Climate change: Strategies for mitigation and adaptation

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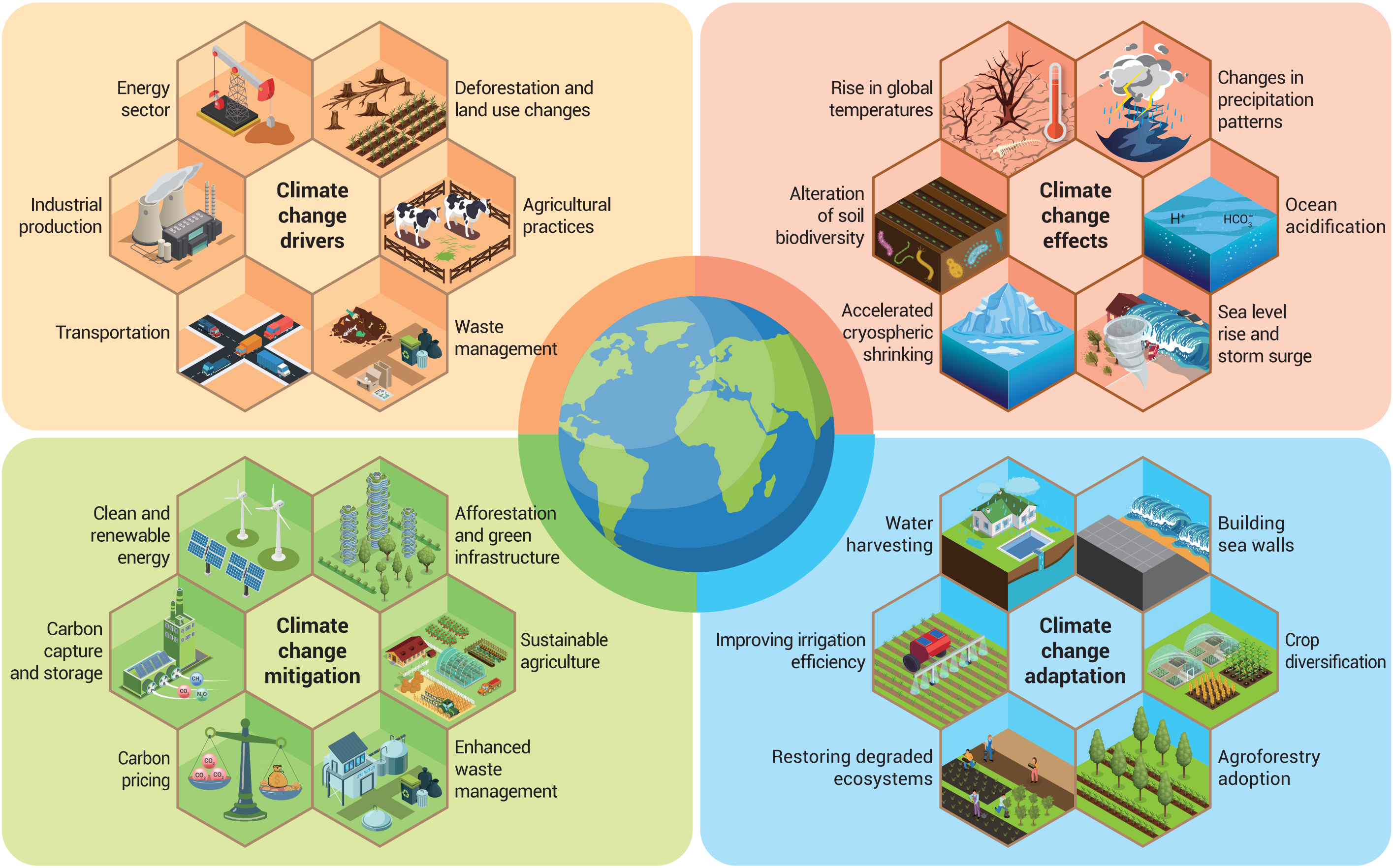
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Climate change is accelerated by anthropogenic greenhouse gas emissions, and its effects are increasingly felt globally.
- Transitioning to renewable energy sources and enhancing carbon sinks are crucial steps in mitigating climate change.
- Adaptation to climate change requires a combination of strategies that foster resilience in local communities and ecosystems.
- Carbon quantification, modeling, and pricing are key areas that need to be further developed to address climate change.
- This review discusses the current status and prospects of global climate change, focusing on mitigation and adaptation strategies.

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The sustainability of life on Earth is under increasing threat due to human-induced climate change. This perilous change in the Earth's climate is caused by increases in carbon dioxide and other greenhouse gases in the atmosphere, primarily due to emissions associated with burning fossil fuels. Over the next two to three decades, the effects of climate change, such as heatwaves, wildfires, droughts, storms, and floods, are expected to worsen, posing greater risks to human health and global stability. These trends call for the implementation of mitigation and adaptation strategies. Pollution and environmental degradation exacerbate existing problems and make people and nature more susceptible to the effects of climate change. In this review, we examine the current state of global climate change from different perspectives. We summarize evidence of climate change in Earth's spheres, discuss emission pathways and drivers of climate change, and analyze the impact of climate change on environmental and human health. We also explore strategies for climate change mitigation and adaptation and highlight key challenges for reversing and adapting to global climate change.

INTRODUCTION

Climate change and environmental destruction are interconnected threats to the future of our planet.[1] These have arisen because, among others, the growing global population is preoccupied with the current race for development, often overlooking the drastic changes in natural systems and their associated consequences.[2] In fact, since the Industrial Revolution, natural resource extraction and the use of fossil fuels have been the backbone of global economic systems, and urbanization, intensification of agriculture, and other land-use changes have prevailed over forestation, leading to widespread environmental change.[3] Notably, burning fossil fuels for transportation, electricity, and heating has increased greenhouse gas (GHG) emissions and affected global temperature and precipitation patterns.[4] The average global temperature in 2022 was about 0.86 °C higher than the 20th-century average (13.9 °C) .[5] This was the 46th year in a row (since 1977) that global temperatures have exceeded the 20th-century average. Moreover, the precipitation pattern has changed globally. Climate change is now a pressing concern, and its effects are manifesting around the world in the form of severe weather events and related disasters, including forest fires in Australia and the United States,[6,7] accelerated melting of high-latitude ice sheets, and sea-level rise,[8] alterations of river flow regimes,[9] extreme rainfall in China,[10] droughts in South Africa,[11] and the extinction of species,[12] as well as the emerging and transmission of infectious diseases,[13] to name a few. Because climate change threatens humans and the environment, it is crucial to find ways to adapt to and mitigate its effects before it becomes irreversible.

There is a growing consensus among experts that climate change adaptation strategies are essential alongside mitigation strategies to address the challenges of global warming. This is because even if all anthropogenic emissions were abruptly stopped, the climate would still change. Since it will take decades for climate change mitigation efforts to have a noticeable impact on rising temperatures, it is imperative to transform global systems to adapt to the changes that are already occurring and will persist in the foreseeable future. This may require developing and adopting strategies across all global development systems to adapt and build resilience to climate change. These strategies include, for example, building coastal sea walls to protect coastal communities from rising sea levels or developing drought-resistant crops to combat water scarcity. To prepare for extreme weather events, we may take advantage of using artificial intelligence (AI), high-resolution monitoring and simulation, and satellite-based remote sensing to develop Earth system and climate models based on current and historical data and records that can reveal the frequency and severity of these events,[14,15] These models may be used to predict when and where future extreme weather events will occur, as well as to predict the magnitude of their impact,[14] and thus, also to protect people and nature in high-risk areas, provided that respective warning systems are in place. Crucially, adapting to the effects of climate change entails raising people's awareness of how to cope with these effects, increasing their ability to respond, and reducing their overall risk and vulnerability,[16] Also crucial is the collaboration of citizens, researchers, and policymakers on specific climate change adaptation measures to be taken at different levels.[17,18]

Decisive action to reduce anthropogenic GHG emissions is another recurring demand of this era because, without strong decisive action, global warming and changing climate patterns will only intensify. As outlined in the Paris Agreement signed by a large majority of countries, GHG emissions must peak by 2025 at the latest and fall by 43% by 2030, and carbon neutrality needs to be achieved by 2050 to limit global warming to 1.5 °C by the end of this century.[3,19] This requires an urgent and unprecedented transition from the current carbon-based energy to low-carbon energy. Even though clean and renewable energy sources are expanding rapidly, the world is not on track to meet its Paris Agreement climate goals.[20,21] Despite longstanding promises to drastically cut GHG emissions, it is becoming increasingly difficult to transition burgeoning societies to carbon neutrality while driving economic development.[22] Ways to mitigate climate change that are compatible with long-term sustainable development goals have been proposed. These include, in particular, transforming and integrating food, water, and energy systems, protecting and developing carbon sinks, and promoting carbon dioxide (CO_2) capture, use, and storage.[3,23] Mitigating climate change also requires changes in human behavior, lifestyle, and food preferences.[24] With climate change posing a threat to all, it is more urgent than ever that the global community come together to take stronger action to avoid dangerous climate change.

In this review, we provide a broad overview of the current state of climate change in global ecosystems and strategies that have been developed for climate change adaptation and mitigation. First, a brief account of the drivers of climate change is presented, focusing mainly on the contribution of human activities such as the burning of fossil fuels and land use change. Then, we discuss studies of evidence of climate change in different spheres of the Earth and its impact on biodiversity, the environment, and human health. Moreover, we address recent developments in climate change adaptation and mitigation strategies, mostly those that are in line with sustainable socio-economic development. Finally, we provide insight into simulation modeling to assess future climate scenarios and the prospects and challenges of adapting to and reversing global warming.

DRIVERS OF CLIMATE CHANGE

Climate change has been a natural occurrence throughout Earth's history, with fluctuations in temperature and atmospheric composition occurring over millions of years.[25] Natural factors such as volcanic activity, changes in solar

