. Targeted measures that are designed and implemented to prioritize equity are needed urgently at all levels: structural, political and individual. The greatest responsibility falls on wealthy, developed countries to rapidly transition away from fossil fuels and support a global shift to clean energy, transport, industry and housing. This is particularly true after decades of insufficient responses to the climate crisis (as evidenced by the roughly 60% rise in fossil fuel emissions since the first IPCC report in 1990).[2]

The most favourable outcome is to keep global warming below 1.5°C, but this is also the most challenging scenario. Exceeding this threshold would degrade ecosystems irreparably, resulting in a negative feedback that further increases emissions of the greenhouse gases carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), with deleterious consequences for the climate system and catastrophic consequences for the most vulnerable populations. Furthermore, many extremes that we already experience – such as megafires – are projected to intensify, and the probability for crossing thresholds of critical components of the climate system will increase strongly with devastating effects for all aspects of the Earth system.

In addition to massive cuts in CO_2 emissions, we must address growing emissions of other greenhouse gases (such as CH_4 and N_2O), as well as other climate forcings. In fact, remaining budgets of all greenhouse gases with respect to the 1.5°C target may have to be revised to account for additional warming sources such as fires, permafrost thaw in the Arctic and accelerating degradation of ecosystems. Witnessing degradation of ocean ecosystems and the implications that this degradation has on the broader climate system – namely affecting their capabilities to store heat and buffer rising CO_2 emissions – should encourage new approaches and scales of governance to recognize and protect the oceans as global commons and to begin to restore marine ecosystems. Particulate matter (PM2.5) pollution, which in some places is compounded by worsening wildfires and which leads to millions of premature deaths and contributes to higher COVID-19 death tolls, is predominantly caused by burning of fossil fuels.[3,4,5] Furthermore, deforestation is linked not only with the exacerbation of global warming effects but also with new infectious diseases.

Harnessing strategies that offer co-benefits is a crucial way to facilitate just transitions to lifestyles in alignment with the 1.5°C target of the Paris Agreement. Moreover, acting on climate change results in multiple short- and long-term benefits. In fact, the Global Commons Alliance survey from August found that the majority of citizens in G20 countries are worried about the global commons and 83% are willing to do more to protect and regenerate them.[6] The implementation of nature-based solutions (NbS) and other strategies to halt deforestation contribute to climate change mitigation by protecting carbon storage, as well as contributing to the reduction in health risks. It is estimated that in many large economies, the cost savings from reduced air pollution alone will offset the costs of mitigation, even in the short term. Meeting World Health Organization guidelines for air pollution is expected to add 17 billion years to life spans globally.[7]

The challenge is massive, but, with willingness, humans have the capacity to overcome great challenges. We are not limited by our knowledge of the problem, by economic factors, or even technology, but by other obstacles. These are structural, social, cultural and especially political, and inhibit the pace and scale of implementation that are needed to achieve the goals of the Paris Agreement. Embracing a sense of the planet as a set of interconnected and integral commons might guide decision-making to hear the voiceless, empower the disempowered, build greater equity through thoughtful resource distribution, and otherwise engage in justice-oriented climate action. This report summarizes clearly the most recent message from science: action to steer away from catastrophic climate change is necessary, urgent, and possible.

Definitions of a selection of terms are provided at the end of this document, preceding references.

All statements in this summary report are based on the following article, except when referring to a specific source: Martin et al. (2021): Ten New Insights in Climate Science 2021 – A Horizon Scan. In Global Sustainability. https://doi.org/10.1017/sus.2021.25

1 Stabilizing at 1.5°C warming is still possible, but immediate and drastic global action is required

Key new insights

- Estimates of the remaining global carbon budget (the overall amount of CO_2 that can be emitted) indicate that rapid reductions averaging 2 gigatonnes of CO_2 ($GtCO_2$) (5% of 2020 global emissions) per year are required to keep global warming to within 1.5°C. This pace of reductions must be maintained until net emissions are zero (around 2040).
- We may have already exceeded the carbon budget necessary to keep global temperature rise to within 1.5°C of warming.
- If these unprecedented cuts in emissions are not made, we are likely to exceed 1.5°C warming and require carbon removal technologies on an enormous scale.
- The short-term emissions drop during the COVID-19 pandemic had a very limited impact on the overall decarbonization towards meeting the 1.5°C target.
- The power sector offers the largest opportunity for near-term decarbonization, but all economic sectors need to drastically reduce greenhouse gas (GHG) emissions (e.g. methane – *see Insight 2*).

Insights explained

In order not to exceed the 1.5°C maximum warming target, the remaining global carbon budget requires that annual global emissions reductions average 2 $GtCO_2$ per year (coincidentally that's close to the level of reduction in emissions in 2020 due to the COVID-19 pandemic of ~7% compared to 2019). Staying within 1.5°C warming also hinges on stringent reductions in emissions of non-CO_2 greenhouse gases such as methane and nitrous oxide (which are further discussed in Insight 2).

While it may still be possible to stay within the carbon budget needed to remain within the 1.5°C target, it is highly unlikely unless unprecedented rapid and massive changes to the world's economy and infrastructure are immediately undertaken. Supply-side changes, such as shifting to renewable energy, need to be implemented alongside changes in demand. With continued progress in solar and wind energy technologies, additional low-carbon generation could soon be sufficient to meet new power demands if deployed in conjunction with demand-side reductions (which is further discussed in Insight 6). However, the residual emissions of existing and proposed carbon-intensive infrastructure alone are enough to exceed the carbon budget. Scrapping planned fossil-fuel based projects is therefore necessary. Additionally, early retirement of some economically viable but carbon-intensive infrastructure as well as deep reductions in every sector will be needed, employing all mitigation levers. By starting with a rapid shift to low-carbon electricity production, electrification of other sectors becomes a more viable option for also decarbonizing these sectors.

Deep societal transformation is needed to stabilize the climate at any temperature target, and we have waited too long to start this process. Unless, beginning immediately, emissions are consistently reduced at an unprecedented scale, it will no longer be possible to keep warming within the 1.5°C target. In fact, most of the scenarios that include drastic action to stabilize global temperatures at the 1.5°C level predict temperatures will initially exceed that target, requiring unproven carbon removal technologies to be deployed on an enormous scale to make global emissions negative for many years. Exceeding 1.5°C even temporarily may have irreversible effects on oceans and other components of the Earth system as well as increasing the frequency of extreme events *(see Insights 3 and 4)*.

Background

Warming is defined as the change between current global temperatures (across multiple years) and the baseline temperature level for 1850-1900. Natural variability will lead to warming being more (or less) in some years and locations, but the limits set by the Paris Agreement refer to long-term, global averages. As of 2020, current estimates are that warming has already raised the global temperature by 1.2°C. The Paris Agreement set 1.5°C as the target for maximum warming because of a growing scientific consensus that the impacts and negative risks would grow unacceptably large beyond that level. This assessment is based both on modelling the future and observing the impacts that have already happened due to existing warming. Additionally, the likelihood of irreversible changes is much higher as warming exceeds 1.5°C.

Recent work indicates, with 50% probability, that for the remaining carbon budget to not exceed 1.5°C is 440 $GtCO_2$. The amount of uncertainty continues to shrink as we collect more data, better understand the underlying science and build improved models. Yet, there is sufficient uncertainty across all the various variables that even these latest estimates find that there is a small probability that we have no remaining carbon budget. This means that even if emissions were zeroed out today, warming would still exceed 1.5°C.

! Implications

At a global level, decision-makers are urged to:

- take immediate and unprecedented actions across all sectors to reduce greenhouse gas emissions, if warming is to stay within 1.5°C above pre-industrial temperatures;
- set both aggressive mid-term goals (e.g. 50% GHG reduction by 2030) and an ambition of net-zero by 2040.

At national and local levels:

- broad and deep electrification utilizing carbon-free sources is a key strategy for decarbonization and sustainable development;
- retirement of economically viable but carbon-intensive infrastructure must begin;
- a diverse portfolio of carbon-removal technologies must be rapidly developed and scaled, though not utilized as a replacement for emissions reductions;
- small but immediate reductions in demand can have large impacts on emissions, by enabling the retirement of carbon-intensive energy production (e.g. coal power plants).

440
gigatonnes of CO_2 that can be emitted from 2020 to stay within the 1.5°C warming threshold (50% probability).

2 $GtCO_2$
yearly reduction in emissions needed to stay within that budget.

10
remaining years until the budget for 1.5°C is exhausted at current (2020) emission levels (around 40 $GtCO_2$).

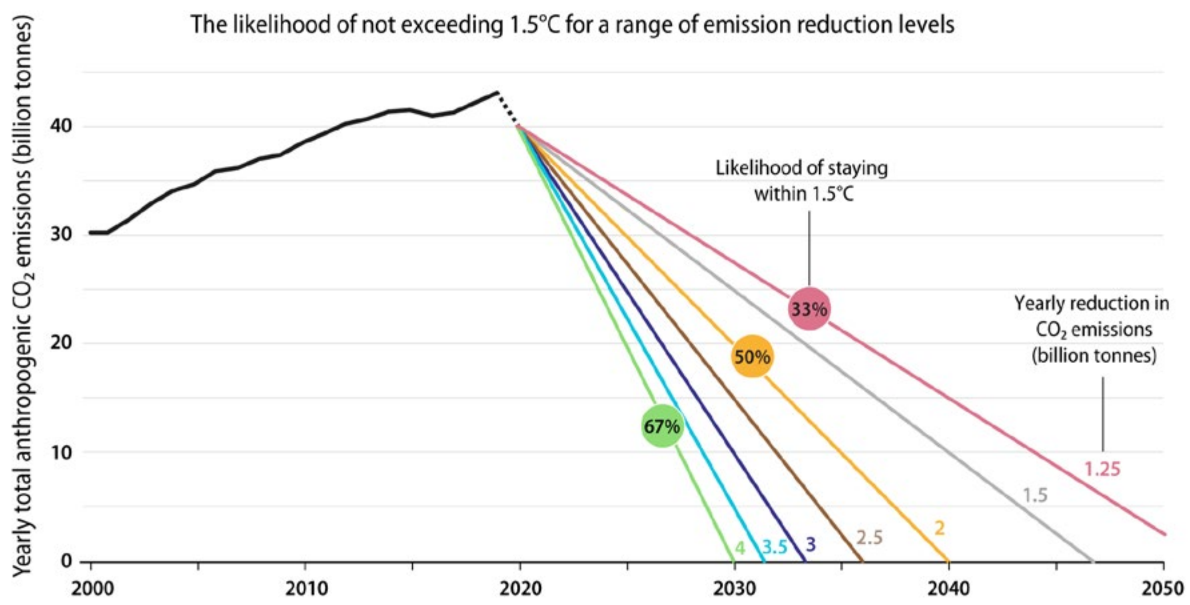


Figure 1. Linear reductions in global CO_2 emissions and the corresponding probabilities that these would enable remaining within 1.5°C warming to preindustrial levels.

2 Rapid growth in methane and nitrous oxide emissions put us on track for 2.7°C warming

Key new insights

- Rapid growth in emissions of methane and nitrous oxide — greenhouse gases that are far more powerful than CO_2 — are worsening the impact of rising levels of CO_2, together putting the world on track for 2.7°C of warming this century.
- Reducing methane emissions is a key lever available to slow climate change over the next 25 years: readily available, low-cost measures (see implications below) could halve methane emissions by 2030 and must go hand-in-hand with CO_2 mitigation and removal efforts to stabilize global temperature in the long term.
- Rapid reductions in aerosol emissions during the COVID-19 pandemic caused a slight warming of the planet, highlighting the fact that cooling aerosols emitted from fossil fuel combustion to date have partly masked warming from greenhouse gas emissions. While declines in aerosol emissions will improve air quality and benefit the health of billions, this will exacerbate global warming in the short term.

Insights explained

Powerful greenhouse gases besides CO_2 must not be overlooked in efforts to limit global warming to 1.5°C. These include CH_4 and N_2O, emissions of which are both showing rapid growth, contributing to a pathway to warming well above 2°C.

Methane is the major component of natural gas and is responsible for about 20% of global warming since the pre-industrial era. Emissions of methane reached a record high in 2020, 6% above levels in the year 2000. Human-induced nitrous oxide emissions have grown by 30% over the past three decades. Emissions of both gases from the agricultural sector are the main cause of this large growth. Waste treatment in landfills and fugitive emissions from fossil fuel extraction are also major sources of methane.

Human emissions of aerosols – tiny particles of sulphur or nitrogen emitted during fossil fuel combustion – have an overall cooling effect on the climate. They have partly masked warming from greenhouse gas emissions to date. Emissions of aerosols are predicted to decline, the extent of which depends on pollution-control policies. This will improve air quality and benefit the health of billions of people worldwide but will exacerbate global warming in the short term. This was clearly illustrated during the COVID-19 pandemic: reduced emissions of cooling aerosols during national lockdowns led to a temperature rise of 0.03°C globally and up to 0.3°C at higher northern hemisphere latitudes in May 2020.

Overall, largely due to a growth in methane and nitrous oxide emissions alongside declines in aerosols, non-CO_2 factors have increasingly warmed the climate over the past 20 years. Ongoing increases in non-CO_2 greenhouse gases and declines in aerosols will reduce the remaining carbon budget.

The good news is that readily available and low-cost measures could reduce the projected anthropogenic methane emissions by more than 45% to 2030. Due to the short lifetime of methane in the atmosphere, addressing the sources of methane emissions will have a rapid impact on climate change.