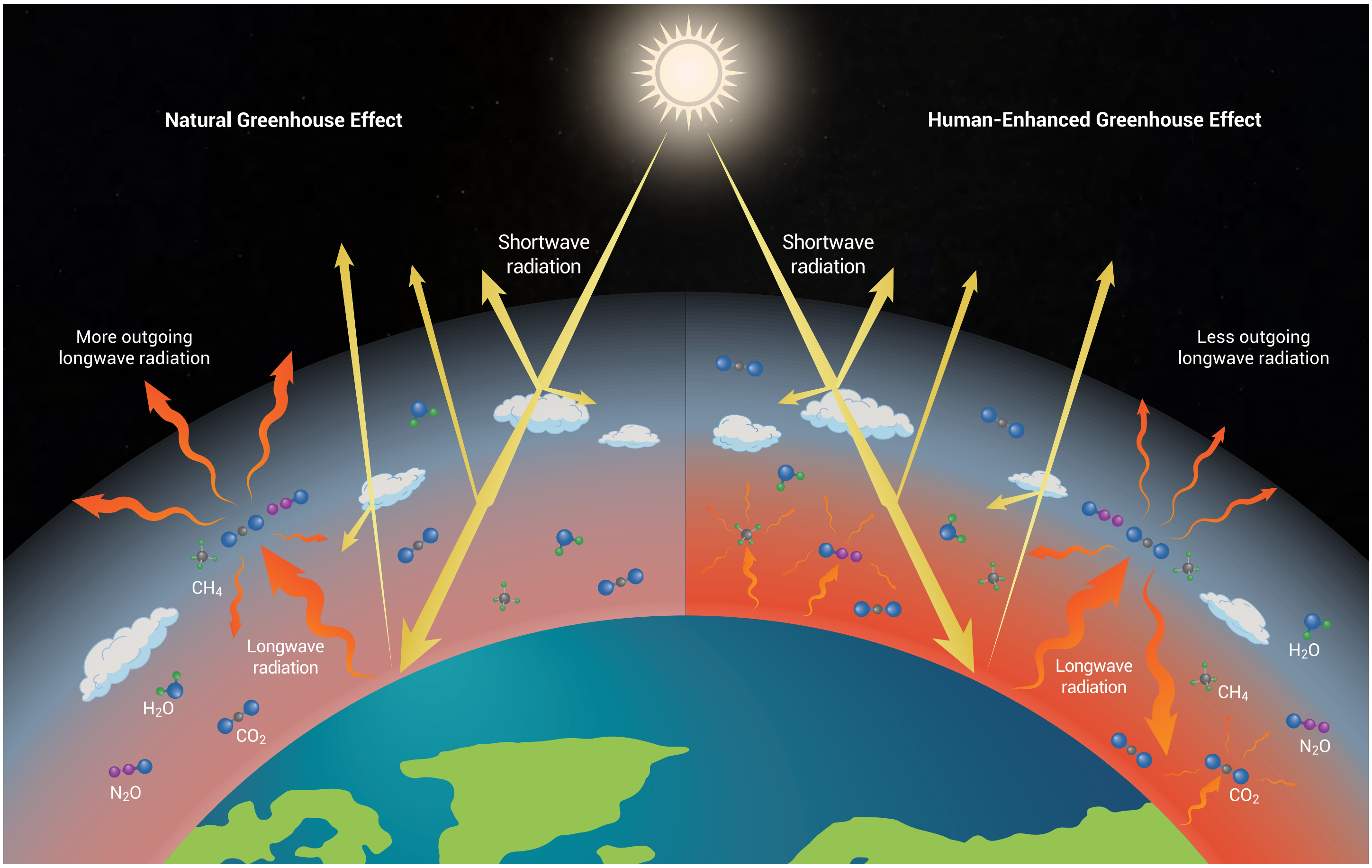


Figure 1. Schematic representation of the global mean energy balance process associated with the natural (left) and human-enhanced (right) greenhouse effect, with bright yellow indicating incoming solar shortwave radiation and red representing outgoing terrestrial longwave radiation.

radiation, and variations in Earth's orbit and tilt have all played a role in these changes. However, human activities during the past two centuries have greatly contributed to climate change by affecting Earth's surface albedo (reflectivity) and changing the amount of heat the planet absorbs (Fig. 1).[26] One of the primary ways that human activities have affected Earth's surface albedo is through land use changes such as deforestation and urbanization. Trees and other vegetation absorb sunlight and reflect less of it into space than bare ground or urban surfaces, which increases the amount of heat absorbed by the planet. More importantly, human activities such as burning fossil fuels for energy release large amounts of CO_2. Meanwhile, human activities produce a significant quantity of GHGs such as methane (CH_4), nitrous oxide (N_2O), Ozone (O_3), chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) into the atmosphere.[27] These gases trap outgoing longwave radiation from the Earth that would otherwise be emitted into space, leading to a warming effect on the planet. This section discusses emissions as the main drivers of climate change and provides a brief overview of climate change in the Earth's history.

Global emission accounts at multiple scales

The increase in atmospheric CO_2 concentrations is a major concern for the planet. The burning of fossil fuels, deforestation, and other human activities have contributed to this increase (Fig. 2). As of 2022, the atmospheric CO_2 concentration has reached 417.2 ppm, which is 51% higher than pre-industrial levels, and is rising at a rate of 5.2 ± 0.02 GtC yr^{-1}.[28] Fossil fuels remain the primary source of anthropogenic emissions to the atmosphere, with emissions continuing to rise. In 2020, the global COVID-19 pandemic resulted in a record decline in carbon emissions, which fell by 5.4% (1.9 $GtCO_2$) compared to the previous year. This decline was short-lived, however, as 2021 saw a rapid rebound to pre-pandemic emission levels.[29] Consequently, by 2022, global emissions from fossil fuel combustion and cement production reached 36.1 ± 0.3 $GtCO_2$, indicating a resumption of the pre-pandemic trend of continuous growth without any global emissions peak in sight. If the current emission growth rate continues, the 1.5 °C budget, which is crucial for mitigating the most severe consequences of climate change, will likely be exhausted within 7.1 years (67% probability). The top five emitters, including China, the United States, the European Union, India, and Russia, collectively account for 65% of global emissions, with emissions of 11.1, 4.98, 2.75, 2.65, and 1.87 $GtCO_2$, respectively. Moreover, while representing smaller emission volumes, emerging economies in Asia, Africa, and Latin America experienced emission growth rates surpassing the global average between 2010 and 2018, emphasizing the critical role these economies play in global climate mitigation policies.[30] Therefore, a comprehensive, multi-scale approach is imperative for addressing the intricate landscape of global emissions and devising effective mitigation strategies tailored to each region's unique circumstances and challenges to limit global temperature increases to well below 1.5 °C.

Historical overview of climate change

The widespread recognition of the Anthropocene concept [33-35] reflects the fact that human activities are now the predominant factor influencing Earth's climate and that the fate of all ecosystems depends on the mercy of humans.[36,37] This, in turn, strongly affects the future of humanity.

Throughout Earth's history, the climate has changed due to a variety of factors (Fig. 2),[38] including changes in solar irradiance,[39-41] movements of tectonic plates,[42-44] magmatic activity [45,46] from the extent of the sporadic Pinatubo eruption of 1991 to the eruption of the Siberian Traps 252 million years ago, changing Earth's orbital parameters,[47-49] continental collisions and uplift of mountains and plateaus,[50,51] changes of ocean currents and gateways,[48,49,52] and changes in atmospheric composition.[53-55] In Earth's history, variations in the atmospheric composition were caused by the chemical weathering of rocks, which consumes atmospheric CO_2. For example, atmospheric CO_2 gradually declined over the last 50 Myr at a long-term rate of

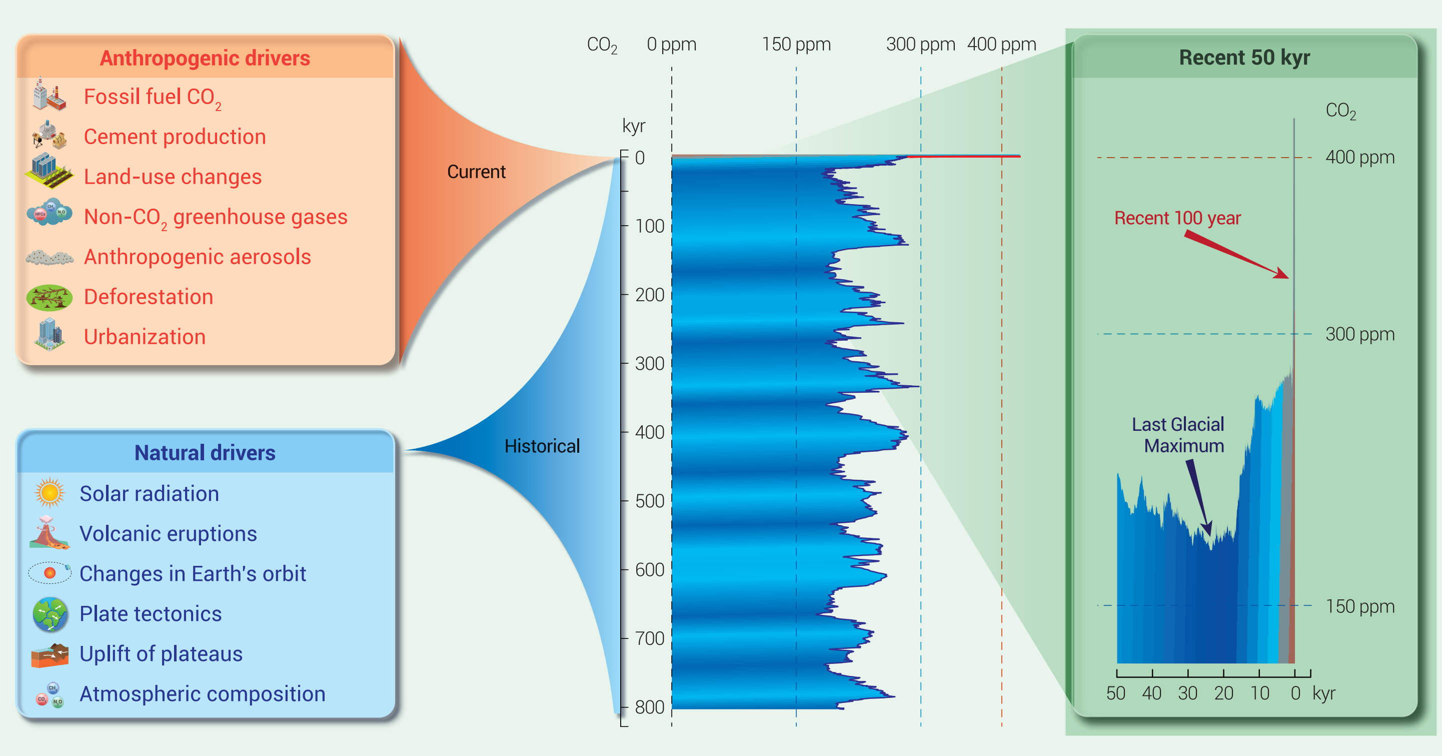


Figure 2. Evolution of atmospheric CO_2 over the past 800,000 years (800 kyr), major climate change drivers, and greenhouse effect Atmospheric CO_2 based on data from air trapped in polar ice and direct air measurements collected at the Mauna Loa Observatory (https://keelingcurve.ucsd.edu).[31,32] The dark and light blue bands in the graph represent interglacial and glacial periods, respectively. The right panel represents the evolution of carbon dioxide over the past 50,000 years (50 kyr). Data for the recent 8,000 years are shown in red.

about 16 ppm Myr^{-1}.[53] Weathering of continental flood basalts is considered to have triggered the Neoproterozoic Snowball Earth glaciations.[54] A recent study[55] also shows that Earth's climate may be stabilized over millennia by the solubilization of atmospheric carbon dioxide as minerals weather. Meanwhile, volcanoes have emitted large amounts of carbon dioxide throughout Earth's history.[56-58] The accumulation of CO_2 has been considered the main cause of the end of Snowball Earth.[59]

Various feedback processes modulate the amplitude of climate change,[60] such as sea ice-albedo feedbacks,[61,62] snow and ice-albedo feedbacks,[63,64] water vapor feedbacks,[65,66] feedbacks due to CH_4 and CO_2 in permafrost,[67,68] feedbacks due to wildfires,[69-71] and vegetation-climate feedbacks.[60,72] It should be noted that most of the feedback is positive, amplifying small warming into strong warming and, conversely, amplifying the cooling.

For most of the Earth's history, however, climate change occurred relatively slowly, taking millions of years or more to produce a measurable signal on a geological time scale. Even some of the most extreme climate change events in Earth's history, which are considered abrupt events in deep time, have been much slower than the global warming we are currently experiencing. For example, during the Paleocene–Eocene Thermal Maximum (PETM) about 55.8 million years ago, when global temperature increased by 4-7 ℃ within 3000-20,000 years,[73-75] atmospheric CO_2 increased from 900 ppm to about 2,000 ppm,[74,76] with an average annual increase of 0.04-0.42 ppm. In contrast, the CO_2 concentration has increased from 280 ppm to about 420 ppm from 1860 to the present, and the growth rate has reached about 2.5 ppm per year since 2000, much faster than during the PETM event.

Climate change may also be superimposed by processes within the climate system,[38] such as changes in the El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole, Pacific Decadal Variability, Atlantic Meridional Mode, Atlantic Multi-decadal Variability, and Northern Annular Mode. Climate evolution can also be interrupted by sporadic events, such as the meteorite impact 66 million years ago that ended the age of the dinosaurs, or the meltwater flood that triggered the Younger Dryas cooling event around 12,800 yr BP.[77-79] Observations show that the Atlantic Meridional Overturning Circulation (AMO) has weakened since the 2000s and may continue to decline in the 21st century;[80,81] the likelihood of this leading to abrupt climate variability is very low.[82]

Over the past half-century, there has been significant progress in analyzing the causes of climate change, i.e., assessing the relative contributions of multiple causal factors to an observed change in climate variables (e.g., global surface temperature or a climate event), thanks to advances in climate modeling and the use of supercomputers. In the 1960s, Syukuro Manabe demonstrated through his research that the increased levels of carbon dioxide in the Earth's atmosphere led to a rise in temperatures near the surface.[83] He also developed early mathematical models of the planet's climate, which helped to understand how the Earth's climate system works. Klaus Hasselmann built on Manabe's work and created a model that linked weather and climate.[84] Manabe and Hasselmann were awarded the 2021 Nobel Prize in Physics for their contributions to advancing our understanding of how the Earth's climate system works and how it changes over time.[85] Climate attribution shows that we cannot reproduce the global warming trend of the past 170 years if we consider only natural drivers.[86] Progress in this field has led to six versions of climate change assessments by the Intergovernmental Panel on Climate Change (IPCC), which have been the basis for global climate action and policy adjustment.

CLIMATE CHANGE EVIDENCE IN EARTH'S SPHERES

Atmosphere

Natural and anthropogenic emissions determine the composition of the atmosphere, and the basic structure of the Earth-atmosphere climate system accounts for the coupling between the atmosphere and climate change. Apart from the variable amounts of water vapor, more than 99.9% of the other molecules in the Earth's atmosphere consist of nitrogen, oxygen, and chemically inert noble gases.[87] Most of these gases have been at nearly constant levels for the past billion years. The remaining atmospheric constituents, representing less than 0.1% of the atmospheric molecules, including CO_2 and CH_4, influence several crucial atmospheric processes.[88]

Since the Industrial Revolution, human activities have increased GHGs, reaching values of 410 ppm for CO_2, 1866 ppb for CH_4, and 332 ppb for N_2O in 2019.[86] CO_2, the chemical feedstock for photosynthesis, is an important factor in the Earth's radiation balance. In the period 1850-2019, a total of

2390 ± 240 GtCO$_2$ of anthropogenic CO$_2$ was emitted. Gases and particulate matter released into the atmosphere are transported by winds. Their radiative absorption influences the atmosphere's temperature structure and climate.[89] The 0.6 ℃ increase in global surface air temperature during the 20th century has been predominantly attributed to the increasing atmospheric concentration of GHG, which has also led to substantial changes in the mesosphere, thermosphere, and ionosphere, including thermal contraction of these layers.[86] Based on current measurements of climate-sensitivity, an increase in atmospheric CO$_2$ results in a temperature increases of ~1 ℃ per 100 ppm CO$_2$.

The stratospheric ozone layer is a region of the Earth's atmosphere that contains high concentrations of ozone.[90] This layer plays a vital role in protecting life on Earth from the harmful effects of ultraviolet radiation from the sun. The ozone layer absorbs most of the sun's harmful ultraviolet radiation, preventing it from reaching the Earth's surface and causing damage to organisms. However, since the 1970s, scientists have observed a significant decrease in the amount of ozone in the stratosphere.[91,92] This depletion was primarily caused by human-made chemicals called chlorofluorocarbons (CFCs), which were widely used as refrigerants, solvents, and propellants in aerosol cans. When released into the atmosphere, CFCs rise to the stratosphere, where they are broken down by ultraviolet radiation, releasing chlorine atoms that react with and destroy ozone molecules.[92] The depletion of the stratospheric ozone layer is closely linked to climate change. Changes in the amount of ozone in the stratosphere can affect atmospheric temperatures and circulation patterns, ocean currents, and the Earth's carbon cycle.[93] Furthermore, concentrations of tropospheric ozone, a secondary air pollutant, have increased in the Northern Hemisphere from 10 to 15 ppb in pre-industrial times to ~50 ppb today, causing premature deaths and threatening food security.[94]

In the lower atmosphere, particular matter (PM), also referred to as aerosols, alters atmospheric visibility and affects biogeochemical cycles and meteorology. Ice cores show increases in aerosols across the Northern Hemisphere since 1700, and reductions since the late 20th century.[86] PM$_{10}$ is one of the most important air pollutants, representing a major component of smog and threatening all forms of life. In the last two decades, a 22% reduction in global PM$_{10}$ levels has occurred, contributed mostly by developed countries.[95] Climate change has noteworthy effects on reactive gases present in the atmosphere, such as reactive nitrogen, ozone, and aerosols.[96] These reactive gases have an impact on the air quality and can cause various environmental problems.[97] The alteration in temperature and precipitation patterns as a result of climate change influences nitrogen deposition and uptake by plants, as well as ozone formation.[98] Additionally, changes in atmospheric circulation patterns lead to changes in the transport and distribution of reactive nitrogen compounds and ozone.[99] Light-absorbing aerosols heat the atmosphere while cooling the Earth's surface, and the atmospheric heating caused by particulate absorption also affects local cloud formation and precipitation.[100] Although the interactions among aerosols, clouds, and radiation are subject to large uncertainties, the cooling effect on the climate system, including the carbon and water cycles caused by changes in solar radiation could offset some of the effects of increasing GHGs (Fig. 3). Climate change is also a factor increasing the long-range transport of persistent organic pollutants from urban/industrial and agricultural source regions in the mid-latitudes in the atmosphere and deposition in e.g., polar environments.[101]

Pedosphere

Soil carbon cycling. Soils play a crucial role in the global carbon cycle, storing up to 2,500 Pg [1 Pg (petagram) = 1 billion metric tons] of carbon in organic (1,550 Pg) and inorganic (950 Pg) forms.[102,103] Soil organic carbon (SOC) is the largest terrestrial carbon pool and is mainly composed of decomposed plant and animal residues.[104] On the other hand, soil inorganic carbon (SIC) refers to carbon present in the form of minerals such as calcium carbonate, magnesium carbonate, and calcium-magnesium carbonate.[105] Both SIC and SOC interact with climate in complex ways. One of the primary effects of climate change on SIC is the alteration of soil pH.[106]

Increased atmospheric CO$_2$ concentrations can lead to the dissolution of carbonates in soils, thereby reducing the soil pH.[105] This process can lead to the release of CO$_2$ into the atmosphere and further exacerbate global warming. Changes in temperature and precipitation patterns can affect the decomposition rates of SOC and the formation of SIC. Warming and increasing soil moisture content can lead to an increase in soil respiration rates by enhancing microbial activity and increasing SOC decomposition rates.[107] This constitutes a positive carbon-climate feedback loop that could also exacerbate global warming. However, excessive soil moisture resulting from heavy rainfall can limit oxygen availability in the soil, leading to anaerobic conditions that reduce the soil respiration rate.[108] Permafrost soils retain an additional 1,460-1,600 Pg C, and permafrost regions are highly vulnerable to warming and predicted to experience greater temperature increases than other regions due to climate change.[109] The thawing of permafrost could release massive amounts of carbon into the atmosphere, further exacerbating climate change. It has been estimated that warming will result in a sustained 30 ± 4% increase in CO$_2$ efflux through the whole-soil profile and could induce a loss of 190 Pg of soil carbon in the upper 1 m over the 21st century.[110] In contrast, warming is also reported to enhance SOC by increasing plant-derived carbon accumulation.[111]

The uncertainty about the effects of warming on soil carbon stocks, therefore, arises from the balance between the climate-driven increases in plant-derived carbon and soil organic carbon decomposition. Moreover, the temperature response of soil carbon is temporally and spatially heterogeneous, with substantial carbon loss due to undetectable changes.[110,112] The effect of warming on soil carbon depends on soil depth and ecosystem type. For example, carbon loss may be restricted to the topsoil in warmed subarctic grasslands [112] but extended to the subsoil (with ~33% ± 11% loss after 4.5 years of warming) in a conifer forest.[113] Warming may also alter the molecular composition of soil organic matter, with microbial carbon accumulation at the expense of plant-derived lignin under stimulated microbial processes.[114-116] Similar to warming, the effect of drought on soil carbon storage is significant, especially in peatlands and wetlands with high soil carbon density. Droughts in these wet ecosystems may introduce oxygen into the anoxic soils and stimulate the microbial decomposition of organic carbon.[117] In other ecosystems, drought and warming result in variable responses of soil organic matter decomposition rates to changes in soil temperature and moisture conditions.[118-120] Therefore, the degradation of wetlands caused by climate change is well reflected in the records of carbon accumulation in soil profiles.

Soil nutrient cycling. Climate change has a significant effect on soil nutrient cycling. Warming, elevated atmospheric CO$_2$, and nitrogen (N) deposition are reported to enhance vegetation growth and increase gross primary productivity, leading to higher nutrient demand, especially for phosphorus (P).[121] Although the impact of warming on P cycling remains controversial, it is widely accepted that P availability may not meet plants' increasing demands.[122] Other rock-derived nutrients, such as calcium, also become an increasingly scarce resource during vegetation succession (e.g., in central African forests[123]). It remains to be examined if climate change-induced vegetation growth may also exacerbate the limitation of these nutrients. By comparison, N can be fixed biologically, relieving N limitation.[124] Noteworthy, the degree of carbon loss by temperature increase depends on the availability of nutrients, particularly of N and P,[125,126] thus resulting in complex feedback loops. However, higher precipitation can increase the risk of N loss through denitrification, leaching, and runoff. Denitrification is particularly important under wet conditions caused by flooding or permafrost thawing and can result in the release of N$_2$O.[127] As a potent GHG with a global warming potential of 300 times that of CO$_2$ on a 100-year timescale,[128] increased N$_2$O emissions will lead to further feedback on climate change, exacerbating the already dire situation.[129] Flooding-induced runoff of nutrients and soil, in turn, may enhance the eutrophication of aquatic ecosystems and reduce drinking water quality (Fig. 3).[130,131]

Climate change has also consequences for the fate and effects of environmental pollutants in the environment. Not only will rising temperature lead to enhanced concentrations in the atmosphere (see Subsection 3.1) but the increasing frequency of extreme weather events remobilizes contaminants by run-off from topsoil contaminated with pesticides in agricultural fields and from river sediments during flooding events.[132] Exposure to organisms with these bioactive substances will impact biodiversity [133] and promote pesticide resistance.[134]