"Low-hanging fruit" options include reducing fossil fuel leaks and improving waste treatment technologies, which alone could avoid 0.3°C of warming by the 2040s. There are also solutions in the food and agricultural sector that could reduce nitrous oxide and methane emissions – a mix of supply and demand options – such as increasing the efficiency of nitrogen use, further improvement and uptake of feedstocks that reduce the methane emissions of ruminants, promotion of healthy low-meat diets and reduction of food waste. These solutions come with additional health and environmental benefits.

Background

Global warming is driven by human activities that produce both positive and negative climate forcing. Overall, about 21% of current net global warming is caused by factors other than CO_2. These include emissions of other greenhouse gases, their precursors or warming aerosols such as black carbon. Non-CO_2 factors driving global warming arise primarily from the burning of fossil fuels, and from land-use including agricultural activities (see image for a full breakdown). They have had an increasing warming effect over the past 20 years, largely due to growth in emissions of the powerful greenhouse gases methane and nitrous oxide. This is worsening the impact of rising levels of CO_2. If anthropogenic emissions of methane and nitrous oxide continue to rise, it will reduce the remaining carbon budget, preventing stabilization of global temperature once net-zero emissions of CO_2 are reached.

! Implications

At national and local levels, decision makers in government and the private sector are urged to:

- reduce fugitive methane emissions from the fossil fuel sector through regulation – for example certification of suppliers, and through investment in new technologies for leak detection and repair, including in production, transmission and distribution systems;
- reduce net emissions from landfill by promoting the separation of waste at source, recycling, incineration with energy recovery and anaerobic digestion with biogas recovery;
- curtail methane emissions from the food and agriculture sectors through a broad portfolio of policies to reduce food waste and improve land and livestock management – for example promoting the use of lower emission feedstock, improving water management in rice cultivation and encouraging healthy, low-meat diets;
- reduce nitrous oxide emissions in agriculture through practices that limit the use of nitrogen fertilizers and promote their efficient use – for example through improved timing of nitrogen application and better management of animal manure.

46%
share of warming factors driving climate change other than CO_2 (cooling factors offset a proportion of this, leading to 21% of net warming).

0.03°C
short-term global warming as a result of COVID-19 restrictions.

45%
methane emission reductions possible by 2030 through readily available and low-cost measures (see implications).

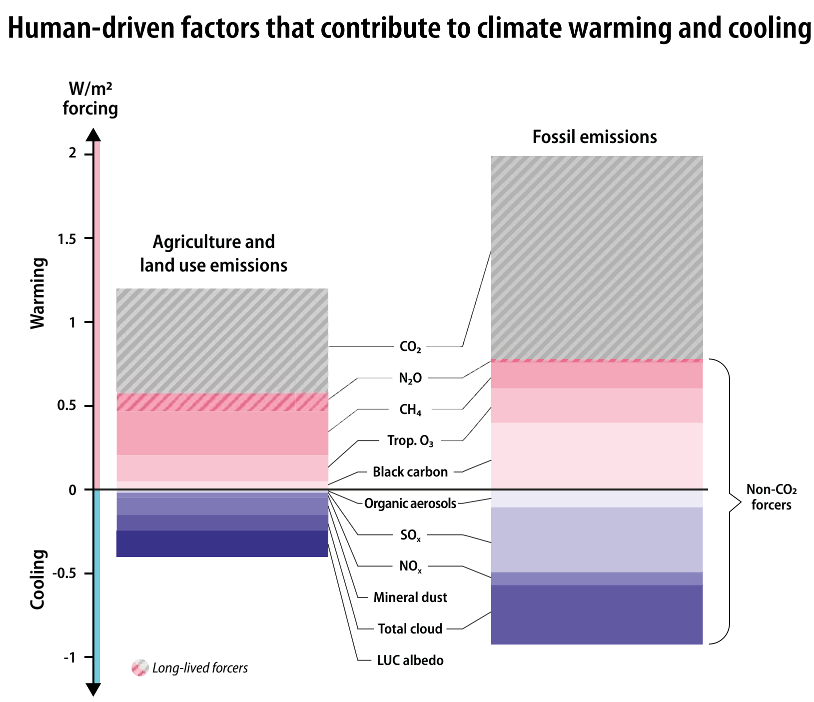


Figure 2. Current human-driven factors that contribute to global warming and cooling. The factors are partitioned by their direct and indirect sources: factors driven by land-use including agricultural activities (left column) and fossil fuel combustion (right column). The atmospheric gases include both long- and short-lived types (see Martin et al., 2021 for references). Abbreviations are: CO_2 – carbon dioxide; N_2O – nitrous oxide; CH_4 – methane; Trop. O_3 – tropospheric ozone; SO_x – sulphate aerosols; NO_x – nitrogen oxides; LUC albedo – changes in the reflectivity of land surface due to land-use changes.

3 Megafires — Climate change forces fire extremes to reach new dimensions with extreme impacts

Key new insights

- We are entering a new age of intensifying extreme fire regimes (megafires). It is likely that these are induced, and certainly exacerbated, by anthropogenic climate change.
- Several megafires have been observed across very diverse regions from high to low latitudes, and are now impacting ecosystems that typically do not have a history of wildfires.
- Megafires can affect entire biomes with unprecedented impacts on flora and fauna, threatening also more fire-sensitive ecosystems such as the World Heritage–listed Gondwana rainforests of Australia.
- Large greenhouse gas emissions released by megafires enhance positive fire-climate feedback, which sustain and worsen conditions that increase the likelihood of even more devastating wildfires.
- Large smoke plumes and aerosols from megafires can impact wide areas due to long-range transport both in the troposphere and stratosphere.
- Worsening fire regimes (more frequent fires, more intense fires) come with increased risks to respiratory and cardiovascular health, birth outcomes and mental health for rural and urban communities.

Insights explained

New scientific advances confirm previous warnings that human-induced climate change is intensifying fire regimes. There have been increases in fire extent, intensity and the duration of the fire season, as well as a change in the available fuels, resulting in an increased frequency and intensity of fires. Megafires, high-intensity wildfires that spread uncontrolled over large areas, reaching extreme fire intensities, are likely to be increasingly frequent. Megafires cause greenhouse gas and aerosol emissions, which are unprecedented for the affected biome, and impact air quality on local and continental scales.

Researchers have recently been able to attribute fire and megafire events more clearly to human interference – such as the 2021 wildfires in western North America that were preconditioned by an extreme heatwave. Evidence for human influence is found in fire seasons of unprecedented magnitude in the modern era in regions and countries as diverse as California, Australia, the Mediterranean basin, Canada and the Arctic. It is now possible, with at least medium confidence, to attribute human influence on weather events, namely extreme drought, heat, lightning activities and often high winds, that increase the fire risk. The IPCC Working Group I Sixth Assessment Report (IPCC AR6 (WGI)) projects future increases of fire weather with medium or high confidence on every inhabited continent, primarily due to higher temperatures and reduced precipitation.[7] There is medium confidence that there is a positive carbon-climate feedback loop with fires releasing greenhouse gases enhancing the drier and fire-prone conditions that favour fires.[8]

Recent fires have caused significant impacts on human health. Wildfire smoke is known to affect respiratory health, and there is growing evidence of impacts on cardiovascular health, mortality, birth outcomes and mental health. Smoke from wildfires also affects local and distant air quality. The 2019-2020 Australian wildfires affected New Zealand and South America, and smoke from Siberian fires has affected North America. Current assessments estimate over 677,000 deaths per year globally from landscape fires with the largest contribution from the Arctic, South East Asia, Central and West Africa and the Amazon.[9]

As climate changes, the occurrence of megafires is not constrained to fire-prone ecosystems alone. A change in tropical forests' moisture, for instance, may promote much larger fires. Changing fire regimes will have important consequences for the world's biodiversity, regional human health and the global climate system.

Background

Wildfires are an intrinsic feature of many ecosystems around the world, and are a prerequisite for many plant species to reproduce. Many factors affect whether a wildfire starts and how severe it is, such as weather, vegetation structure (fuel availability), terrain (or topography), land and fire management practices and human presence that may – on purpose or by accident – ignite a fire. Wildfires occur in some ecosystems, such as Australian savannahs, almost annually; in Australian temperate forests they occur multiple times in a decade (potentially increasing in frequency now), and in ecosystems such as undisturbed rainforests wildfires only rarely occur, usually on centennial scales, such as in boreal forests in North America and in Siberia (100-300 years between events). In Siberian boreal forests normal fire conditions burn only the forest floor, leaving standing trees alive. Extreme drought conditions that burn entire forest stands (crown fires – burning even forest canopies) used to occur only every 10-15 years and affected 3-10 million hectares in Siberia. Climate change is impacting the frequency and severity of fires, causing extreme fire years to become more extreme.

! Implications

At a global level, decision-makers are urged to:

- limit global warming with all measures possible to decrease the risk of more frequent and intense megafires.

At a regional level, governments need to:

- revise and adapt fire management planning to account for a diverse range of affected ecosystems, which requires land management methods that are region- and context-specific.

At national and local levels, policymakers need to:

- include megafires and their impact on greenhouse gas emissions in the budgets for the 1.5°C-target;
- implement monitoring and forecasting systems of weather conditions and wildfires, which may support adaptation to the devastating effects of these fires;
- provide protection measures by controlling and penalizing illegal deforestation where fire is used as a land-clearing technique;
- adapt forest management methods such as forest fuel treatments, the intentional reduction of material that burns in fire-prone forest areas, to local biomes and climatic conditions;
- consider collaborating with indigenous communities to re-engage with traditional land management practices, such as cultural burning;

- increase the resilience of communities in affected areas (taking account of an increased fire risk when planning, building and improving infrastructure);
- consider techniques to reduce exposure to $PM_{2.5}$ from wildfire such as the use of air cleaners in indoor spaces, thereby protecting people's health;
- increase monitoring of air pollution, including with low-cost sensors, and the development of better forecasting to warn people about air pollution levels.

9,000
plant species (more than one-third of all Australian species), 832 vertebrate fauna species, including 21 threatened species were affected across the 2019/20 fire grounds in Australia.

0.67
gigatonnes of carbon stocks net loss of biomass in the Amazon from 2010-2019, largely due to fires, contributing to the conversion of the Amazon from a carbon sink into a source.

35%
more CO_2 released from Arctic wildfires in the first 8 months of 2020 compared to the entire previous year (2019).

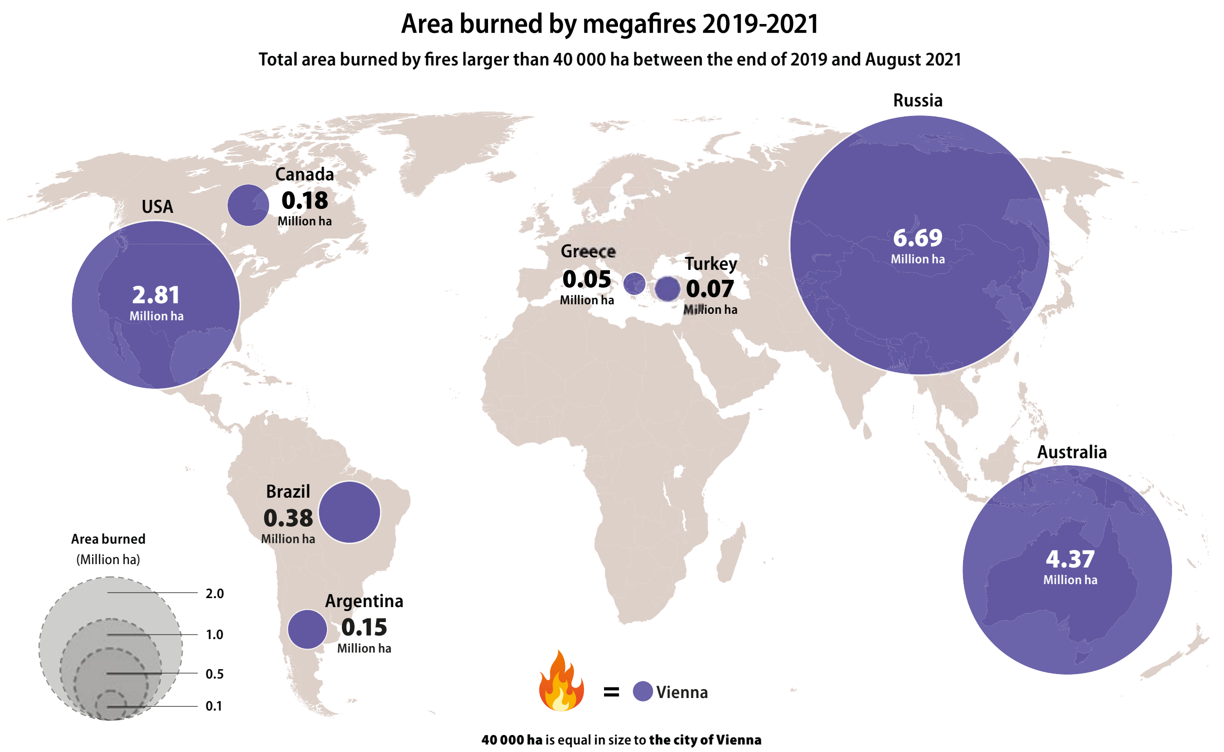


Figure 3. Cumulated selected fires larger than 40,000 ha between November 2019 and August 2021. 40,000 hectares is 4% of 1 million hectares.