Soil diversity. Soil fauna, microorganisms, and viruses are integral

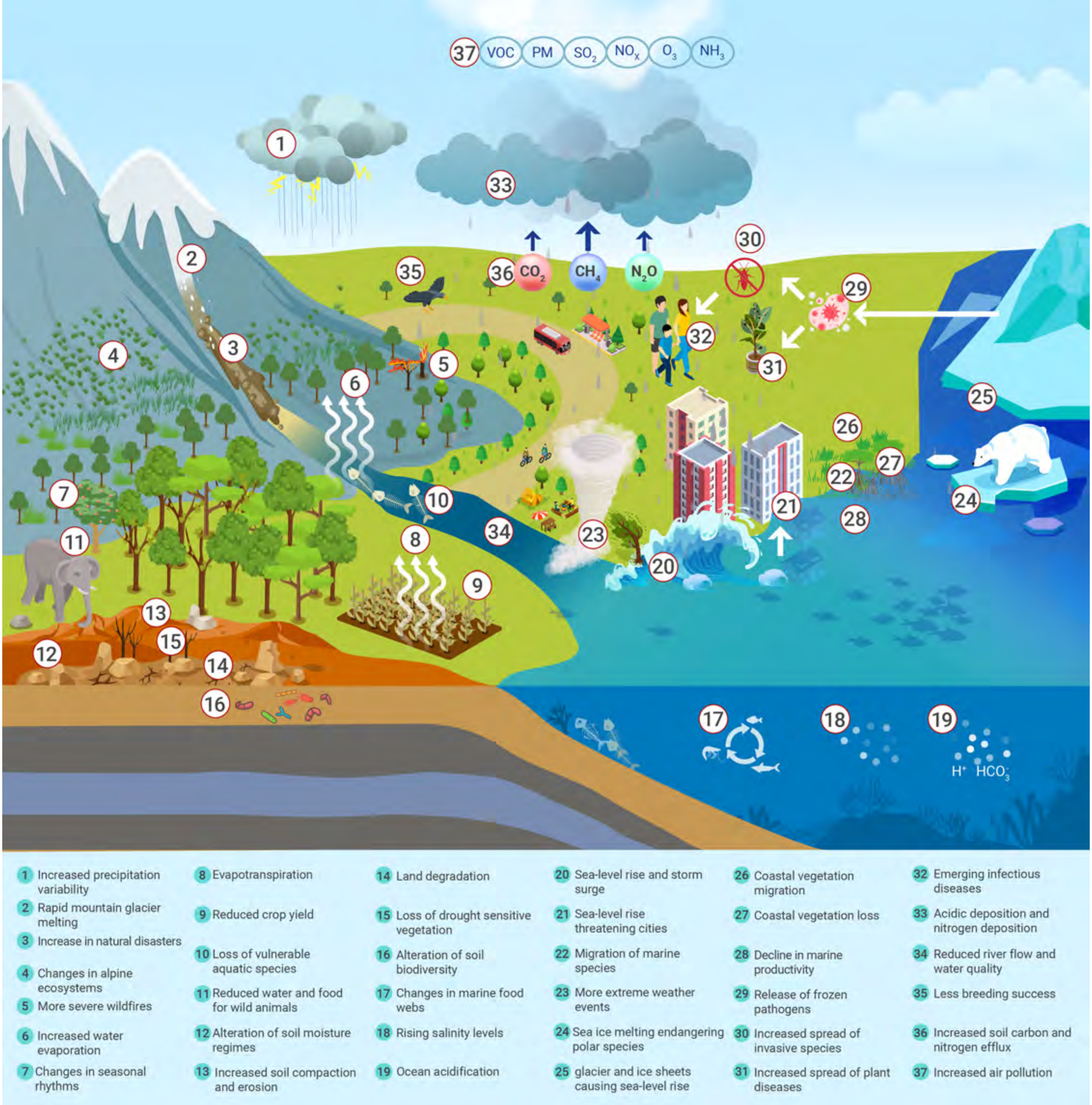


Figure 3. Evidence of global climate change and its effects on the environment.

elements of the soil biota and play key roles in many ecosystem functions, which are recognized to be sensitive to climate change.[135,136] Climate change, directly and indirectly, shifts the geographical range of soil biota species and affects their diversity and abundance through several interrelated factors, such as temperature, moisture, soil physical and chemical properties, and plant input.[137,138] Although responses of various soil biota to climate change differ, there is consensus that climate change is causing changes in soil biota community density, diversity loss, and extensive habitat shift, as soil biota are subjected to heat or moisture stress, with the tendency to migrate to high latitudes and high elevations along with plants (Fig. 3).[139] In addition, soil microorganisms need both energy and carbon for growth and to maintain their activities for soil functions.[140] Therefore, a minimal amount of consumable energy-containing substrates is needed in agricultural soils, such as provided by crop residue return or the application of biochar. Given that soil biota play a critical role in ecosystem functions, the potential consequences of biomass and diversity loss, composition shift, and local extinction are enormous.

Hydrosphere

Global warming may affect the hydrosphere through the melting of glaciers, inducing droughts and floods, partially desiccated river beds, and rising sea levels,[141] resulting in a series of cascading problems threatening global sustainable development, ecosystems, and biodiversity.[142] As such, the climate change crisis is also a water crisis, and climate change affects global water resources in complex ways.[141] Therefore, it is essential to consider water management when drafting climate policies and strategies and ensure water security and resilience for humans and ecosystems.[143]

Climate change significantly impacts the complex water cycle system (Fig. 3). Firstly, climate change exacerbates evaporation rates. The globe is experiencing smaller ice coverage, and the average annual global lake evaporation rate is expected to increase by 16% by 2100.[144] Also, accelerated vegetation transpiration may lead to water stress and reduced photosynthesis and growth.[145] Moreover, global land evapotranspiration has increased substantially, resulting in a decrease in terrestrial water storage, which causes droughts in many regions of the globe.[146] By the late 21st century, it is projected that 67% of the land area (excluding Greenland, Antarctica, and mountain glaciers) will experience a decline in water reserves.[146] Secondly, climate change could alter precipitation patterns. For example, according to Piao et al.,[147] the precipitation disparity between different regions in China has become even more apparent. While the wetter southern areas have witnessed a rise in rainfall, the northern territories, which are already relatively dry, have experienced a decrease of 12% in precipitation since 1960.[147] Therefore, dry places are drier due to the combined effects of lower precipitation and higher evapotranspiration.[147,148] On the other hand, increased atmospheric water vapor in the wetter region can give rise to more intense precipitation events,[149] intensifying extreme hydrological events such as more frequent storms and floods.[142,150] Water-related natural disasters have been the most common natural disasters over the past 50 years, accounting for 70% of all related deaths.[151] Thirdly, climate change can impact surface water runoff. Reduced runoff can occur due to factors such as decreased precipitation, increased evapotranspiration, and excessive water consumption by humans and agriculture.[152] Also, dry soil moisture can cause a stronger and faster reduction in runoff than evapotranspiration.[152] However, climate change can also lead to increased surface water runoff and flood risk in some regions, due to increased rainfall during rainy seasons and glacier meltwater caused by rising temperatures.[142,153-156] Finally, the primary source of groundwater recharge is infiltration, and the quantity and quality of groundwater can differ due to changes in precipitation, evapotranspiration, and surface runoff caused by climate change.[155,157,158] In addition, land use and urbanization are among the most immediate factors that change the groundwater response to climate change by polluting and depleting groundwater resources.[155,157]

Climate change and water affect the environment and ecosystems in several ways. In the ocean, rising temperatures and carbon dioxide concentrations are causing ocean water to decrease in pH.[159] The heat exacerbates pressures on oceanic ecosystems from declining local water quality and overexploitation of key species.[159] The reproduction of maritime animals depends on the seawater temperature, and species such as reef corals are increasingly approaching the point of functional collapse.[159,160] Changes in the marine environment are related to both terrestrial and freshwater environments. Harmful algal blooms can occur in freshwater and marine environments,[161] threatening ecosystems through factors such as changes in temperature and seasonal rainfall.[162] Warmer ocean temperatures can also contribute to exacerbating extreme weather events on land, such as more frequent typhoons.[148] Hydrological extreme events will also change the migration and transformation of pollutants and water dilution capacity, affecting the hydrological cycle and water environment.[150] According to projections, the average intensity of lake heatwaves [defined relative to the historical period (1970 to 1999)] will increase from 3.7 ± 0.1 ℃ to 5.4 ± 0.8 ℃ by 2099 under the scenario of elevated greenhouse gas emissions.[163] Their average duration will dramatically increase from 7.7 ± 0.4 to 95.5 ± 35.3 days. Also, fish diversity in freshwater decreases with higher temperatures and lower precipitation.[164] Moreover, more than 16% of wetlands will be at risk of disappearing, endangering countless species.[165] Additionally, global warming has dramatically impacted the cryosphere, accelerating the retreat of glaciers and reducing the number of days and depth of snow cover.[150] On land, precipitation, and vegetation transpiration influences plant growth productivity, causing reductions in phytocoenosium.[145,166] Temperature, moisture availability, and precipitation are the main variables affecting wildfires.[167] The area affected by wildfires is projected to increase by 35%-40%, significantly reducing forests by 50% worldwide by the end of the century.[150] Generally, under the scenario where temperatures will increase by 2-4 ℃, 10%-13% of species in terrestrial and freshwater ecosystems will be at high risk of extinction, and ecosystem structures will be transformed by 15%-35%.[150]

Water has hydro- and biophysical characteristics and socio-political and cultural dimensions.[143] More than 2 billion people live in countries with severe water shortages, which will affect food supplies as agriculture accounts for 60% to 70% of the water used by humans.[150] The rise of sea levels associated with global climate change is a significant social effect that will have a disproportionate impact on coastal and low-lying areas.[168] In addition, the impact of climate change will have a greater effect on disadvantaged communities in less developed regions, resulting in a lack of access to food and water, as well as the deterioration and disappearance of habitats.[143,169] This will lead to an increase in food and water insecurity, as well as a loss of biodiversity. The most vulnerable groups, such as women and children, will be the most affected by these changes. In addition, the degradation of natural resources will exacerbate poverty and inequality in these areas. However, current climate solutions often ignore issues of injustice and fail to address the urgent need for targeted action in the right places.[169] To improve water adaptation efforts, a reorientation towards a justice- and rights-based framework is necessary.[143]

In summary, climate change and water are closely interconnected. The solution to climate change requires integration and interplay coordination across all aspects of hydrology, ecosystems, and sustainable development. To address climate change effectively, we need to restore aquatic ecosystems, improve water management to mitigate the risks of climate change, enhance early warning systems for water-related disasters, develop new agricultural systems that reduce water usage, and create a more equitable social distribution system that meets the needs of everyone. Climate solutions must prioritize water and consider those facing water insecurity, taking into account local contexts and ensuring that all voices are heard.[169]

Biosphere

The biosphere is severely impacted by climate change (Fig. 3). Two of the most widely discussed changes in the biosphere are shifts of biomes towards the pole regions or higher elevations [170,171] and changes in plant, microbial, and animal phenology.[170,172] The shifts of plant species towards the pole or higher elevation are especially pronounced as the cold regions or high elevations become warmer and more suitable for their growth, with changes in plant productivity, mortality, recruitment, and greenness starting along the climatic margins of the concerned biome.[171,173] As a result of climate change, the forest biome, for example, expands its range or simply shifts its distribution towards the pole or higher elevation as the lower latitude or elevation regions become too hot or dry for tree growth.[174] In the northern hemisphere, evergreen forests are expanding into areas currently occupied by tundra, while grasslands or temperate forests are replacing evergreen forests at the southern edge of the boreal forest biome.[175] The species that expand their range are more responsive to climate change and more mobile. On the other hand, species that are less responsive to climate change or mobile or have slower rates of niche divergence may shrink their geographical distribution as they are outcompeted by other species that expand their range.[170,176] Range shifts can lead to the loss of some species in certain areas and the arrival of new species in others.

Plants and animals with an annual cycle in response to changes in temperature will alter their phenology in response to climate change. Phenological changes could include changes in the timing of flowering or leaf senescence of plants and the mating, breeding, and spawning or hibernation time of animals.[170] These changes are linked to altered temperature, precipitation, and other climate variables. Phenological changes are widely recorded and are one of the most visible and sensitive responses of natural ecosystems to climate change.[177] The documentation of plant phenology dates back thousands of years.[172] Earlier leafing out of plants and delays in autumn color change and leaf fall of deciduous plants have been widely reported.[170,178,179] For example, the greening of temperate forests in Europe has started 8 to 15 days earlier since the 1950s.[180] Piao et al. [172] provide a comprehensive review of the evidence for climate change to alter plant phenology based on in situ and satellite observations and discuss the factors and mechanisms driving plant phenological changes. They show that phenological changes are affected to a greater extent in China than in North America, with Europe falling between those two regions.[172] There has also been widespread vegetation greening since the 1980s primarily due to the CO_2 fertilization effect.[181] Climate change-induced changes in biome shifts, vegetation density, and phenology have implications for increasing vegetation activity and the uptake of carbon dioxide,[175,182] providing negative feedback on climate change. Other evidence of climate change reflected in the biosphere includes the die-off of plants and animals due to climate change-induced stresses such as heat waves, drought, fire, or outbreak of insects and diseases.[183-186] In some areas, climate change lengthens the growing season and increases the temperature in both the dormant and growing seasons, favoring the reproduction and spread of pests and diseases. For example, the outbreak of pine beetles in North America has been linked to higher temperatures, as the beetles can survive in areas where cold winter temperatures previously kept their populations in check.[187] Climate change-induced changes in precipitation patterns impact the distribution and abundance of insects and diseases that rely on moisture.[188] Such changes undoubtedly affect various ecosystems' biodiversity and community.[176]

Cryosphere

The cryosphere is integral to the Earth's climate system, including glaciers, ice sheets, snow cover, permafrost, sea ice, ice shelf, etc. Over the past few decades, the cryosphere has experienced significant and widespread shrinking in response to global warming.[189,190]

Glaciers worldwide have been shrinking since the second half of the 19th century.[38] Excluding peripheral glaciers of ice sheets, the mass loss rate of glaciers worldwide was 170 ± 80 Gt yr^{-1} from 1971 through 2019 and 240 ± 40 Gt yr^{-1} during 2006-2019.[38] Glacier mass loss has increased significantly in the past few decades due to global warming, influencing river systems by altering discharge timing, quantity, and quality (Fig. 3).[38] Between 2006 and 2015, the Greenland Ice Sheet lost mass at a mean rate of 278 ± 11 Gt yr^{-1} while the Antarctic Ice Sheet lost mass at a rate of 155 ± 19 Gt yr^{-1} which is equivalent to 0.77 ± 0.03 mm yr^{-1} and 0.43 ± 0.05 mm yr^{-1} of global sea level rise, respectively.[191,192]

The monthly snow cover extent (SCE) in the Northern Hemisphere has experienced a declining trend for all seasons during 1981-2018, especially in November, December, March, and May. The reduction rate of SCE was more than 50×10^3 km^2 yr^{-1}.[193] At the same time, snow depth has shown a negative trend, and snowmelt advanced in spring.[194] Permafrost temperatures increased by 0.29 ± 0.12 ℃ from 2007 through 2016, reaching the highest level since the 1980s.[195] Soil temperatures near the depth of 30 cm below the surface have significantly increased in permafrost regions over the last 30-40 years.[189,190] The active layer thickness has generally increased in high-elevation areas since the mid-1990s in Europe and Asia [196-199] and in the early 21st century across the European and Russian Arctic.[200,201]

Monthly sea-ice extent and area in the Arctic have declined since 1979, with most of the decline occurring after 2000.[189,190] Compared with the period of 1979-1988, the monthly mean Arctic sea-ice area decreased by 2 million km^2 from August through October between 2010-2019, and the greatest reduction was observed in late summer-early autumn.[190] In addition, sea-ice thickness and volume are decreasing. First-year sea ice has become dominant, while multi-year ice is diminishing or almost disappearing.[202] In recent years, there has also been a discernible decrease in the monthly extent and area of sea ice in the Southern Ocean, which is thought to be linked to various environmental factors, including rising temperatures and alterations in wind patterns.[203] According to some studies, the rate of decline in sea-ice extent in the Southern Ocean may be even more rapid than in the Arctic.[204]

Rapid changes in the cryosphere have significant impacts on natural hazards, hydrology and water resources, ecosystems, and human livelihoods. Firstly, glacier retreat and permafrost degradation reduce the slope and rock stabilities, leading to a higher frequency of landslides and related infrastructure destructions.[205-207] An increase in wet-snow conditions causes an increasing trend in avalanches in the western Indian Himalayas and Europe.[189,208] Glacier and snow cover melt-related floods have increased in recent decades. The increase in the number and area of glacier lakes has led to more abundant glacier lake outburst floods (GLOFs) that can result in significant loss of life. Populations in High-Mountain Asia are most exposed to impacts from GLOFs, with nearly 1 million people living within 10 km of such glacier lakes.[209]

Secondly, cryosphere shrinking can cause changes in runoff and water supply. Glacier-fed basins' runoff will peak before or around the middle of the 21st century in High-Mountain Asia, the European Alps, Western Canada, and the USA, affecting downstream water resources and ecosystems.[210] In addition, glacier decline and permafrost degradation can accelerate the release of long-stored legacy pollutants (persistent organic pollutants, particularly polychlorinated biphenyls, dichlorodiphenyltrichloroethane, polycyclic aromatic hydrocarbons, and heavy metals), with potential risks on ecology and human systems.[211] Cryosphere changes also pose challenges for terrestrial ecosystems. On the one hand, snow cover, and glacier changes have altered soil moisture in river catchments, providing new conditions for survival and adaptation for many plants and animal species, increasing plant productivity, and expanding species habitats.[212-215] On the other hand, the rapid shrinking of the cryosphere has led to the loss or disappearance of habitats that depend on snow and ice cover, reducing species richness and habitat migration upward.[216-218]

The cryosphere provides humans with essential recreational and cultural services.[219] The shortening of snow cover duration and the decrease in snowfall have affected the development of skiing and winter tourism and caused great economic losses.[220,221] Cryospheric changes also impact cultural values and human well-being.[222] Humans pursue cryospheric aesthetics and religious beliefs. For example, the loss of glaciers could threaten the local ethnic identity and be viewed as the result of a failure to show respect to sacred beings, leading to environmental degradation and the decline of natural and social orders.[223,224]

Impact of climate change on the fate and effects of environmental pollutants

Climate change, particularly global increased temperatures, will alter Earth's physical, chemical, and biological processes, thus influencing the profile and transformation patterns of environmental pollutants in the different environmental media.[225] Higher temperatures, thawing of permafrost soils, rising sea levels, shrinking ice cover, changing patterns of precipitation, etc., could impact the deposition, dispersion, and in some cases effects of pollutants on environmental organisms and human beings.[226] Specifically, rising temperatures can lead to higher water vapor pressure and may cause certain pollutants to evaporate more easily and enter the atmosphere, where they can be transported globally.[227] Extreme weather events can cause significant environmental damage by re-mobilizing pollutants previously contained in sediments and permafrost.[101,228,229] A warmer climate increases crop losses by pests, and extensive pesticide applications expend pesticide resistance, thereby threatening global food security.[134,230] Increasing pollutant load exacerbated by climate change may directly threaten human and environmental health, as well as planetary safety.[231] Dramatic climatic change is the grave consequence of excessive consumption of materials and energy; it also amplifies hazardous pollutants.[232] Sustainable management of chemical substances and material cycles, involving greater resource efficiency, sufficiency, and consistency, can slow and reduce contaminant fluxes regionally and globally under climate change scenarios.[225] Therefore, we recommend that an international framework, endorsed by many governments and global health agencies, be established to effectively manage these substances, avoiding potential pollutants.

Impact of climate change on public and environmental health

Climate change has emerged as a significant threat to global public health.[233] Extreme weather events, including heatwaves, wildfires, hurricanes, droughts, and floods, have led to a series of adverse health impacts from excess mortality[234,235] and morbidity[236,237] to negative birth outcomes[238,239] and mental health issues.[240,241]

One of climate change's most immediate impacts is the increase in temperature extremes. Specifically, a multicity study in China indicated that heatwaves increased risks of non-accidental mortality, with 0-10 day lags exhibiting pronounced effects.[242] Heatwaves cause heat stroke and dehydration, exacerbating existing health conditions such as cardiorespiratory diseases.[243] A 1 °C temperature rise was associated with a significant increase in morbidity due to arrhythmias, cardiac arrest, and coronary heart disease.[244] Notably, compared to morbidity, cardiorespiratory mortality appeared to be more vulnerable to heat waves.[242,245] Furthermore, heat waves have been linked to adverse birth outcomes. During 2010-2020, heatwave exposure in China caused an average of 13,262 preterm births annually, of which 25.8% were attributed to anthropogenic climate change. This consequently leads to substantial human capital losses exceeding $1 billion.[246] The mental health impact of heat waves cannot be ignored either. A recent meta-analysis showed that for every 1 °C rise in temperature, there was a 2.2% increase in mental health-related mortality and a 0.9% increase in mental health-related morbidity.[236]

Due to increasing dryness and rising temperatures, more frequent wildfires will likely occur worldwide. In addition to the direct health effects such as burns, injuries, or death caused by flames or radiant heat,[247] wildfire smoke is a risk factor for various health outcomes, contributing to significant elevations of air pollutants.[248] A global study found that for every 10 μg/m^3 increase in wildfire-related $PM_{2.5}$ exposure, there was a 1.9, 1.7, and 1.9 higher risk of all-cause, cardiovascular, and respiratory mortality, respectively.[249] Moreover, exposure to wildfires was associated with adverse birth outcomes, including preterm birth and low birth weight.[250] Residents affected by wildfires may also experience enhanced risk for mental conditions, such as post-traumatic stress disorder (PTSD), depression, and insomnia, due to traumatic experiences, property loss, and displacement.[251] The psychological consequences of wildfire events can persist for years, as observed in some cases.[252]

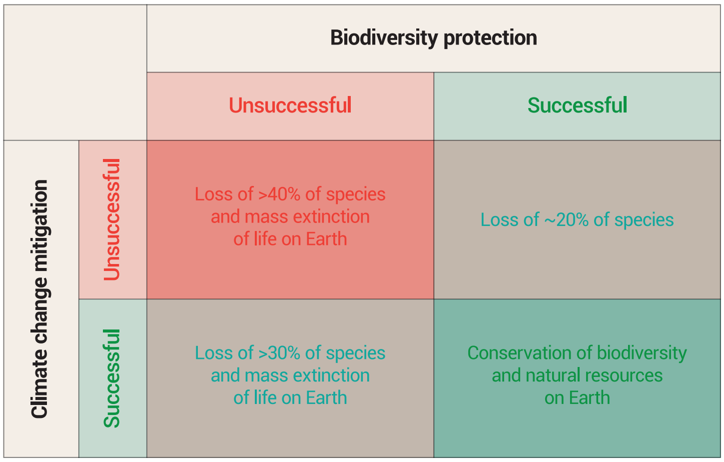
Climate change has been linked to severe storms, cyclones, and heavy rain events that lead to flooding. According to a study by Dosa et al.,[253] in Florida, there was an increased odds ratio of mortality at 1.12 within 30 days post-exposure to Hurricane Irma, with a higher odds ratio of 1.18 observed in long-stay residents. Watkins et al.[254] suggest that the elevated exposure to phthalates due to hurricanes, coupled with extensive infrastructure damage, limited access to basic necessities (e.g., food and water), and prolonged loss of electricity and communication services, may heighten the risk of adverse birth outcomes among susceptible pregnant women. Furthermore, Schwartz et al.[255] found that the co-occurrence of individual and structural damage resulting from Hurricane Sandy was significantly associated with the long-term persistence of PTSD symptoms. Hurricane-related PTSD symptoms can promote the risk of cardiovascular disease among older adults according to Lenane et al.[256]

Females, children, adolescents, the elderly, and socio-economically disadvantaged individuals are all vulnerable to the health impacts of climate change.[257,258] Children are more susceptible to heat-related and infectious diseases, while the elderly are particularly vulnerable to temperature extremes and air pollution.[243] Additionally, they experienced 3.1 billion additional person-days of heatwave exposure and 626 million additional person-days of heatwave exposure in 2020 compared to the 1986-2005 baseline average.[259] Residents living in tropical and subtropical climate zones were found to be more vulnerable to heat-related mortality and morbidity.[236] In Brazil, individuals living in less developed cities were more likely to experience hospitalizations related to temperature variability.[260]

In summary, climate change poses challenges to global public and environmental health. Addressing the health impacts of climate change requires a multi-dimensional approach that includes reducing GHG emissions, improving public health infrastructures, proposing adaptation strategies, and promoting sustainable development. It is crucial to prioritize the health and well-being of all individuals and communities worldwide in the pursuit of mitigating the impacts of climate change.