Megafires can enhance emissions of methane

Intensifying fire regimes have devastating effects on ecosystems. The increased occurrence of fires as well as their growing intensity threatens biodiversity and can lead to an increase in emissions of greenhouse gases including CH_4. An increase in fire activity in both 2019 and 2020 associated with deforestation in the Amazon region significantly increased emissions of methane, with direct emissions of methane of 0.5-7.0 megatonnes of CH_4 per year (depending on the severity of the burn season), not including additional indirect emissions due to ecosystem degradation.[10] The unprecedented Arctic wildfires in 2019 and 2020 represent another significant source of methane, both directly from burning, but also indirectly from accelerated permafrost thaw.[11] In both regions, direct and indirect emissions of greenhouse gases now largely exceed carbon uptake by regrowth of vegetation. Although the carbon-climate feedback of accelerating fire activity and emission of greenhouse gases is expected to increase strongly, this is currently underrepresented both in coupled climate models as well as in international considerations when estimating global greenhouse gas budgets to stay within the 1.5°C target.

Spotlight: Selected megafires

Australia

After record heat and drought, Australia experienced abnormally severe fires of unprecedented extent, including the largest single-ignition fire on record, which was greater than 500,000 hectares, in the season of 2019-2020. An estimated 715 (range 517-867) Mt gross CO_2 in total were emitted from these fires. Furthermore, these megafires affected entire biomes in southern and eastern Australia with unprecedented impacts on flora and fauna. The fires not only affected savannahs and eucalypt forests that are well adapted to wildfire, but also more fire-sensitive ecosystems, threatening the World Heritage–listed Gondwana rainforests.

Arctic and Siberia

In the Arctic Circle and Siberia, a rise in arctic temperatures and dry lightning caused large areas to burn. In 2019 about 10 million hectares – more than the size of Portugal – burned in Siberia and the Russian Arctic. This was followed by another extreme fire year in 2020 when nearly 14 million hectares burned in the region. Extreme fires occurred again in 2021. Altogether, the fires in the Arctic and Siberia released about 175 Mt of gross CO_2 in 2019 and nearly 250 Mt of gross CO_2 in 2020.

Brazil

In the world's largest wetland, the Brazilian Pantanal, there was a 245% increase in burned areas in 2020 compared to the previous 10 years. Reasons for this are extreme drying (due to 50% less rain than in the previous year) and intensified anthropogenic burning for intentional legal and illegal deforestation to reform pastures or make room for agriculture.[12] It led to emissions of 115 Mt of gross CO_2 and 524 tonnes of harmful fine $PM_{2.5}$. Populations of many animal and plant species were affected, many of which are rare or endemic. There is growing concern that the fragile ecosystem of the Pantanal area may never recover.

United States

Since 2018, the US south-west has experienced some of the worst fires ever seen in the region. Californian megafires burned for months and became the seven largest wildfires ever recorded until 2020. The largest megafire, the August complex fire, burned more than 400,000 hectares of different forest and shrubland types. Such high fire severity over an extremely large area puts the recovery of plants and animals, most of them rare or endemic, under threat. Smoke released by these fires reached critical levels for human health along the US west coast, with San Francisco covered under an orange sky for days. The smoke travelled across the northern hemisphere and aerosol particles from the fires were measured as far away as Germany. The 2020 California and Oregon wildfires led to excess carbon emissions of at least 30 Mt of gross CO_2 in a single year.

Satellite images

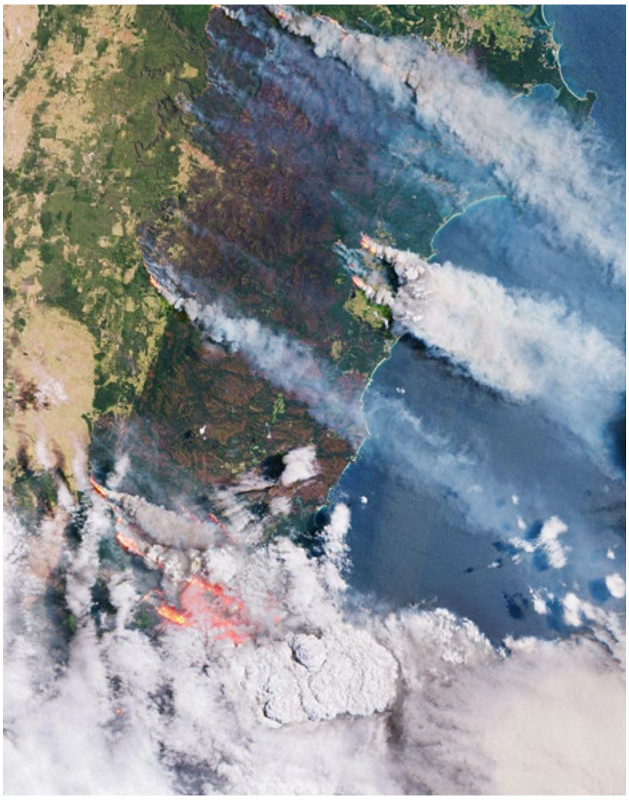


Image 1: Bushfires on December 31, 2019 burning along the east coast of Australia. The brown area is burned vegetation with a width of about 50 km and a length of 100 km. Source: European Space Agency (ESA), contains modified Copernicus Sentinel data (2019), processed by ESA, CC BY-SA 3.0 IGO

Image 2: Wildfires on August 19, 2020 burning on the West Coast of the USA in California. Source: European Space Agency (ESA), contains Copernicus Sentinel data (2020), processed by ESA, CC BY-SA 3.0 IGO

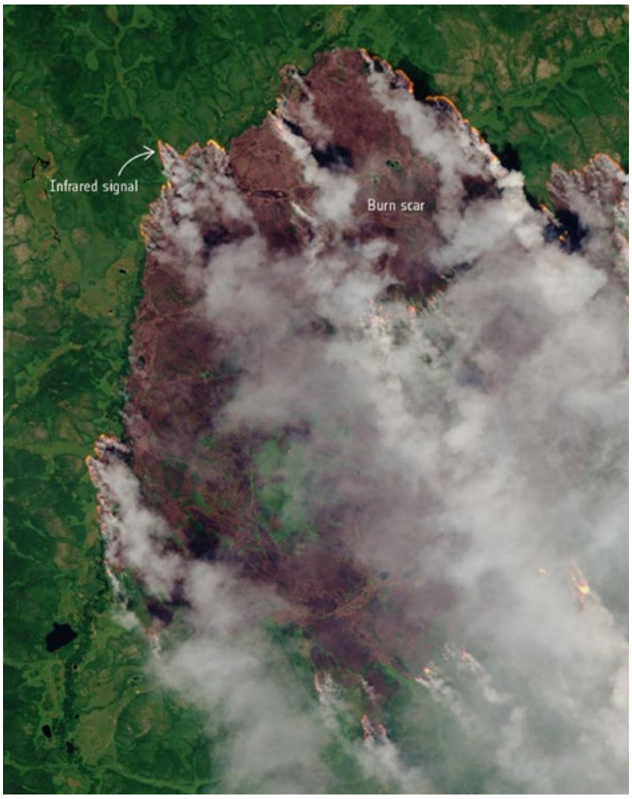


Image 3: Wildfires on July 25, 2021 in the Sakha Republic, Siberia (Russia) close to the Arctic cycle. Source: European Space Agency (ESA), contains Copernicus Sentinel data (2021), processed by ESA, CC BY-SA 3.0 IGO

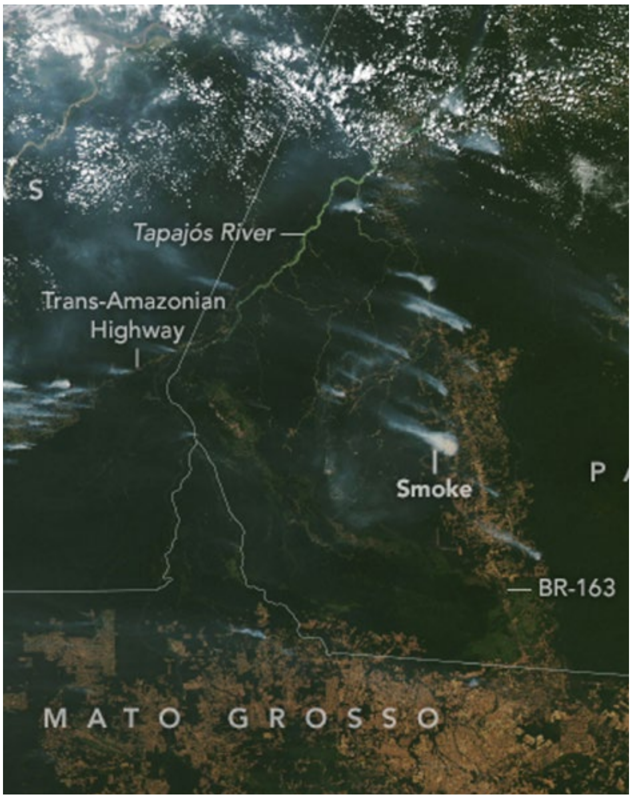


Image 4: Wildfires on August 1, 2020 in the Amazon in Brazil. Source: NASA Earth Observatory, image acquired by Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite.

4 Climate tipping elements incur high-impact risks

Key new insights

- The IPCC AR6 acknowledges that many human-caused changes, especially to the ocean, ice sheets and global sea level, are high risk and irreversible for centuries to millennia – some of them involving tipping processes (see Background) – and that these changes are key to a comprehensive risk assessment.
- Significant destabilization of several key climate tipping elements is already being observed today.
- In many cases, the dominant driver of this destabilization is global warming. But direct human influence on land cover change, such as degradation and active deforestation of the Amazon rainforest, can play an equal or even stronger role.
- Some tipping elements, for example melting ice sheets and changes to ocean currents, but also deforestation of rainforests, influence each other. Recent research indicates that interactions among tipping elements can ultimately cause shifts to happen at lower levels of global warming than anticipated.

Insights explained

The IPCC has, over the past two decades, continually strengthened their risk assessment concerning so-called "large scale singular events". Stronger than before, the most recent report (IPCC AR6 WG I) recognizes risks from non-linear changes in tipping elements in the climate system (see Background) as well as irreversible long-term commitments, as possible outcomes of anthropogenic climate change and direct human pressure. Changes in tipping elements are particularly afflicted with high uncertainties (in terms of likelihood or timing, or both), but also associated with large risks for societies and ecosystems. These high-impact, high uncertainty risks are termed "low-likelihood, high-impact outcomes" in IPCC AR6 – even if, as the authors explicitly state, probabilities are not necessarily known to be low, but simply not well constrained. The consequences are large, long term and associated with existential risks for nature and societies.

Among these risks associated with selected tipping elements, as discussed in the Spotlight, are

- **from an increased disintegration of the ice sheets:** a catastrophic 2 metres of sea level rise by 2100 and even more devastating 5 metres by 2150 (which are explicitly not ruled out by the IPCC AR6 WGI, 9.6.3.3). In the long term, we are committed to a similar degree of sea-level rise, for instance of 2-6 metres in the two millennia following peak 2°C warming (IPCC AR6 WGI, 9.6.3.5 and Cross Chapter Box 12.1);
- **from a slowdown or shutdown of the major Atlantic Ocean circulation:** abrupt changes in weather patterns, for example in Europe, which are currently highly dependent on the inflow of heat from the Atlantic Ocean circulation;
- **from a shift in the Atlantic circulation:** shifts of water cycles affecting several monsoon systems, and specifically a heat redistribution that alters precipitation patterns over the Amazon, although it remains unclear whether overall rainfall will be increased or reduced;
- **from a climate regime shift in the Amazon:** a feedback to regional climate conditions (loss of rainforest vegetation changes the moisture exchange with the air, for example), and a potential permanent loss of the Amazon basin as a major carbon sink.

A number of recently published research results confirm and refine the IPCC's assessment, and furthermore indicate that several climate subsystems are already showing signs of losing stability today and are moving towards critical thresholds (tipping points, see Spotlight).

In addition to the risks from individual tipping processes, science has identified an overarching, additional layer of risk: tipping elements may be involved in domino-type cascades – with one tipping process (for example Greenland ice loss) triggering another one (in that case a slowdown of the major Atlantic Ocean circulation due to meltwater intrusion). Therefore, in addition to the risk from each tipping element alone, their interaction exacerbates the situation and compounds the overall risk – tipping could happen more easily (at lower global temperatures) than if they were separated.

Background

Global warming and direct human pressure impose significant changes to key components of the climate system. Next to gradual changes that are proportional to the level of global warming, some components face the risk of undergoing dramatic and non-linear transitions at varying timescales, often without a chance to turn back to normal for a long time. These parts of the climate system are called tipping elements.

The actual transition can unfold over centuries to millennia (when ice sheets melt or disintegrate), over decades to centuries (when ocean currents slow down or reshape) or years to decades (especially when direct human interference pushes a transition, like deforestation in the Amazon rainforest).

The challenge with tipping elements is that we do not know exactly at what levels of global warming thresholds will be passed, given the complex nature of interactions. The danger is that once the thresholds are crossed there may be no realistic turning back. Even if levels of global temperature are brought back down again, self-reinforcing effects can drive further ice loss, forest die-back or other shifts, until the system can no longer be recognized.

! Implications

Climate negotiators and decision makers on all levels – international, national and local, need to:

- be aware of high-impact risks from climate tipping elements, and incorporate the remaining uncertainties about likelihood and timing in their risk assessments;
- apply the precautionary principle and aim for more ambitious climate protection, rather than the reverse. This is analogous to the approach to other societal risks, like that of a catastrophic nuclear accident, where large safety margins are prudent.

At a local level, where direct human influence has the potential to initiate tipping processes, for instance in parts of the Amazon rainforest, actors must take all possible measures to avoid tipping risks.