Climate change, biodiversity, and reducing extinction risks

Climate change has been driving shifts in the distributions of species for decades, including thousands of marine species at a global scale.[261-263] This shows that many species are adapting to climate change by moving where they live. The changing environments may allow some species to expand their geographic range. However, where species such as endemic species restricted to isolated mountain tops and islands cannot shift their distribution, their extinction risk is increased.[264] Indeed, the only two species extinctions attributed to climate change are of two endemic species. The extinction of the golden toad and the Bramble Cays mouse was attributed to global warming and sea-level rise on their mountaintop and low-lying island habitats, respectively.[265]



		Biodiversity protection	
		Unsuccessful	Successful
Climate change mitigation	Unsuccessful	Loss of >40% of species and mass extinction of life on Earth	Loss of ~20% of species
	Successful	Loss of >30% of species and mass extinction of life on Earth	Conservation of biodiversity and natural resources on Earth

Figure 4. The consequences of protecting and not protecting biodiversity from human impacts with and without mitigation of anthropogenic climate change The diagram outlines four scenarios of successful and unsuccessful conservation of biodiversity and mitigation of climate change. See Costello[265] for details of extinction estimates.

Considering the numerous papers claiming actual or predicting climate-related extinctions, it seems surprising that only two species may have gone extinct due to climate change. This is because some studies only record local extinctions which should be called extirpations because the species still live elsewhere, and/or may have moved elsewhere. Others report "extinction risk" which is difficult to quantify. Furthermore, such studies often omit to count species that have shifted their range into their study area. Species richness is generally increasing in higher latitudes and decreasing in low latitudes. Because higher species richness has been conventionally considered better than low species richness, the increasing diversity in mid and high latitudes may be considered as a positive effect of climate change. However, from a human perspective these geographically variable, climate change-induced, environmental changes can lead to a loss of traditional natural wildlife resources and impacts on agriculture and aquaculture.[266] Changes to biodiversity are not limited to shifts in species distributions but include changing abundance, ecological interactions, and maximum body size in ectotherms such as fish, mollusks, and crustaceans of commercial importance.[267,268] Thus, the challenge for climate change and biodiversity is that people must adapt how they use the natural resources which are part of biodiversity.[269,270] This requires planning, including changes to farming practices and fishing quota, but also the adaptation of markets, diet, and associated infrastructure.[271,272]

By far, the greatest threats to biodiversity are not climate change, but the well-known over-exploitation of wildlife through hunting and fishing, destruction of habitats through deforestation, mining, seabed dredging and trawling, freshwater abstraction, river barriers, fishery bycatch, and invasive species on islands.[272-275] The extinction risk for freshwater biodiversity is already 3 and 10 times higher than for terrestrial and marine species, respectively,[276] and 130 times higher from present threats than posed by climate change.[277] Climate change effects, including chronic warming, heatwaves, floods, droughts, and storms, compound biodiversity pressures. Without addressing these causes of biodiversity loss, extinction rates will increase regardless of climate change. Thus, governments and local communities must work together to restore and protect biodiversity and build natural resource resilience to climate change. Already, 30% of assessed species are threatened with extinction, and without mitigation of climate change through reducing GHG emissions, over 40% are threatened as reviewed by Costello (Fig. 4).[265]

Restoring, protecting, and sustainable use of the environment to maintain biodiversity, are a prerequisite to mitigating the added effects of climate change on biodiversity.[278] Without a change from people living 'on' to 'with' nature, as traditionally practiced by some indigenous peoples, the resilience

Table 1. Examples of "Nature-based solutions" (NBS) that aid adaptation to, and mitigate against the effects of, climate change, while restoring and protecting biodiversity.

Actions	Terrestrial	Freshwater	Marine
Protect biodiversity	Protect native forests, bush, and grasslands	Stop pollution and sedimentation into streams, rivers, ponds, and lakes	Ban seabed trawling and dredging
	Control the introduction and spread of invasive species and pests		
Reconnect habitats and populations	Use riverbank and hedgerow corridors to connect protected native habitats		Restrict fragmentation of habitats by coastal development and seabed trawling and dredging
	Reduce habitat and species loss outside protected areas to add species dispersal (corridors)		
Living with nature	Environmentally sustainable agriculture, tourism, and other land and freshwater use		Environmentally sustainable aquaculture, fisheries, tourism
Restoration and recovery	Rehabilitate old mines, quarries, and industrial lands	Stabilize riverbanks. Remove weirs and artificial barriers to fish migration	Ban removal of marine life and habitat fishing in selected areas to allow passive recovery of habitats, natural population structure, and food webs
Rewilding	Reintroduce extirpated native species		
Reduce erosion, soil loss,	Plant forests and control grazing to enable uplands to absorb rainfall and reduce flash floods		Protect sand-dune systems from erosion due to human and farm animal trampling
Control flooding	Set aside land for salt marshes and mangroves to buffer against river and seawater flooding; Link estuarine and upriver protected areas to provide more wildlife habitat and absorb storm surges and floods		
Urban development	Concentrate development to more cost-efficiently manage transport and waste management infrastructure	Limit upland development to protect the freshwater quality	Ban construction in areas at risk of sea level rise and associated storm surges
Greenhouse gas mitigation	Reforestation (especially mangroves); Revegetation; Fewer farm mammals	Repair and expand wetlands to capture and deposit carbon in soils.	Limit seabed disturbance by trawling and dredging that releases CO_2 and CH_4. Eliminate harmful fishery subsidies.
	Reduce the use of fossil fuels and reapply subsidies to renewable energy sources		
Carbon sequestration	Allow biodiversity to flourish and capture CO_2 from the air and sequester it in biomass, soils, and sediments		
	Manage forestry to maximize biomass and ecosystem complexity.	Reduce nutrient input from land and cities to restore ecosystem complexity	
Social	Communicate information on the benefits of adaptation measures to the public		
Political and economic	Provide leadership and governance of mitigation and adaptation measures, through regulations and economic incentives that guide the transition to a low carbon emission economy		
Scientific	Rapidly release and explain monitoring data to society so that the public and policymakers are informed of trends in biodiversity and related factors, including climate variables, extreme weather-related events, threatened and invasive species, natural habitats, and their relationships		
	Conduct research to improve understanding of cause-effect relationships regarding environmental factors and biodiversity trends, including in nature conservation, forestry, agriculture, fisheries, and food production sectors, and improve projections of consequences of management action and inaction		

of biodiversity and associated natural resources to climate change will be compromised.[265] While the effects of climate change vary geographically, and some biodiversity richspots may have been climate refugia in the past, they will all, terrestrial, freshwater, and marine, be affected to some extent.[279]

One solution to reverse this loss of resilience is "nature-based solutions (NBS)" which benefit biodiversity and ecosystem services and boost resilience to the effects of climate change (Table 1).[274] These may be achieved through passive restoration and rewilding when species are already present in the area and their populations can recover after the cessation of human impacts. This is especially effective in the ocean through Marine Protected Areas, but in some situations, and frequently on land and in freshwaters active restoration efforts are needed to regenerate biodiversity (Table 1).

OPTIONS FOR MITIGATION OF CLIMATE CHANGE

Nature-based solutions for climate change mitigation

Protection of natural carbon-sink resources. Protection and utilization of natural carbon-sink resources are critical strategies to mitigate the impact of climate change.[3] Natural carbon sinks are ecosystems that trap and store carbon dioxide from the atmosphere, such as forests, wetlands, and oceans (Fig. 5). By protecting these carbon sinks from human-induced activities such as deforestation, land-use change, and drainage, we can prevent the release of large amounts of carbon dioxide into the atmosphere. Additionally, efforts to restore and enhance natural carbon sinks can help to sequester carbon and mitigate climate change impacts. For example, reforestation projects can help to reestablish forests that have been lost due to deforestation or land-use change, while wetland restoration can help to enhance carbon sequestration in coastal ecosystems. In agricultural systems, any efforts to increase yields and carbon return as well as measures to reduce carbon losses can also contribute significantly to climate change mitigation.[280] Overall, the protection and intelligent utilization of natural carbon-sink resources are critical in mitigating the impact of climate change, and efforts to restore and enhance these ecosystems must remain a priority for sustainable development.[3]

About a fifth of all terrestrial organic carbon globally is stored in organic soils,[281] despite them covering only 3% of the land surface.[282] There are different kinds of organic soils, such as bogs, which are fed by rainwater, fens, which are fed by groundwater; and the so-called Folic Histosols with large organic surface layers that accumulated mainly due to cold climatic conditions.[283] Naturally, these soils sequester annually about 0.1 Pg C.[284] Due to the lack of mineral matter, all these soils are very vulnerable to land-use change, particularly when it involves drainage. Between 1850 and 2015, ca. 50 Mha of bogs and fens were drained, half of it for agriculture, which released about 80 Pg carbon dioxide equivalent (CO_2e).[285] This carbon loss, however, can be significantly reduced if not even reversed when such ecosystems are rewetted[286] and restoration of organic soils matches up with a carbon sequestration potential of 0.1-1.3 Pg C yr^{-1}.[287]

The current net flux of carbon from the atmosphere to terrestrial ecosystems is 3.1 Pg yr^{-1}, which is about 30 % of the total CO_2 flux by fossil fuel combustion.[28] Hence, natural-based carbon solutions can contribute significantly to climate change mitigation, but cannot be the sole solution. Utilizing renewable energy sources such as wind, solar, and hydroelectric power can replace fossil fuels that emit CO_2 into the atmosphere, while the use of carbon capture and storage technologies will additionally help to reduce the amount of carbon released into the atmosphere from industrial processes.

Afforestation and forest ecosystem restoration. Limiting global warming to the 2 °C threshold set by the Paris Climate Agreement requires both reducing emissions and removing GHGs from the atmosphere.[288,289] Therefore, terrestrial ecosystems play a critical role in climate change mitigation alongside the large reductions needed in fossil fuel consumption. As indicated above, over the past ten years, terrestrial ecosystems have removed ~30% of human carbon emissions each year,[28], and forests account for most of this uptake.[290,291] Afforestation and reforestation, key approaches in natural climate solutions (NCSs), have been focused on for decades as potential major contributors to climate change mitigation.[290,292,293] With a potential annual climate mitigation contribution of up to 7 Pg CO_2e by 2030 at a carbon price of \$100 per Mg CO_2e, afforestation, and reforestation are among the most cost-effective and viable NCSs for mitigating climate change.[294] However, while forest-based strategies are currently the widely accepted and practiced methods for carbon sequestration, recent studies have indicated possible limits and climate-driven risks to the climate mitigation potential of afforestation.[294,295] Moreover, Fleischman et al. [296] highlighted ten pitfalls and misperceptions when large-scale afforestation campaigns fail to acknowledge the social and ecological complexities of the landscapes they aim to transform. Thus, when planning and implementing afforestation activities, the expense, risk, and damage to ecosystems and humans due to poor designs and hasty implementation should be fully recognized and mitigated.[295,296]

Although terrestrial ecosystems are essential for carbon sequestration, approximately one-quarter of post-industrial GHG emissions have come from ecosystem degradation.[293] As a result, efforts to describe and quantify the potential contribution of ecosystem restoration to climate change mitigation have gained significant traction in climate policy discourse in many countries.[288,289] According to Strassburg et al.[297], restoring 15% of converted lands in priority areas at a global scale could prevent 60% of anticipated extinctions and sequester 299 gigatonnes of CO_2. This amount is equivalent to 30% of the total CO_2 increase in the atmosphere since the Industrial Revolution or 14% of total emissions. Although reforestation is still one of the most commonly used restoration measures, ecosystem restoration refers to more than reforestation or forest restoration. Many non-forest ecosystems, such as grassland and wetland, also provide great restoration potential for climate mitigation.[288,297] However, the implementation of restoration activities for biodiversity and carbon sequestration could face severe feasibility constraints and must also be aware of the risks of overstating the climate benefits induced by ecosystem restoration, which may undermine mitigation efforts and distract from the core task of reducing carbon emissions from energy and industry sectors.[298] Moreover, shifting restoration practices from ecologically centered actions to a synergy across climatic and social dimensions is critical for sustainable ecosystem restoration.[299] Therefore, long-term policies, monitoring frameworks, and standardized protocols for fully considering the benefits, costs, and risks of ecosystem restoration are urgently needed to realize the co-benefits of ecosystem restoration and climate mitigation.[300]

Potential and challenges of soil carbon sequestration to mitigate climate change. Crop production is one of agriculture's predominant sources of CO_2, N_2O, and CH_4 emissions.[301] However, croplands can become carbon sinks through soil carbon accumulation if they are managed purposefully and properly. Globally, annual land-based emissions of N_2O and CH_4 are approximately 17.0 Tg N yr^{-1} (7.96 Pg CO_2-eq yr^{-1}) [302] and 550-594 Tg CH_4 yr^{-1} (13.7-14.8 Pg CO_2-eq yr^{-1}) [303], respectively. Flooded paddy soils are an important source of global CH_4 emissions, accounting for 15%-20% of global anthropogenic CH_4 emissions. Thus, enhancing soil carbon sequestration and reducing GHG emissions from crop production is vital for mitigating climate change.

Soil carbon sequestration. Organic material (OM) amendment in soils is a common practice that has been shown to improve soil quality and crop yield by increasing soil organic carbon (SOC). For instance, the SOC stocks of croplands in China could be further increased by more than 25.0 Tg C yr^{-1} or 0.63% yr^{-1} with OM input.[304] Yet, simply adding OM (e.g., straw remains or animal dung) only increases the organic carbon content of the treated cropping fields, not the whole regions, because OM is still missing elsewhere.[280] This may be a different story if mulches are placed on cropping fields, such as from green clover in rotations, significantly improving SOC.[305] Biochar addition in soils has also been advocated as a viable alternative strategy for boosting SOC stocks due to its resistance to microbial degradations. According to a paddy field experiment by Liu et al.,[306] both straw and biochar additions were found to increase the topsoil SOC potentially. Additionally, it was found that the biochar treatment sequestered 2.6-fold more SOC than the straw treatment after six years, even though the carbon application rates of straw and straw-derived biochar were the same. This suggests that biochar addition in the soil may be more effective for sequestering carbon in paddy fields than straw.[307] Furthermore, the integration of biomass pyrolysis and electricity generation systems with biochar amendment can achieve carbon-neutral in staple crop production by reducing emissions through soil carbon sequestration and CO_2 emission mitigation because the electricity generated by bio-energy from pyrolysis displaces traditional emissions from fossil fuels.[308] However, a certain flux of energy-containing carbon input from plants (litter or crop residue return) is always needed to keep microbial soil functions active.[140]

Typically, reduced tillage or no-tillage can increase SOC sequestration in the upper soil layers (0-15 or 0-20 cm). For instance, no-tillage improved SOC storage by 5.85 Mg ha^{-1} after 11 years in a crop residue-retained farming system.[309] This fits well into the average magnitude reviewed by Six et al.[310] that approximately 325 kg SOC per ha that can be annually sequestered by no-till agriculture to a depth of 20 cm. Uncertainties derive, however, from increasing N_2O emissions[310] in selected observations of topsoils. SOC stocks in subsoils with conventional tillage were found to be higher than those under no-till management in the early years of adoption, but the initial carbon loss in the short term can be offset in the long-term run.[311]

Crop rotations with higher intensity and more aboveground biomass tend to enhance SOC stocks and reduce GHG emissions without sacrificing yields.[312] Specific options such as planting deep-rooting cultivars, can leave suberin-rich root carbon in the soil after crop harvest.[287]

N_2O emission reduction. Reducing nitrogen fertilizer application rate is vital for mitigating N_2O emissions from cropping soils.[313] Emission reductions can be achieved through regional nitrogen fertilizer optimization techniques based on the trade-off between economic risk and environmental benefit.[314] Mitigating N_2O emissions can also benefit from precision field management, such as soil pH adjustment, OM input, and decision support tools.[315] Two-thirds of the mitigation potential for N_2O emissions could be achieved on one-fifth of croplands in the world, mainly located in humid subtropical climates and across Gleysols and Acrisols.[316] Nitrification inhibitors, such as N-(n-butyl) thiophosphoric triamide (NBPT) and 2-(N-3,4-dimethylpyrazole) succinic acid (DMPSA) effectively reduce N_2O emissions and do not harm crop yields.[317,318] Reducing N_2O emissions can also be accomplished through other means, such as increasing the activity of N_2O-reducing organisms or N_2O-consuming microbes in soils through bioaugmentation or biostimulation.[319,320] Furthermore, research has shown that arbuscular mycorrhizal fungi can reduce N_2O emissions by promoting the growth of plants that have a high affinity for nitrogen uptake.[321] These plants can take up excess nitrogen from the soil, thereby reducing the availability of nitrogen for microbial processes that produce N_2O. Overall, enhancing these microbial processes has the potential to reduce N_2O emissions from agriculture while also improving soil health and productivity.

CH_4 emission reduction. Besides the reduction of losses during biogas production, intermittent irrigation or mid-season drainage is another important option for mitigating CH_4 emissions from paddy fields, as it is a result of inhibiting its production and increasing oxidation.[322] The plantation of suitable rice varieties could achieve CH_4 emission mitigation without negatively

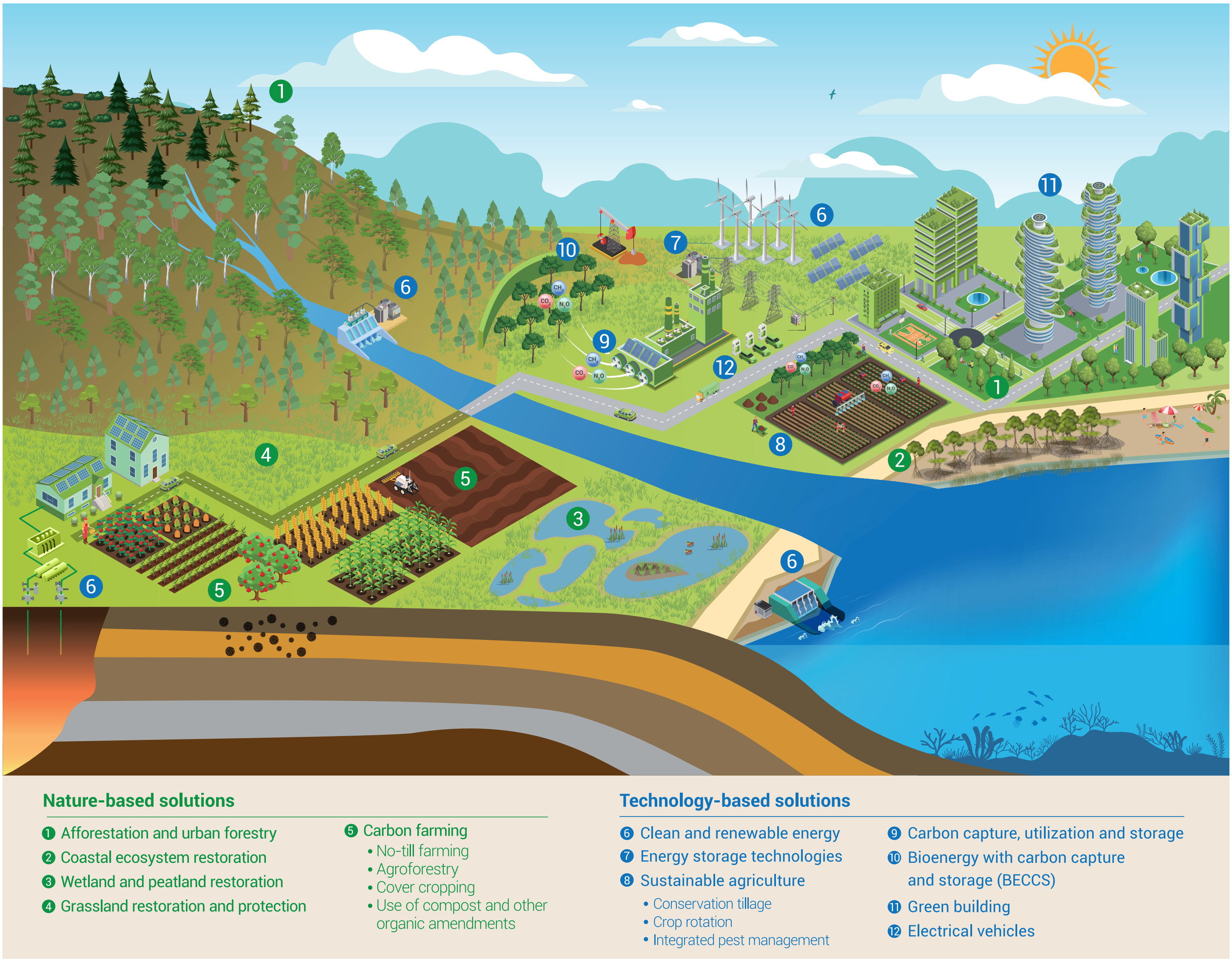


Figure 5. Nature- and technology-based solutions for climate change mitigation.

affecting crop yield. For example, high-yield transgenic rice with limited aerenchyma could reduce CH_4 emissions by up to 60%.[323] Applying biochar in paddy fields also reduced CH_4 emissions by up to 50% by improving soil aeration conditions.[324] Removal of rice straw, composting rice straw and manure, and applying sulfate-containing fertilizer are also considered potential options to reduce CH_4 emissions in paddy fields.[325] Reducing CH_4 emissions from paddy fields could be also achieved by the application of microbial CH_4 emission inhibitors[326-328] as well as through fertilization for enhancing CH_4 anaerobic oxidation.[329]

Adopting and developing organic farming. The global food system is also a major source of GHG emissions, emitting ~30% of the global total. The food system's emissions under business as usual are projected to reach 1356 Gt CO_2e between 2020 and 2100, which is projected to exceed the 1.5 °C limit between 2051 and 2063 and prevent the achievement of the 1.5 °C and 2 °C target even if fossil fuel emissions were immediately stopped.[330] In the five strategies for mitigation of the global food system GHG emissions.[330] organic farming can play an important role since it aims to supply high-quality food with a positive response to the climate change crisis using a sustainable production approach,[331,332] including implementation of an extended rotation, cover of herbaceous plants, reduced tillage or no-tillage, return of plant and animal residues as organic fertilizers, and limiting any synthetic input sources (chemical fertilizers and pesticides). Organic farming could provide a clue to solve the problem of climate change, as a climate-friendly way to economically use resources.