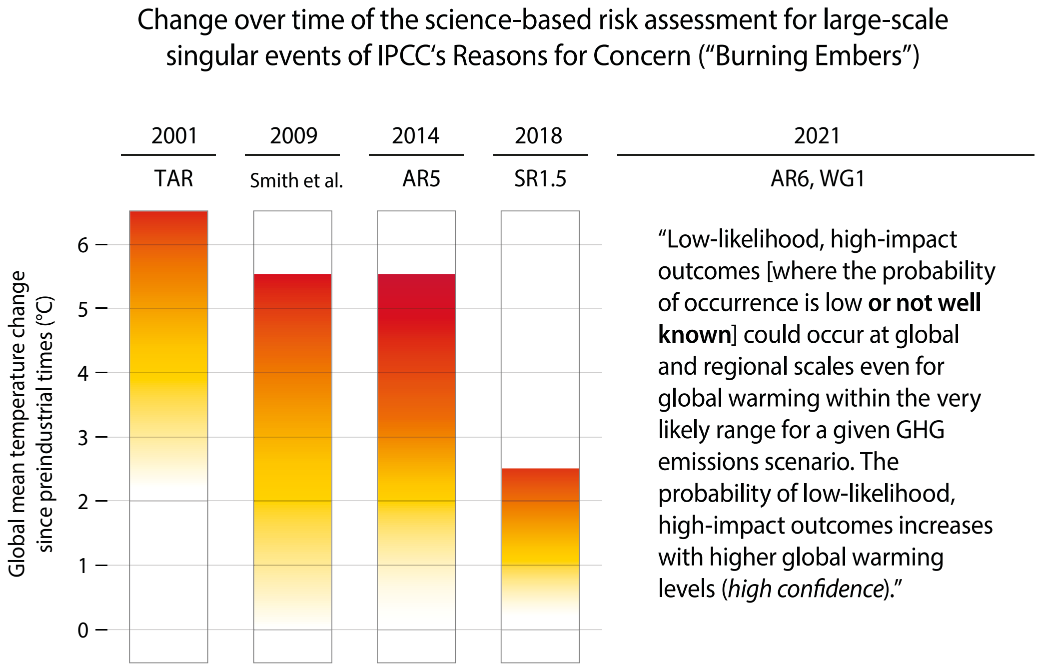


Figure 4. Change over time of the science-based risk assessment for large-scale singular events of IPCC's Reasons for Concern ("Burning Embers"). The first "burning ember" is based on the first IPCC report on climate change,[13] the second is based on Smith et al. (2009),[14] the third refers to IPCC AR5,[15] and the last "burning ember" is derived from the IPCCs' special report on 1.5°C.[16] The quote replaces a "burning ember" from IPCC AR6, which usually appears in the contribution by Working Group II (which is not yet published).

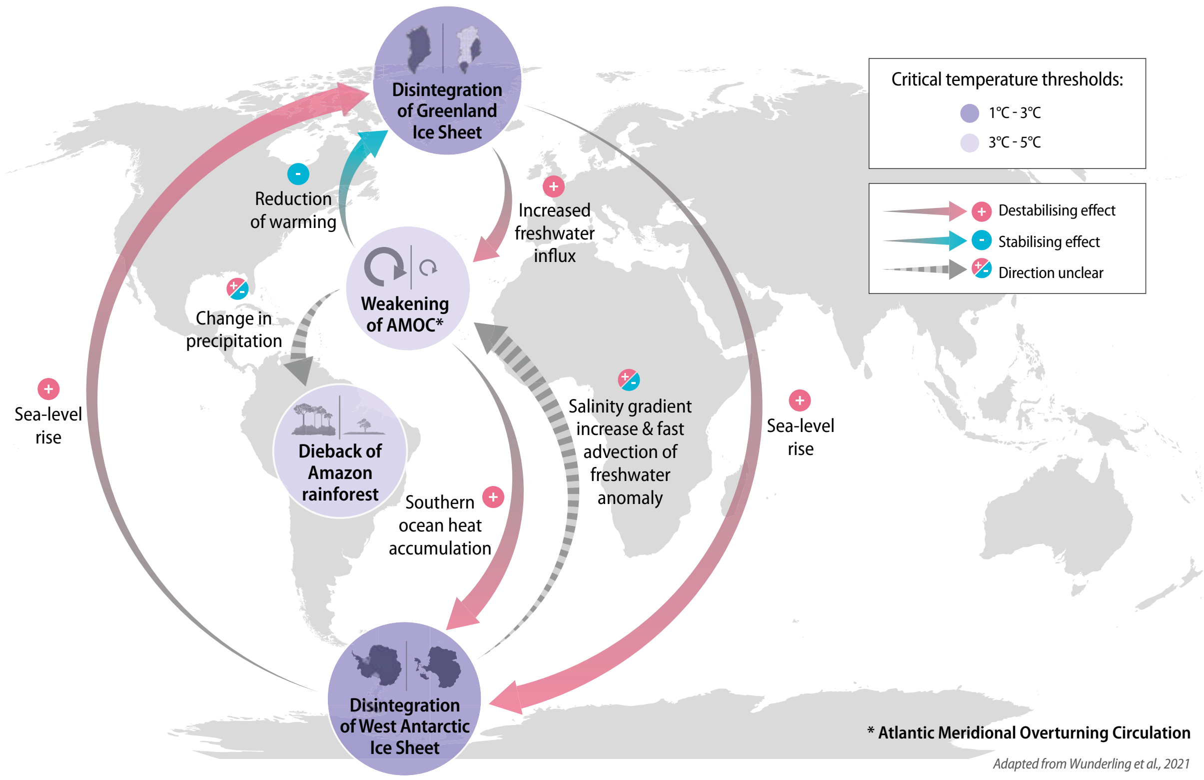


Figure 5. Physical interactions between four selected climate tipping elements: Greenland and West Antarctic Ice Sheets, Atlantic Meridional Overturning Circulation (AMOC) and Amazon rainforest (see reference in Martin et al., 2021).

Spotlight: Selected climate tipping elements

Greenland

The Greenland Ice Sheet is losing mass at accelerating rates, due to meltwater runoff and ice discharge at outlet glaciers. Surface melt will continue to increase with further atmospheric warming. While ice discharge is 14% greater now than during 1985-1999, the reasons for this increase differ from region to region, making it difficult to project future developments.

West Antarctica

Observations and modelling have shown that there are several processes that could lead to self-enforcing ice loss and sea-level rise, once a weakening of the ice and/or a retreat of the line where the ice starts to float is initiated. In the past, meltwater from the Greenland Ice Sheet has raised global mean sea level, directly influencing Antarctic Ice Sheet retreat.

Atlantic Ocean circulation

Studies of prehistoric climate, combined with modern sea level and salinity observations, show that the main Atlantic Ocean circulation system has weakened significantly in the past decades and is at its weakest in at least a millennium. Recent statistical analyses of sea surface temperature and salinity observations give rise to the concern that this decline is indeed a sign of an ongoing loss of stability of the circulation, rather than just a temporary weakening.

The Amazon

The Amazon rainforest is the world's largest tropical rainforest and plays an important role in global carbon budget and water circulation. The south-eastern part of the Amazon basin has turned into a net source of carbon to the atmosphere, not even taking the effect of fires into account (see more details in *Insight 8*). Observations show that changes in rainfall do alter vegetation types within the Amazon – though climate change alone will most likely not cause a basin-wide dieback. But in combination with human-caused forest degradation (at 17% of the Amazon basin, higher than previously estimated), and deforestation (at 18% already), climate change could trigger climate regime shifts in parts of the Amazon rainforests.

5 Global climate action must be just

Key new insights

- Climate action must support just transitions, as it could otherwise slow down improvements in living standards in low- and middle-income countries and burden disadvantaged people globally.
- Working towards just, equitable and low-carbon development for poorer countries:
  - requires the richest 1% to cut their emissions by a factor of 30, which would
  - enable the poorest 50% of the world's population to increase their emissions up to three-fold.
- Justice-oriented climate action is more likely to achieve public acceptance, improving uptake of implementation.

Insights explained

Global climate action must be designed to tackle rising inequalities and injustices between social groups and across generations living in different countries around the world. A just distribution of the carbon budget would require the richest 1% of the global population to reduce their current emissions by at least a factor of 30, while per capita emissions of the poorest 50% of the global population could increase by around three times their current levels on average. This would require the decarbonization of existing production and consumption infrastructure and the promotion of low-carbon lifestyles. Targets and incentives to facilitate this transition would necessarily result in a two-speed global process, with a high rate of change perceptible at the G20 level. Justice-oriented climate policies are likely to be more widely acceptable, increasing the potential for effective implementation for the benefit of all.

Not only are climate impacts unfairly distributed, but actions to mitigate climate change also risk having an undue impact on the most vulnerable. Climate policies that increase the cost of basic goods such as domestic energy, water or food – for example through taxation or through adding the cost of limiting environmental damage into the provision of these goods and services – tend to have regressive distributional effects as they hit people on low incomes harder than richer people in relative terms (discussed further in *Insight 7*). Policies and processes that seek to shrink high-carbon economic sectors and expand the low-carbon economy can threaten the livelihoods of workers in high-carbon sectors unless they are coupled with skills-upgrading and job-creation schemes. Mineral resources needed for low-carbon technologies, such as batteries and photovoltaic panels, are often mined in poorer countries in ways that generate detrimental environmental and social effects. Furthermore, climate action could slow down increases in living standards in the lower- to middle-income countries, while poorer countries and people have less capacity to act on climate change.

Lack of infrastructural development in many developing countries, not least in sub-Saharan Africa, may provide an opportunity to leapfrog to resource-efficient and climate-resilient infrastructure systems. This requires a political economy supportive of countries with lower capacities to balance mitigation, adaptation and development priorities. For instance, richer countries should contribute to low-carbon investments in poorer countries. These shifts require disruption of the status quo, transforming systemic inequalities and the structures that maintain them.

International climate ambition can and must ensure co-benefits for vulnerable societies. Moreover, it should not undermine people's access to basic goods. In order to achieve just and ambitious action, the past, present and future rights derived from a just distribution of the global carbon budget must be protected.

Background

When comparing carbon footprints per capita across the world, huge disparities emerge (within and across countries). For instance: the richest 10% of the world's population was responsible for 52% of cumulative carbon emissions (based on consumption) through the 1990-2015 period, while the poorest 50% accounted only for 7% of them. During this period, the carbon footprint of the richest 10% continued to rise, and there is a lack of mitigation policies to limit the emissions of this population segment.

It is worth noting that, despite the recorded increase of the global carbon footprint since the 1970s, inequities in its distribution tend to decline. This is in part due to the economic growth of China and to the strong coupling between income level (GDP) and carbon footprint. Achieving the decoupling between these two variables will be a great challenge in order to mitigate climate change while pursuing well-being for all and advancing development and climate agendas. Evidence is accumulating that wealthier countries may be well advised to prioritize environmental and social objectives in their policymaking and their measurement of social and economic progress in place of growth in GDP.

Climate change impacts have already, and continue to, affect vulnerable people and countries who have least contributed to the problem. The G20 member countries account for around 78% of global GHG emissions, and will thereby largely determine global emissions trends in the coming decades.

Rich countries' current and promised actions are inadequate for tackling the climate crisis, and do not take responsibility for the disparity of emissions and impacts. A glaring example is the near-term commitments of the G20 countries based on Nationally Determined Contributions under the Paris Agreement, which are insufficient for achieving net-zero reduction targets.

! Implications

At a global level, it is important for negotiators and decision makers to:

- use pricing on CO_2 emissions strategically (discussed further in *Insight 7*), with redistribution of resources and financial transfers from rich to poor countries to avoid regressive effects of low-carbon transitions;
- support low- and middle-income countries in their endeavours to leapfrog directly to low-carbon and climate-resilient infrastructure, drawing benefits from the lower costs and infrastructural requirements of distributed renewable energy;
- develop a just system of global burden sharing, for instance through a greenhouse development rights approach[17] or an equal cumulative per capita emissions approach,[18] which can reduce global poverty;
- reset deliberations on national climate ambitions in terms of targets that are designed to further reduce the disparity of the carbon budget distribution;
- reconceptualize how growth is achieved, decoupling income level (GDP) and carbon footprint, in order to simultaneously prioritize the pursuit of well-being for all and the advancement of development and climate agendas.

At a national and local level, it is important that governments:

- in the context of the wealthiest nations, establish much more aggressive policies in alignment with not only the best available climate science (i.e. achieve or exceed compliance with the Paris Agreement and net-zero targets), but also in line with equity-oriented targets. This requires a reduction in consumption emissions to a per capita lifestyle footprint of around 2-2.5 tonnes CO_2eq by 2030;
- establish policies to heavily tax luxury products and activities with a high carbon footprint;
- conduct careful advanced analyses of potential distributional and justice implications of low-carbon transitions;
- compensate disadvantaged populations where emission-reduction policies have regressive distributional impacts, ideally with measures that directly help people to reduce their emissions.

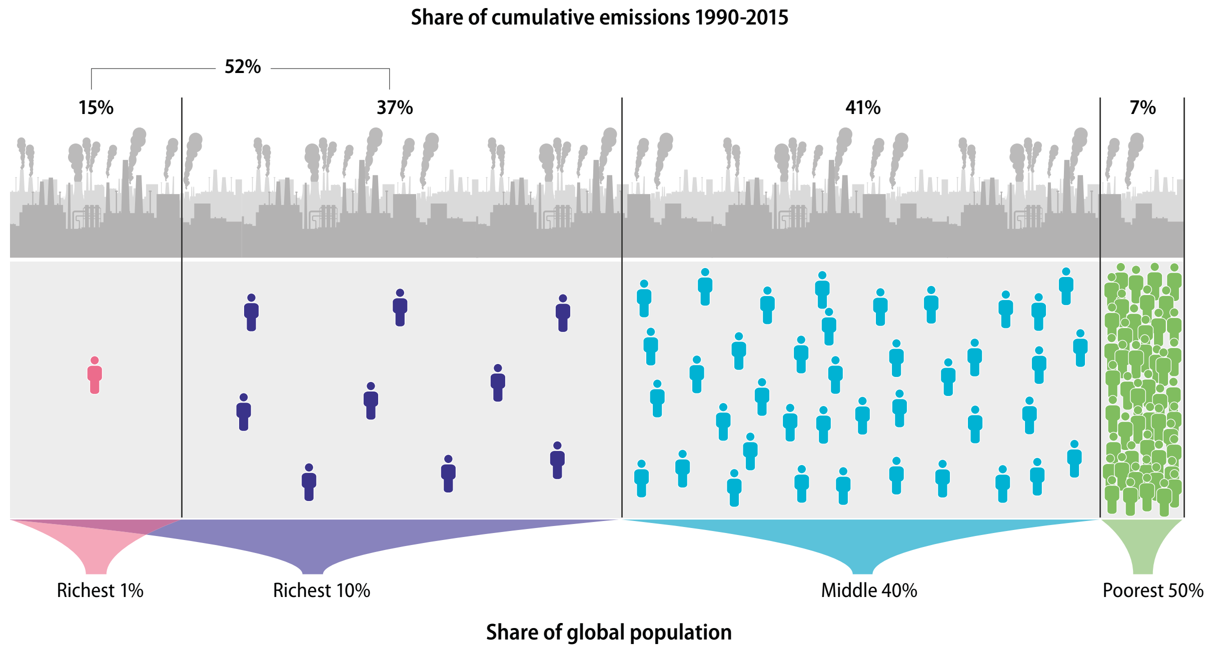


Figure 6. Share of the cumulative GHG emissions relative to the global population, in terms of wealth between 1990 and 2015. Adapted from the "Summary of headline findings from Oxfam and SEI's new research" figure in Gore, T. et al. (2020).[19]

6 Supporting household behaviour changes is a crucial but often overlooked opportunity for climate action

Key new insights

- Fighting climate change means making changes in lifestyles, particularly for the wealthy, to complement efficiency and decarbonization strategies.
- Sticking to the status quo in terms of consumption growth puts any supply-side decarbonization achievements at risk (e.g. solar deployment).
- For changes in individual behaviour to make a difference, they must be combined with mutually reinforcing changes by the public and business sectors.
- Lifestyles compatible with the 1.5°C goal can result in a "good life" for all (i.e., "1.5°C lifestyles").
- "Consumption corridors", which set the upper and lower consumption levels of acceptable individual carbon emissions, should serve as a guide.

Insights explained

Households have both a direct and indirect influence on a large share of global CO_2 emissions through their consumption patterns. Targeting these demand-side sources has been overlooked in present climate change strategies, which should better balance supply- and demand-side interventions. In order to stay within the 1.5°C target it is necessary to at least halve mean global household CO_2 emissions by 2030, with very steep reductions required for wealthy households (e.g. the wealthiest 10% in the EU will have to cut their footprint by almost 90%). Given the noticeable difference in carbon emissions between households in less developed countries and more developed countries as well as within countries, response measures will have to be targeted, guided by climate justice and equity ideals (*see Insight 5* for more). Beyond equity justifications, these high-consuming households also offer the greatest behaviour change levers for demand-side mitigation.

Stimulating new value systems and behaviour change at the household level has the potential to create system-wide effects. The emission-intensive consumption areas of food, housing and mobility need specific attention. To make the changes necessary for 1.5°C lifestyles, households will need support from the public and business sectors. Evidence suggests that this process could drive a virtuous cycle of accelerating progress towards decarbonized societies. System-wide changes, such as shifts to low-carbon energy and transport, can make it possible to provide a good quality of life while staying within the stringent individual carbon budgets of a 1.5°C lifestyle.

A concept that is helpful in defining a 1.5°C lifestyle is "consumption corridors". This is the space where the lower limit of emissions per individual is determined by the absolute prerequisites for a decent standard of living, and the upper limit is set by global emissions targets to achieve set climate goals. Moving the entire global population into this space would greatly improve life for billions while requiring significant changes to wealthy, high-consuming elites.

The COVID-19 pandemic instigated rapid and large changes in household behaviour (if not without contentious debate). This points to the possibility of achieving 1.5°C lifestyles via demand-side interventions, given a global crisis that was recognized by the public as requiring behavioural change. Importantly though, supply-side interventions must utilize democratic processes to assure that the burdens for change are equitably distributed both locally and globally.

Background

There are huge inequalities in household carbon footprint both among and within countries and regions and social groups (refer to *Insight 5* for more on the disparity in emissions globally). Demand-side solutions are those that involve households as the end users of products, services or processes. These are distinct from supply-side solutions that principally include changes in energy supply and deployment of CO_2 removal technologies. Demand-side solutions are enhanced by transdisciplinary and bottom-up actions towards climate mitigation measures globally.

! Implications

At a global level, decision makers need to:

- define equitable "consumption corridors" through democratic processes and place the burden of demand-side changes on high-emitting consumer elites.

At regional and national levels, governments are urged to:

- translate national policies to achieve the 1.5°C target into concrete measures, including creating the infrastructure needed for 1.5°C-compatible lifestyles;
- pay particular attention to solutions in areas of food, transport and housing that are of crucial relevance;
- support changes to household consumption patterns via policy and infrastructure that spur mutually reinforcing transitions.

50%
share of global carbon reductions (or more) that could come from demand-side solutions.

75%
share of demand-side solutions found to additionally have a positive impact on well-being.

2.5
tonnes of carbon per capita (half of 2020 levels) that can be emitted per household globally by 2030 to be on track.

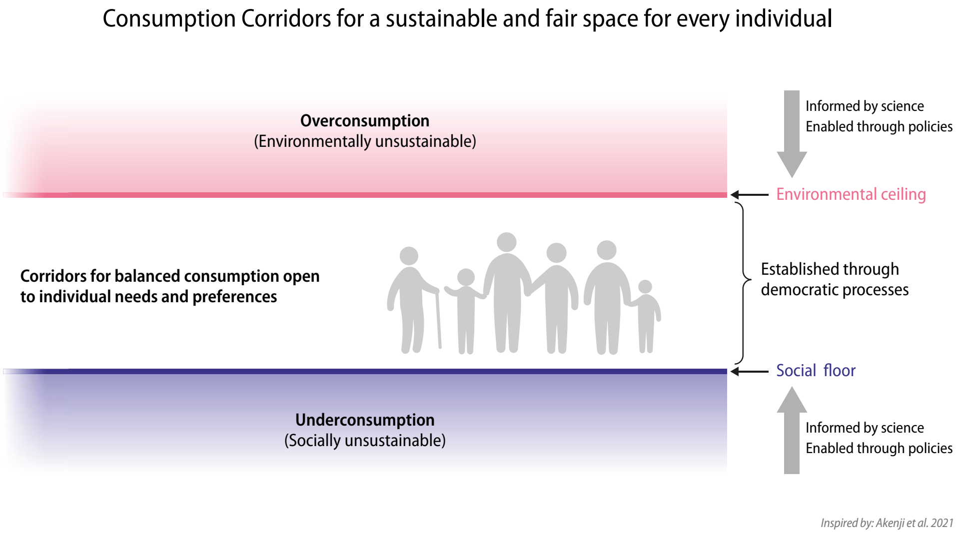


Figure 7. Conceptual illustration of consumption corridors.[20]

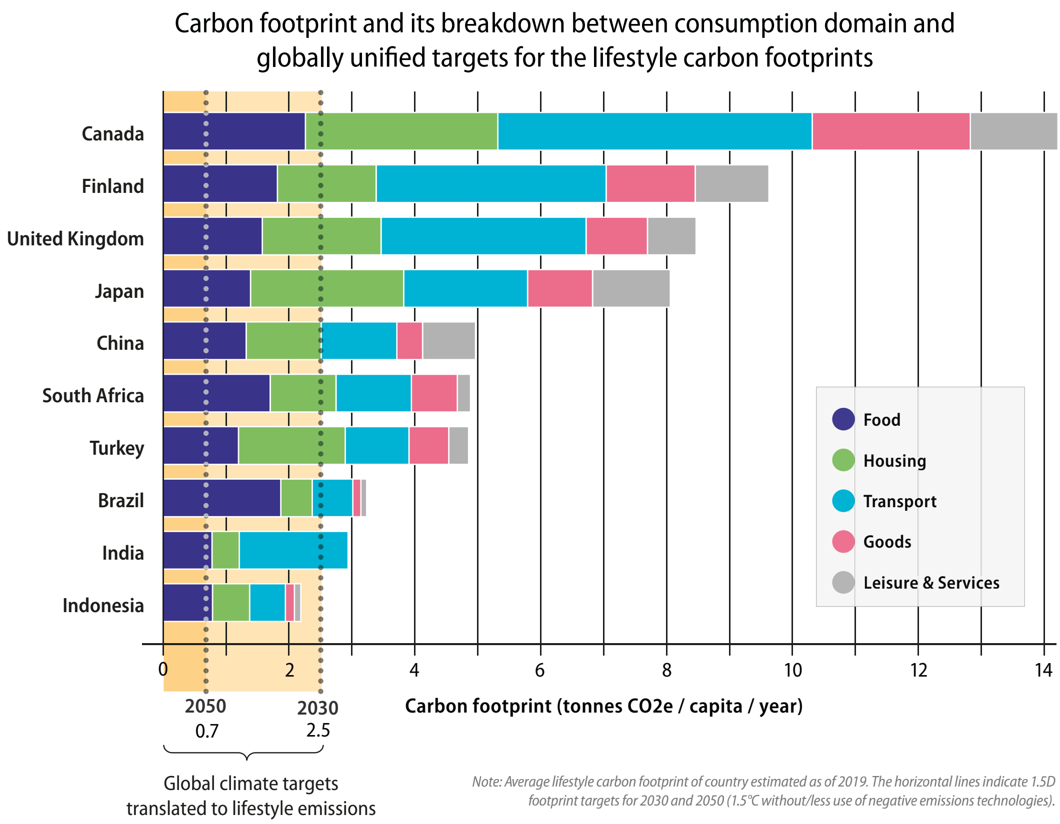


Figure 8. Current carbon footprints of different countries compared to global climate targets.[20]

Measures to reduce emissions in three key sectors

Mobility

The required footprint reductions in mobility are at least 72% in overconsuming developed countries.

Reducing individual car mobility.
Individual car mobility is one of the largest drivers of CO_2 emissions. Relying on switching cars to electric means utilizing scarce resources and locks in car-based mobility (and all its negative externalities) with investments in new infrastructures. Policies which support demand-side solutions in the mobility sector include investment in and increasing subsidies for public transport, urban and rural development which reduces the need for commuting, providing obligatory space for non-motorized transport, and establishing and enlarging congestion charge zones for individual car use.

Food

Required footprint reductions in nutrition are at least 47% in overconsuming developed countries.

Switching to plant-based diets
The best ways to achieve the necessary changes in nutrition are large reductions in meat and dairy consumption, as well as minimizing food waste. Policies that support demand-side solutions in the food sector include a removal of subsidies for meat and dairy production, financial and regulatory support for plant-based production and fostering community and urban gardening.

Housing

Required footprint reductions in housing are at least 68% in overconsuming developed countries.

Low-carbon housing can be created through efficiency and sufficiency measures.
The decarbonization strategies of thermal renovation, efficiency of heating and switching to renewables need to be accompanied by demand-side solutions reducing individual per capita living areas. Policies that support demand-side solutions in the housing sector include progressive property taxation (based on per capita levels), regulation and taxation encouraging smaller housing and a moratorium or cap on further soil sealing.

7 Political challenges impede effectiveness of carbon pricing

Key new insights

- Carbon pricing has not yet delivered substantial emissions reductions.
- To be effective, carbon prices need to increase rapidly in the near term, be sector-specific and be part of larger policy packages.
- To be publicly accepted, carbon pricing schemes need to consider equity and justice.

Insights explained

Carbon pricing policies are implemented in a steadily growing share of markets. In 2020 they covered 22% of global emissions, but only 3.76% of these are priced above 40 USD/tonne CO_2eq. The High-Level Commission on Carbon Pricing recommended that CO_2 be priced between 40-80 USD/tonne by 2020 to be consistent with the Paris Goals.[21] The limited global coverage and generally low price levels mean that carbon prices have only had a small impact on emission trajectories.

Several economic and political obstacles have been identified as causes. Carbon pricing creates short-term costs to consumers, but is perceived to only deliver future benefits. This often creates opposition, from both firms and consumers, reducing political acceptability. The result is often that prices are set too low to create substantial climate benefits, which may also fail to adequately consider climate risks and risk overrunning our collective carbon budget. Instead, some research suggests that, in the near term, carbon prices should be raised sufficiently to achieve rapid and substantial emissions reductions and then decrease over time.

A universal carbon price has been discussed but the difficulties in finalizing the rules for Article 6 of the Paris Agreement, which creates new global mechanisms for carbon trading, are evidence of the political challenges of this approach. Sector-based carbon prices and border tax adjustments could help overcome some resistance. However, border tax adjustment policies will raise new political and economic challenges for trade, particularly for some low- and middle-income countries, and there are important equity implications.

There are also intrinsic limitations to carbon pricing as a mechanism. Carbon pricing can be regressive and impact poor households more than the rich, even if the former use less energy. This can be balanced through redistribution schemes, making sure that revenues from carbon taxes benefit low-income groups. Another limitation to the effectiveness of carbon pricing is that a large share of the world's emissions comes from maintenance and use of large-scale infrastructures, with lock-in effects and long lead times, leading to low price elasticity. In addition, carbon pricing has been found to mainly drive efficiency improvements and fuel switching but have limited effect on decarbonization. Therefore, carbon pricing should only be seen as one tool among many for green transitions.

Background

In order to apply the "polluter pays" principle and internalize the negative externalities of climate change, academics and policymakers have long championed carbon pricing. Carbon pricing may take the form of carbon taxes, which levy a price per tonne of carbon emitted, or an emissions trading scheme (ETS), where carbon allowances are traded. Economists view carbon pricing as efficient, since companies have flexibility in deciding how to meet the reduction requirements set by governments.

! Implications

At a global level, decision makers need to:

- apply carbon prices to a larger share of global emissions and the prices must be high enough to stimulate significant decarbonization;
- acknowledge the diversity of economic and political circumstances, rather than seeking a global carbon price. Sector-based carbon pricing can address potential competition challenges.
- control the use of carbon offsets carefully and reduce fossil fuel subsidies quickly, for carbon pricing to be effective.

These implications are also very relevant at a national level.

At a national level, governments should:

- use or refund revenues from carbon taxes in a transparent and fair manner, including to lower other taxes, fund public goods and climate investment, to avoid regressive effects and to increase acceptance;
- use carbon pricing only as one policy in "bundles" of climate policy instruments to drive transformative decarbonization.

137
USD per tonne, highest national carbon price currently globally available.

61
countries with carbon pricing.

+800
companies adopting internal carbon prices.

22%
of global emissions covered by a carbon price.

61 countries have set a price on carbon

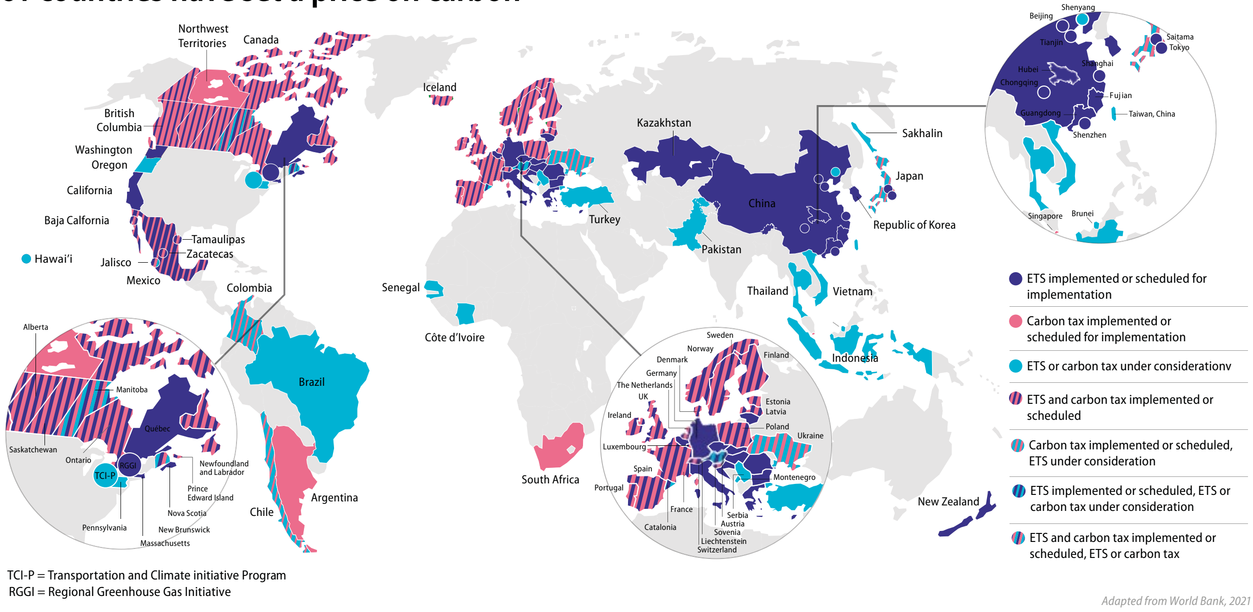


Figure 9. The map shows territories that have implemented or plan to implement a price on carbon, as a carbon tax, emissions trading scheme (ETS) or a combination of both.[22]

Spotlight: Important carbon-pricing schemes

EU ETS

The European Union ETS covers approximately 40% of EU emissions.[23] It plans to implement a "carbon border adjustment mechanism" which will levy a fee on imports from jurisdictions without a carbon price.[24]

China ETS

The world's largest emitter, China, launched an ETS in 2021 which covers 40% of national emissions focused primarily on the power sector.[25]

CORSIA

The 2015 aviation emissions agreement (CORSIA) will create a new demand for carbon offsets – between 142 and 174 Mt CO_2 in 2025.[26]

Article 6 of the Paris Agreement

Two new market mechanisms will be created through the Paris Agreement. Article 6.2 creates a framework for countries to trade emissions reductions activities (i.e. "internationally traded mitigation outcomes"), while Article 6.4 allows countries to purchase emissions reductions compared to an emissions baseline through a "sustainable development mechanism", similar to the Kyoto-based Clean Development Mechanism. The rules for both mechanisms are still being negotiated.

8 Nature-based Solutions are critical for the pathway to Paris – but look at the fine print

Key new insights

- Nature-based Solutions (NbS) can offer multiple benefits to climate, ecosystems and societies, but must not replace or delay decarbonization efforts in other sectors.
- With further warming, Earth System feedbacks may increasingly destabilize ecosystems and undermine the long-term mitigation potential of NbS.
- Investing in NbS now to protect biodiversity will make them more climate resilient and strengthen their ability to act as long-term carbon sinks.
- Much potential for NbS is situated in the less developed and developing countries and in areas inhabited by indigenous peoples who often have limited land rights. Effective decentralized governance and robust regulation and finance can be particularly challenging in these contexts.
- To successfully include NbS in National Determined Contributions (NDCs) and effectively implement policies and direct funding, comprehensive metrics and monitoring, reporting and verification (MRV) are needed that include biodiversity, ecosystem services and local livelihoods, alongside carbon sequestration.

Insights explained

Recent findings highlight that NbS, next to opportunities for CO_2 removal, contribute considerably to climate adaptation and risk mitigation. Positive effects include flood control, increased resilience to droughts, biodiversity conservation, socio-economic development and improvements to human health and wellbeing. See Insight 10 for more on the benefits of NbS.

One expectation for NbS – offsetting residual emissions – has been set into context within the scientific debate. Scenarios that limit warming to 1.5°C are based on significant assumptions: full decarbonization within 30-40 years, shifting agriculture from carbon source to sink, considerable CO_2 removal and maintained resilience of natural ecosystems. Well-designed NbS play a pivotal role – not as a means to delay the phase-out of fossil fuels, but as a much-needed supplement that can contribute to a range of Sustainable Development Goals (SDGs). Importantly, further warming risks altering Earth System feedbacks and destabilizing ecosystems, which may undermine the long-term mitigation contribution of NbS and their benefits to people and the planet. Evidently, this makes rapid decarbonization ever more urgent, and highlights the need to strengthen the resilience of ecosystems through protection and restoration (see *Insight 9*).

At COP26, parties have an opportunity to address questions of equity and procedural justice that are central to the success of NbS. While cumulative emissions predominantly come from more industrialized countries, much of the carbon-saving potential of NbS has been identified within less industrialized countries, particularly in areas occupied by indigenous communities with insecure rights. There is a risk that NbS could shift the responsibility for decarbonization onto vulnerable communities if there is insufficient regulation.

Background

NbS are systems-based approaches to societal challenges such as climate change, biodiversity loss, and social inequality. They are actions that protect, restore and better manage natural or modified ecosystems. Research has shown that NbS can provide relatively low-cost and readily available opportunities for CO_2 removal compared to other options. But more than that, well-designed and implemented NbS can deliver multiple benefits for climate change mitigation and adaptation, biodiversity conservation and local livelihoods. Under the mitigation umbrella, however, parties to the UNFCCC increasingly fund the expansion of plantations with non-native species, even though they remove little carbon and place local livelihoods and ecosystems at risk, especially in non-forested ecosystems.

! Implications

Fulfilling the Paris Agreement requires rapid emissions reductions in tandem with well-designed CO_2 removal, including NbS. COP26 is an opportunity to align the goals and procedures of the United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity, for instance by adjusting metrics and MRV for NbS.

At a global level, it is suggested that parties at COP26:

- set clear reporting guidelines under Article 6 of the Paris Agreement, as NbS are increasingly included in NDCs. These should be based on comprehensive performance metrics for climate, biodiversity and livelihood outcomes, as well as science-based and transparent MRV;
- tackle the disproportionately small share of NbS in mitigation finance and lack of appropriate multilateral finance and governance structures.

At a national and local level, policymakers must:

- regulate NbS to avoid shifting the responsibility for decarbonization onto vulnerable communities.

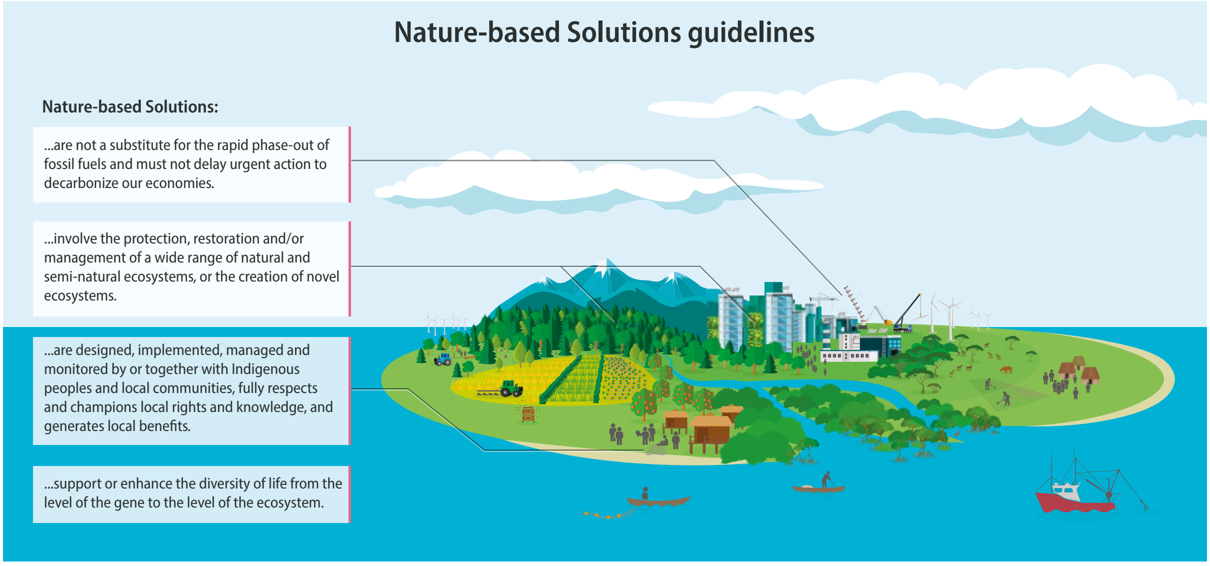


Figure 10. Four guidelines for Nature-based Solutions.[27]

Extreme events threaten the climate-mitigation potential of forests

- Wildfires have become more extreme both in intensity and frequency, and are burning now in regions that are not typically prone to wildfires. While normal wildfires are often assumed to be "net zero" with regard to CO_2 emissions (all CO_2 emitted would be taken up by regrowing vegetation), the more frequent occurrence of megafires that burn very large areas (*Insight 3*) is now likely to change this balance due to ecosystem degradation.
- Events such as the 2015/2016 El Niño caused an extreme and prolonged drought, which fuelled extensive and damaging fires. This put some regions of the Amazon under such pressure that plant mortality rates remained elevated for 2-3 years after the event – particularly where forests had already been modified by human activities.
- Even though the net biome exchange of carbon with the atmosphere in most parts of the Amazon still works as a carbon sink, the effects from fire in association with other environmental changes have already turned large parts into an effective net source of carbon to the atmosphere. The south-eastern part of the Amazon basin, particularly, is a net carbon emitter even if the effect of fires is ignored. Here, temperatures during the dry season have strongly increased, precipitation has decreased and deforestation has been especially severe.

These effects reduce the climate-mitigation potentials of forests and other vegetation prone to fires. This needs to be taken into account when assessing the effect of forest-related NbS on CO_2 emissions. In the case of the Amazon, wildfires contribute to potentially triggering a climate regime shift towards an open and degraded state in some parts of the basin (*Insight 4*).

9 Building resilience of marine ecosystems is achievable by climate-adapted conservation and management, and global stewardship

Key new insights

- The oceans play a key role in regulating the Earth's climate. Protecting the oceans as a carbon sink, including marine sediments and vegetation that bind substantial carbon stocks ("blue carbon"), is an important climate change mitigation action.
- Integrated, tailored and innovative solutions are needed to preserve ocean ecosystems threatened by accelerating climate change and other anthropogenic pressures.
- There is a growing recognition of the importance of integrated governance in building ocean resilience by:
  - involving all levels from local to global as well as the private sector;
  - providing clear targets, strong actions and global stewardship.
- When expanding the global marine protected area (MPA) network, climate-smart adaptation measures need to include areas with climate refugia, hotspots of change, migration corridors, biodiversity havens as well as addressing damaged areas in need of recovery.

Insights explained

Marine biodiversity is fundamental for well-functioning ecosystems ("healthy oceans") that provide essential services and benefits for human societies. The latest projections from the Working Group I contribution to the IPCC AR6 indicate that several climate-induced anthropogenic pressures such as ocean warming, marine heat waves, ocean acidification and melting of the Arctic and Antarctic ice sheets will continue to worsen under all emissions scenarios.[8,28] Improving or restoring marine life will only be possible if climate change and other anthropogenic pressures are mitigated.

With effective coordinated multi-level protection, the oceans offer triple benefits: unique biodiversity preservation, seafood provision and carbon storage. Substantially restoring key components of marine ecosystems by 2050 will be very challenging but recent findings indicate this is still achievable. Urgently, this requires new integrated, targeted and innovative solutions of ecosystem conservation and management. Ocean stressors generally do not occur in isolation, requiring management strategies that address cumulative effects. This includes cumulative-impact assessment and ecosystem-based management, which consider major interactions within an ecosystem, including those involving humans.

Effective conservation management should be guided by ocean governance that is flexible and iterative, coordinated across different levels and responsive to shifting ecological and climate dynamics as well as social norms. This is a vital requirement for effective biodiversity protection and marine ecosystem recovery. Policymaking should be inclusive and adaptive; set clear targets with respect to timelines, actions, and goals; and facilitate global stewardship of the oceans. Some targets and actions that were successful in the past include exploitation bans and restrictions, endangered species legislation, habitat protection and restoration and invasive species and pollution controls.

Another necessary management component is to strive for climate-smart conservation addressing how climate change affects marine species, ecosystems, management targets and conservation efforts. It can provide climate adaptation by building resilience into the global network of MPAs.

This works by incorporating climate refugia with little projected change, areas of high environmental change and species turnover with rapid evolution potential, hotspots of thriving as well as threatened biodiversity and corridors for migrating species. Expanding the MPA network could yield 90% of maximum potential biodiversity benefits if 21% of oceans would be protected by the network, including mainly national exclusive economic zones (43%) and part of the high seas (6%) that are currently largely unprotected.

If anthropogenic pressures on marine ecosystems can be contained and restoration efforts are applied, most marine species and habitats will require one to three decades to return to an undisturbed state or to allow for sustainable fishing.

Background

The oceans, the largest ecosystem in the world, are a key element in the Earth and climate system. Some of their most important functions include their capacity to buffer heat, store carbon and provide food. Currently, about 17% of global animal protein consumption is provided by the oceans, which is likely to increase with expanding global food demand. SDG 14 ("life below water") aims at conserving the oceans and ensuring sustainable use of their resources. Many of the indicators that investigate the progress of SDG 14 show that we are not on track: for example, marine litter and ocean acidification are increasing, the expansion of the MPA network to 10% by 2020 failed and several countries have not yet fully implemented international law as reflected in the United Nations Convention on the Law of the Sea to adapt to a global ocean governance system. The United Nations Decade of Ocean Science for Sustainable Development (2021-2030) now provides a chance for countries to reach SDG 14 and other SDGs that rely on a "healthy ocean".

! Implications

At a global level, decision makers need to:

- strategically strengthen the global Marine Protected Area (MPA) network (current international efforts aim at expanding the global MPA network from 7.7% to 30%) by:
  - ensuring proper representation of diverse habitats and marine biomes;
  - including corridors enabling connectivity between habitats and species movement;
- protect blue carbon stocks beyond national jurisdictions (e.g. deep-sea sediments), which requires internationally coordinated efforts;

- develop a multi-level ocean governance system to overcome the growing challenges in marine management and conservation that:
  - acknowledges the interconnectedness of the ocean as a whole; and,
  - is coherent, responsive and adaptive to rapidly shifting ocean dynamics in time and space to allow for rapid decision-making despite uncertainty.

At a regional and local level, governments need to:

- consider important features in sustainable management and restoration efforts including:
  - context-specific evidence-based solutions, underlying socio-ecological dynamics and connecting ocean health to human health;
- deal with accelerating pressures and balance resource use with the protection of biodiversity and ocean ecosystem health. These efforts must be informed by:
  - marine spatial planning, ecosystem-based management and climate-smart conservation;
- shift currently often fragmented and disconnected ocean governance to a reflexive and inclusive multi-level governance system, which would facilitate more informed policy over time as well as increased cooperation between actors at different scales across policy levels.

93%
excess heat in the Earth's climate system, as a result of increased GHG emissions from human activities, that is taken up by the ocean. About one quarter of anthropogenic greenhouse gas emissions are taken up by the oceans (and another quarter by the land).

7.7%
of the world's oceans that are protected via the MPA network, failing by 2.7% to reach the Aichi Biodiversity Target. A novel framework to set new goals is expected to be adopted in autumn 2021.

17%
of global animal protein consumption is provided by the oceans, which is threatened by global warming. Fish stocks are projected to decline in some areas by up to 40% in the high-emission scenarios.

34.2%
of fish stocks are overexploited.

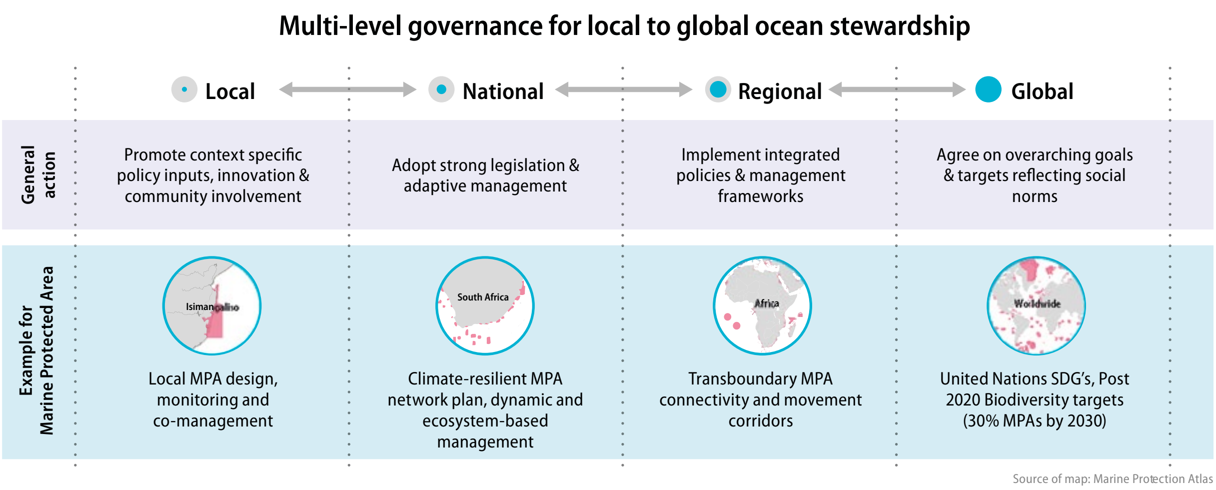


Figure 11. How ocean governance should work on different levels (local, national, regional and global) with examples of how this could work while implementing MPAs.

Strengthening the resilience of marine ecosystems through protection and restoration as an NbS

Capturing blue carbon, the carbon that is stored and sequestered in marine sediments and coastal vegetation, is a substantial contribution to climate-smart conservation. The protection of blue carbon stocks is an important NbS and climate-mitigation action, with co-benefits for biodiversity protection. Blue carbon stocks located in Australia alone save about US$23 billion annually in climate-mitigation costs worldwide, but are threatened by global warming and other anthropogenic pressures.[29] The lack of protection of marine sediments makes their substantial carbon stocks highly vulnerable to human disturbances such as seafloor trawling and seabed mining. Around aqueous 1.47 $GtCO_2$ emissions, equivalent to about 15-20% of total atmospheric CO_2 absorbed by the oceans each year, are bound in marine sediments.

Spotlight: The oceans are in a dire state

Climate change and other anthropogenic pressures have continuously been threatening the oceans and their health. Among those pressures are ocean warming, marine heatwaves, acidification, marine pollution, deoxygenation, exploitation and mining. Most of these pressures are threatening the marine food web and thus food security, by degrading habitats or directly affecting a diverse range of marine species. Today, more than 1,300 marine species are threatened with extinction, 34.2% of fish stocks are overexploited, most ocean areas experience cumulative impacts of several of the above-mentioned pressures and one-third to half of vulnerable marine habitats have been lost. While efforts have been undertaken to reduce, for instance, pollution by reducing the amount of nutrients (eutrophication – an increased amount of nutrients that leads to excessive algal blooms) or toxins, many pressures will continue to threaten marine ecosystems. Among those are **ocean warming** and marine heat waves. Both have contributed to habitat degradation such as coral bleaching. According to the Working Group I contribution to the IPCC AR6, about 83% of the ocean's surface is very likely to continue warming during the 21st century even under low-emissions scenarios.[30] **Marine heatwaves**, prolonged periods in which the ocean's surface temperature are anomalously high, are not just occurring more often – their frequency has doubled since the 1980s – but they have also become more intense and last longer. The Working Group I contribution to the IPCC AR6 shows that this trend is likely to continue under most of the emissions scenarios in the future.[28] Projections with high confidence show furthermore that the oceans will continue to acidify both in coastal and in open ocean regions under all emissions scenarios.[30] **Acidification**, the reduction of the ocean's pH, is a result of the ocean's uptake of atmospheric anthropogenic CO_2. If emissions of CO_2 are not reduced, the capacity of the oceans to take up CO_2 from the atmosphere will not be as effective anymore, which will further intensify global warming.

Ocean pressures also act cumulatively. One example is ocean **deoxygenation**. Due to warming and excessive nutrient input, the oceanic oxygen content has demonstrably declined since around 1960, leading to an expansion of oxygen-minimum zones and more frequent hypoxia (events of very low oxygen in the water column) in coastal systems ("dead zones"). Predicting how hypoxia will develop in the future is challenging due to limited mechanistic understanding. For instance, coastal hypoxia could decrease with less anthropogenic nutrient input;[8] however, nutrients dissolved from deoxygenated sediments may refuel algal blooms that would further reduce oxygen in the water column.

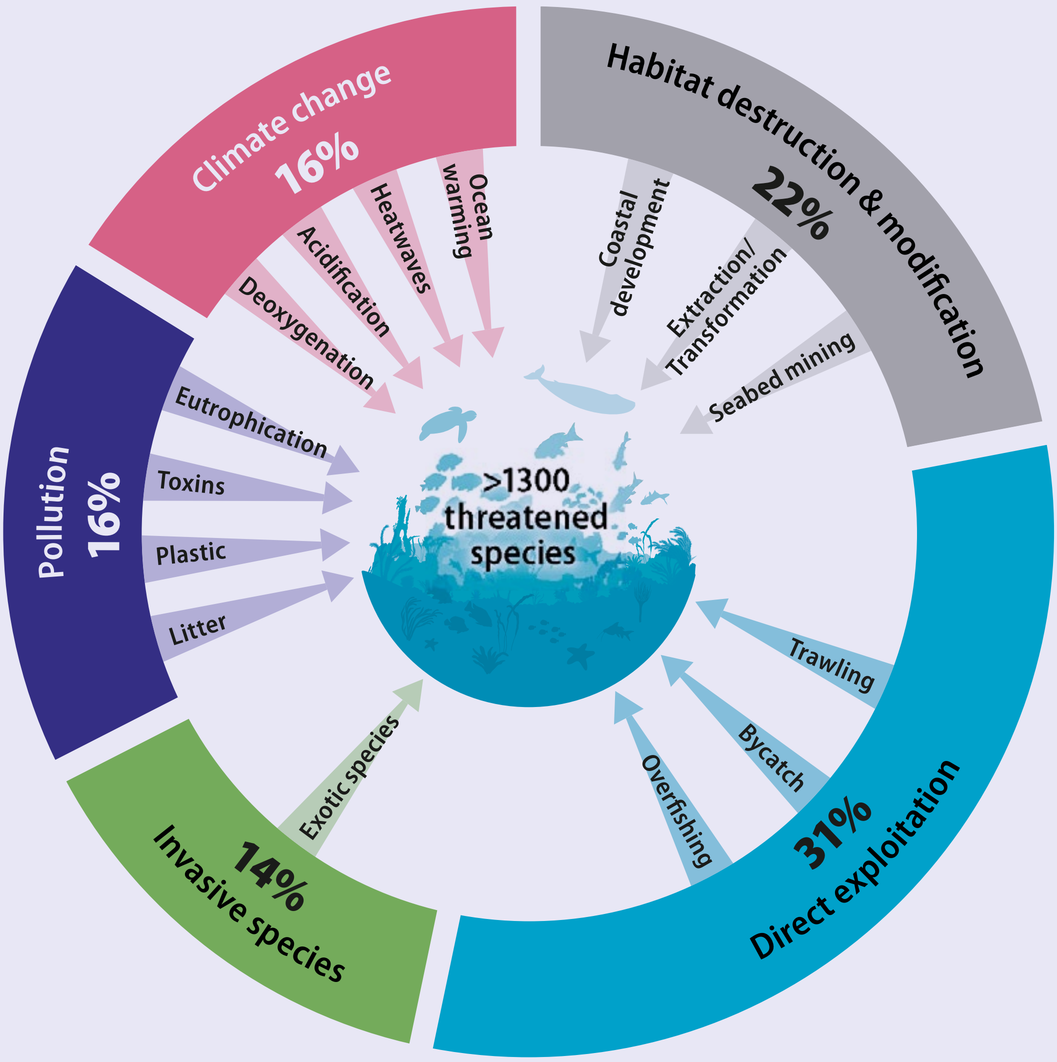


Figure 12. The percentage of all vulnerable, endangered or critically endangered marine species that are threatened by different anthropogenic impacts including climate change (references can be found in Martin et al., 2021). Boxes show selected individual pressures. The circle in the middle represents the marine ecosystem.

10 Costs of climate change mitigation can be justified by the multiple immediate benefits to the health of humans and nature

Key new insights

- Benefits of mitigation to human health and nature accrue before the benefits of mitigation are apparent.
- Health benefits are of higher economic value than the cost of mitigation policies.
- Rapid emission reductions are needed across all sectors; adopting the right policies can make a big difference to health and wider environmental benefits.
- The value of health co-benefits can justify rapid scaling up of mitigation policies and technologies, and thus accelerate progress towards a zero-emissions economy.

Insights explained

The increasingly intensive emissions of GHGs that cause human-induced climate change have negative health effects on humans and the natural environment. Estimates of the costs of mitigation (e.g. with renewable energies, active transport or NbS) are comparable to or lower than the full economic value of saved lives and reduced illness and protecting or restoring the natural world. In other words, investments in mitigation are well worth making and will save communities and countries money in the long term. Biodiversity losses lead to losses in ecosystems and their corresponding contributions to humans. These losses include reduced crop yields and fish catches, losses from flooding and erosion and loss of potential new sources of medicines. Furthermore, many of the co-benefits to human health and nature take place shortly after mitigation investments are made (e.g. when reducing CH_4 emissions).

Without immediate investments in emissions reduction, it will not be possible to fully protect and enhance the resilience of those who are most at risk from the health impacts of climate change, many of whom already face increasing health inequities. Failing to act swiftly will enlarge the social gap not only among low-, middle- and high-income countries but also within countries. There are trade-offs to manage, including job losses in certain industries compared to job gains in others. Importantly, a transition to a less polluting and healthier society must consider the importance of a diversified and context-specific approach. This indicates that the distribution of benefits is as important as the magnitude of the benefits.

Background

Improvements in health and economic data availability, including in low- and middle-income countries, have strengthened the science of climate change mitigation and its resulting health co-benefits. Advancements in the understanding of the drivers of health impacts resulted in a shift from improvements in technological efficiency, which in turn led to increased energy consumption, to a systems approach that recognizes the impact of human activity on the health of humans and nature. To date, there are examples relevant to all sectors that can support decision makers to incentivize transitions in transport, agriculture, forestry, food production, energy, industry and lifestyles that ensure Planetary Health in All Policies (PhiAP).

While the drivers and solutions are increasingly becoming well known, the economic benefits are not yet always well understood. More research is needed to develop frameworks that systematically define indicators of health co-benefits, to better be able to compare across studies, and to understand how they can be consistently reflected in economic terms.

! Implications

At a global level, decision makers need to:

- adopt a PhiAP approach to better leverage health benefits when developing policies as well as reducing the emergence of health risks;
- raise awareness of the health co-benefits and associated economic savings to increased climate-change mitigation investments in low-, middle- and high-income countries;
- support countries to assess the health costs and benefits of mitigation action (or inaction).

At a national level, governments are urged to:

- stop direct and indirect support of activities that harm health, harm natural systems and increase greenhouse gas emissions, e.g. conventional approaches to infrastructure development including in transport and energy. Instead, take on an approach that incorporates health and climate mitigation;
- carefully design mitigation and adaptation interventions so that they promote healthy ecosystems, lower public health risks and save costs while minimizing trade-offs;
- invest in conserving, restoring, rewilding and improving the management of forests, grasslands, wetlands and agricultural lands because they could deliver an estimated 23.8 $GtCO_2$ cumulative emissions reductions by 2030.[31] Substantial carbon is also stored and captured by marine ecosystems (see *Insight 9*).

Individuals should consider:

- taking immediate action, such as insulating their homes to lower their energy consumption, buying from sources that do not harm nature and choosing sustainable energy and food providers if they have the options available;
- reducing meat consumption to prevent cardiovascular disease as well as to reduce methane emissions that are contributing to climate change (applies mainly in wealthy countries);
- taking on an active travel approach with walking, cycling or public transport to maintain their health and that of the environment. Car sharing is a good alternative to conventional ownership.

6.67 million

annual deaths caused by air pollution.

Every million

tonnes (Mt) of methane reduced:

- prevents approximately 1,430 annual premature deaths due to ozone globally;
- increases yields with 55,000 tonnes of wheat, 17,000 tonnes of soybeans, 42,000 tonnes of maize and 31,000 tonnes of rice annually;
- avoids the annual loss of roughly 400 million hours of work, approximately 180,000 years, globally due to extreme heat.[35]

2.2 years

reduction in average life expectancy due to $PM_{2.5}$ exceeding the World Health Organization guideline.[4]

23.8 $GtCO_2$

emissions reductions by 2030 that can be made when conserving, restoring and improving the management of forests, grasslands, wetlands and agricultural lands.

A study

on Brazil, China, Germany, India, Indonesia, Nigeria, South Africa, the UK and the USA showed that investing in mitigation can reduce:

- 1.18 million air pollution-related deaths,
- 5.86 million diet-related deaths and
- 1.15 million deaths due to physical inactivity in the countries stated above by 2040.

70%

of cancer drugs are natural or inspired by nature.[34]

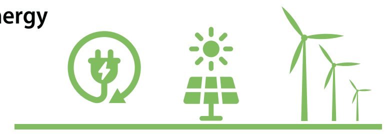
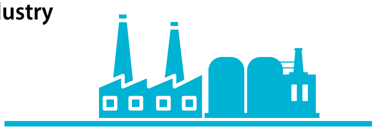
Transportation 	Shorter travel distances, reduced car use and more active travel through better urban planning and electrification of the remaining vehicles can benefit health through reducing air pollution, noise pollution, traffic injuries and physical inactivity.
Agriculture, forestry, and food 	Prevention of biodiversity losses can protect human health and global critical ecological systems. Climate change mitigation would also prevent losses in nutritional value in crops from climate change. Reduction in red meat intake would reduce cardiovascular disease and corresponding methane emissions.
Energy 	Across different scenarios, depending on the scale and context, shifting to renewables and bioenergy have quantified co-health benefits that exceed mitigation costs. Insufficient evidence exists on the scalability of carbon capture and storage technology.
Industry 	Changes in material flows, improved efficiency, and changes in production methods and technologies are associated with health economic co-benefits.
Lifestyle 	Individual's lifestyle choices such as investing in insulation, divesting from fossil fuels, and making overall choices in line with strong sustainable principles can provide health and ecosystem co-benefits. These choices are strongly influenced by policy settings.

Figure 13. Examples of how improvements to the health of humans and nature can be achieved by directed policies in key sectors.

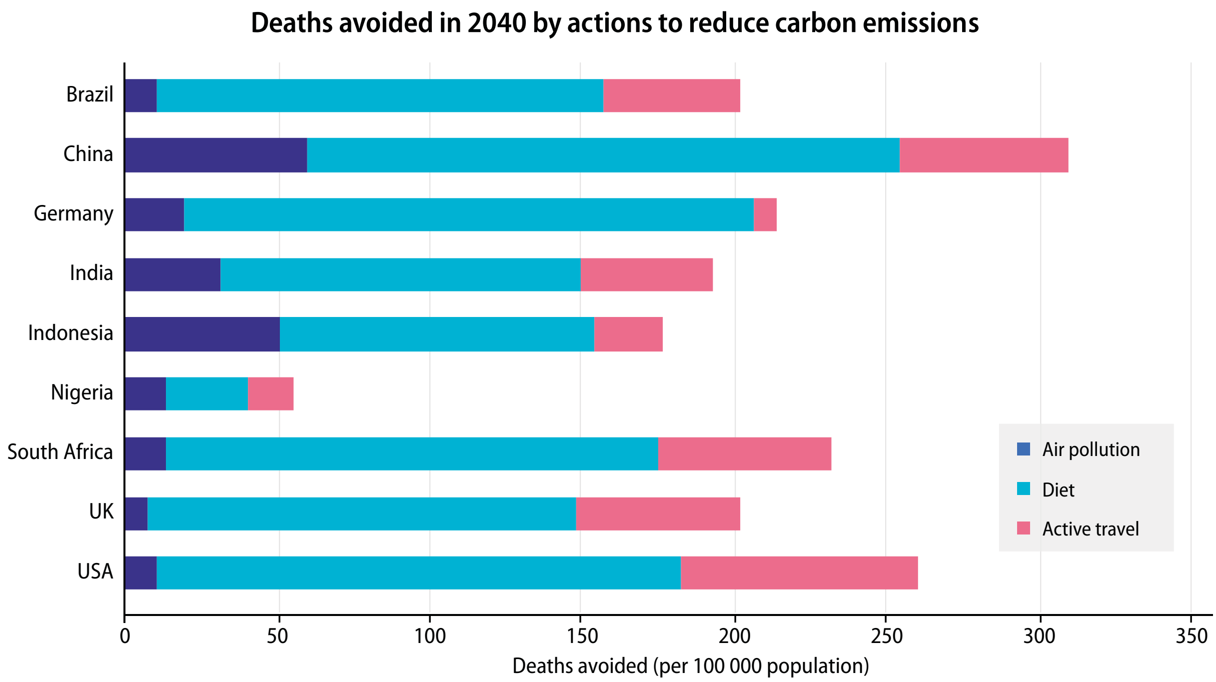


Figure 14. Premature deaths that can be avoided in 2040 based on integrating health in all climate policies. Adapted from Hamilton et al. (2021).[32]

London, United Kingdom

Retrofitting urban planning for low traffic neighbourhoods in London has shown reductions in car ownership and use, plus large increases in physical activity, reductions in injuries and reductions in street crime. This is a low cost (placing planters and cameras), equitable and scalable intervention, covering over 300,000 people in 6 months with hopeful implications for health and climate.[36,37,38]

New South Wales, Australia

A farmer in Australia reported ecosystem co-benefits when engaging in regenerative farming practices as part of a climate-change mitigation strategy. The Australian farmer who participated in the study estimated that his costs were 80% lower since transitioning to regenerative ranching compared to conventional practices due to eliminating chemical fertilizer and insecticides and reducing fuel costs.[39]

Flanders, Belgium

The Sigma Plan in Belgium is a long-term landscape project that improves water safety (the plan provides controlled flooding to increase resilience from weather extremes for local communities and nearby cities). Concurrent to water safety, it also focuses on the development of river nature, recreational facilities and local economies directly providing NbS for the health of humans and nature.

Definition of terms

Biome:
A biome is a large area that is characterized by specific vegetation, climate and wildlife. Examples of terrestrial biomes are forests or grasslands. Lakes or rivers are examples of freshwater biomes, and coral reefs or estuaries are examples of marine biomes.

Carbon footprint:
A carbon footprint of a household (alternately called household CO_2 emissions) is defined as GHG emissions (expressed as CO_2 equivalent (see definition below)) directly emitted and indirectly induced due to household consumption.

Carbon pricing:
Carbon pricing refers to setting an economic price on emitting or storing a quantity of CO_2 or other greenhouse gases. It is typically measured in USD/tonne CO_2eq (or other currency). This refers to US dollars per 1 tonne of a CO_2 equivalent (see definition below).

Climate refugia:
Areas with natural buffers from the effects of a changing climate relative to their surroundings.

Consumption corridors:
Consumption corridors are a concept used to define the space between the minimally (fulfilling basic needs) and maximally (carbon budget and other factors) acceptable consumption, relative to the 1.5°C target, within which individuals may choose their lifestyle.

CO_2 equivalent (CO_2eq):
A CO_2 equivalent is used to compare the radiative forcing (see definition below) of different greenhouse gases. It is calculated from the global warming potential (GWP), which is the heat absorbed by a greenhouse gas equivalent to a multiple of the heat absorbed by the same mass of CO_2. The CO_2eq refers to the amount of CO_2 that warms the Earth as much as a certain amount of a greenhouse gas (GWP times the amount of gas) over a given time period. CO_2 has a GWP of 1.

Fire regime:
A fire regime is the pattern, frequency and intensity of the bushfires and wildfires that prevail in an area over long periods of time.

Global carbon budget:
The (remaining) global carbon budget sets the limit on cumulative emissions of carbon dioxide (CO_2) to not exceed a given global temperature increase with a specific probability. From 2020 onwards the global carbon budget is currently estimated to be only 460 GtCO_2 to achieve the 1.5°C target.

$GtCO_2$:

Gigatonnes (Gt) is a unit of mass. One gigatonne of CO_2 corresponds to one billion tonnes of CO_2 (equal to about 200 million elephants).

NDCs:

National Determined Contributions. Citing the UNFCCC website: "Nationally determined contributions (NDCs) are at the heart of the Paris Agreement and the achievement of these long-term goals. NDCs embody efforts by each country to reduce national emissions and adapt to the impacts of climate change."

Radiative forcing:

The immediate effect of a GHG, other pollutant or other factor on the radiation balance of Earth is called radiative forcing. It could be warming, such as the absorption of heat radiation by methane, or cooling, as with aerosols that influence the formation of clouds.

SDGs:

The 17 Sustainable Development Goals, adopted by the United Nations member states in 2015, intend to provide a "blueprint for peace and prosperity for people and the planet, now and into the future".

The 1.5°C target:

The Paris Agreement of 2015 set the limit for long-term global warming above pre-industrial levels to well below 2°C, aiming at 1.5°C.

Tipping element:

Tipping elements are components of the climate system that face the risk of undergoing dramatic and non-linear transitions at varying timescales, often without a chance to turn back to normal for a long time.

Value of a statistical life:

The value of a statistical life (VSL) is the local trade-off rate (in monetary terms) between fatality risk and money. VSL serves as both a measure of the population's willingness to pay for risk reduction and the marginal cost of enhancing safety. It's noteworthy that estimates of VSL vary greatly across countries and that it is commonly used by transport planners.

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Except when specifically stated otherwise, all statements in this report refer to the article:

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