Organic farming technologies are helpful for agriculture systems to adapt to climate change. Increasing temporal plant diversity through crop rotation diversification as a form of organic farming helps enhance the resilience of the agriculture system to warmer, drier climates. Renwick et al.[333] show that diversifying maize-soybean rotations with small grain cereals and cover crops mitigated maize water stress at the leaf and canopy scales and reduced yield losses to drought by 17.1±6.1%. Herbaceous cover favors species richness and the abundance of insectivorous species whose populations are declining due to climate change.[334]

Organic farming technologies can potentially reduce global agricultural GHG emissions by increasing SOC.[331,335,336] Reducing the intensity of tillage, such as inter-row loosening, inter-row cutting, and shallow inversion tillage showed increased soil C stocks, minimal reductions in yield (~5.5%), and non-significant increases in weed incidence[337] since any form of tillage may result in the redistribution of carbon gains to deeper depths and mineralization of labile carbon fractions. Zani et al.[338] reported that integrated crop-livestock systems (ICL) increasing proportions of grass-clover leys compared with short non-grazed ley periods in crop rotations can play an important role in achieving a net carbon benefit. It is still a matter of debate whether organic systems have the potential to act as carbon sinks due to the influence of numerous specific factors on carbon decomposition and sequestration. These factors include soil type, plant type, and the properties of the organic amendment. The impact of these factors on carbon sequestration is complex and requires further research to gain a better understanding.

So far, the available evidence suggests that the impacts of organic compared to non-organic farming on soil-derived N_2O and CH_4 emissions are complex and context-dependent[339]. More research is needed to better understand the mechanisms underlying these effects and to identify best practices for reducing greenhouse gas emissions in agriculture. In the conventional cultivation (CVN) and zero-tillage (ZTL) plots (nitrogen-based inorganic fertilizers), the GWP was higher for CH_4 and N_2O compared with the system of rice intensification (SRI, organic manure as fertilizer). However, all three cultivation strategies acted as carbon sinks, with SRI cultivation yielding the highest sequestration values.[340] Skinner et al.[341] observed a 40.2% reduction of N_2O emissions per hectare for organic compared to non-organic systems. However, yield-scaled cumulated N_2O emissions under silage maize were similar between organic and non-organic systems. Cumulated CH_4 uptake on area scale under silage maize was modest for organic farming systems-biodynamic (BIODYN) and non-organic systems-solely mineral fertilization (CONMIN), and high CH_4 emissions for mixed farmyard manure (CONFYM).

Organic farming relies strongly on the farm's resources, hence the energy consumption per unit area of organic crops and farming could be lower than that of non-organic agriculture. For conventional sugar beet production, an efficiency ratio of 9.59, specific energy of 0.41 MJ kg^{-1}, and energy productivity of 2.41 kg MJ^{-1} were obtained by disc harrow soil loosening on 80-ha farms, whereas, for organic production, the lowest energy input (25862 MJ ha^{-1}) and specific energy (0.46 MJ kg^{-1}) and the greatest yield (55.82 t ha^{-1}), energy efficiency ratio (8.21), and energy efficiency (22.16 kg MJ^{-1}) were obtained using inter-row loosening on 80-ha farms.[336] The carbon emission ratio to carbon inputs of the most environmentally friendly conventional farming process involving no-tillage technology is 19.75, whereas the ratio of the most environmentally friendly organic farming process involving inter-row loosening is 4.85 with numbers close to zero approximating a neutral carbon balance.[336] Organic agricultural systems use organic fertilizers and eliminate synthetic chemical fertilizers and pesticides, thus reducing global agricultural GHG emissions.[335]

Whatever is grown on the field depends on food consumption, and changes in our global dietary patterns would significantly affect global CO_2 mitigation potentials. As outlined by Costa et al.,[342] this might shift from the current +21.4 Pg C yr^{-1} to -2 Pg C yr^{-1}, thus, turning a significant carbon source even into a carbon sink—not only by organic farming but also by related other management techniques, reduced meat consumption, etc. Agroecosystem's Life Cycle Analysis (LCA) is a good tool to evaluate and compare the impact of conventional and organic agriculture on environmental sustainability. Miksa[343] suggested that a reasonable crop mix within the crop rotation schemes may lead to the reduction of CO_2 emissions and mitigation of climate change based on the LCA of the whole crop rotation. Through a comprehensive LCA, Xai et al.[344] showed an integrated biomass pyrolysis and electricity generation system coupled with commonly applied C and nitrogen mitigation measures can help reduce staple crops' life-cycle GHG emissions from the current 666.5 to -37.9 Tg CO_2e yr^{-1}. Emission reductions would be achieved primarily through carbon sequestration from biochar application to the soil, and fossil fuel displacement by bio-energy produced from pyrolysis.

For future research, comprehensive assessment through combing energy efficiency, energy displacement, GHG emission capture, and carbon sequestration is necessary to develop innovation in organic farming techniques and to evaluate the role of organic farming on climate change.[331,345,346]

Technology-based solutions for climate change mitigation

Developing and adopting renewable and clean energy technologies. The expansion of the world population, globalization, and rapid industrialization rely on exploiting and consuming fossil fuels. Fossil fuels are hydrocarbon-containing materials formed naturally in the earth's crust from the remains of plants and animals. The main fossil fuels are coal, oil, and natural gas.[347] When humans are powering our modern and comfortable lifestyles with fossil fuels, there are significant hidden costs behind their market price.[348] The whole supply chain of fossil fuels (extraction, transportation, and use) leads to various adverse impacts on the environment and human health. Extraction processes cause severe CH_4 emissions, air and water pollution, and ecological harm to the surrounding area.[349] Accidents and leaks during the transport of fossil fuels can also have devastating effects.[350] Burning fossil fuels emits toxic chemicals, causing harmful effects on ecosystems and human health, and generating GHGs contribute to global warming.[351] Thus, it is urgent to explore renewable, sustainable, and environment-friendly alternative energy sources to meet future energy demands and ensure a safe and clean energy system for our planet.[352] Renewable energy sources, such as biomass, geothermal resources, solar, water, and wind, are natural resources that can be converted into these types of clean energy. It is estimated that renewables will transform the global power mix through 2027, becoming the largest source of electricity. Hydropower accounts for more than 90% of all grid-scale capacity, however, it is restricted by the availability of suitable locations and multibillion-dollar capital costs. Solar photovoltaic (PV) and wind account for almost 90% of all new renewable energy installations in 2022. Solar PV's installed power capacity is poised to surpass that of coal by 2027, becoming the largest in the world.[353] Noted that it is crucial to develop large-scale energy storage technologies to integrate intermittent and fluctuating renewable energy into the electricity grid.[354] Several technologies could be potential candidates for renewable energy and utility applications, including lithium (Li)-ion batteries, flow batteries, lead-acid batteries, supercapacitors, flywheels, compressed air energy storage, and hydropower.

Potential and impact of carbon capture, utilization, and storage on global change. Carbon capture, utilization, and storage (CCUS) is a process that involves capturing CO_2 emissions from industrial processes or power generation, utilizing the captured CO_2 for various purposes, and storing the remaining CO_2 in geological formations or other long-term storage facilities.[355] CCUS is considered a critical technology for reducing greenhouse gas emissions and mitigating climate change.[356] In this process, CO_2 is captured from emission sources such as power plants or directly from the air that is then transported to be stored in geological sites for a long time or to be converted into products. By reducing CO_2 emissions from fossil fuels or recovering CO_2 directly from the air, CCUS plays an important role in global warming mitigation (Fig. 5). CCUS can make significant contributions to global GHG emission reduction, and without CCUS the CO_2 equivalent concentration in the atmosphere cannot be controlled below 450 ppm in 2100.[357] IPCC [86] reported that CCUS can reduce CO_2 emissions by 3.0-6.8 billion tons per year in 2050, and in International Energy Agency (IEA)'s sustainable development scenario, CCUS can contribute to 15% of the accumulated CO_2 emission reduction to realize net zero emission in 2070.[358] In the energy sector, CCUS is the only technology to realize near-zero-emission through the utilization of fossil fuels, and coal power plants equipped with CCUS can enforce the flexibility of the whole energy supply systems.[357] Besides, in steel and cement industries, CCUS can also contribute around 34% and 48% to achieve net zero CO_2 emissions.[357] Also, when combined with direct air capture or bioenergy, CCUS can realize negative CO_2 emissions, and thus, can create emission space for other technologies. Direct air capture (DAC) may be one of the last technical solutions to capture CO_2 directly from the air, and this technology is still in its research and development (R&D) stage and is expected to play an important role in the future.[358] Bioenergy with carbon capture and storage (BECCS) is attractive to energy systems by providing energy and storing carbon at the same time, which is widely employed to balance over-budget emissions.[359] Considering the cost-effectiveness, BECCS is promising for its technological maturity, including biomass energy acquisition, CO_2 capture, transport, and storage,[360] commercial maturity,[361], and a high potential for application in vast rural areas.[362] However, the large-scale deployment of BECCS also raises concerns about its impact on the environmental and ecological systems, due to its large demand for land in growing plants,[363] potential threat to biodiversity,[364] soil erosion and degradation,[365] pressure on the terrestrial and freshwater systems,[366] as well as the additional demand for fertilizers to reach nutrient balance in agricultural systems and the associated GHG emissions.[367]

Smart management of agri-food systems in the face of climate change. To achieve ambitious mitigation targets, we need to smartly implement mitigation technologies and improve the structure of agri-food systems, since it was responsible for one-third of anthropogenic GHG emissions.[368] Better irrigation practices to reduce CH_4 emissions from rice cultivation,[369] and improved dietary management to reduce CH_4 emissions from ruminant animals,[370] need to be taken as priorities over all other measures for the purpose to control temperature increases smartly and quickly. This will save more space and time for other sectors and was highly recommended by the latest Conference of the Parties (COP) 26.[371] In addition, there are large differences in GHG emissions intensity between different crop products and livestock products, expressed in the CO_2e emission per kilogram of protein or kcal of calorie produced, with few products contributing little to total food production but responsible for the majority of GHG emissions.[372] These products need to be identified in the future and should be replaced by low-emission intensity but high-yield products.

A smart crop production system requires to re-design the crop production structure towards crops with less environmental and carbon footprints. In addition, consideration should be given to the spatial redistribution of crops in regions suitable for intensive management where the water supply is sufficient and the productivity is high.[370,373] Together with new technologies to boost crop productivity, such as genotyping, marker-assisted selection, and genome editing,[374] these measures will free more land for bioenergy production to reduce GHG emissions or for afforestation to increase carbon sequestration. In addition, measures to smartly enhance the efficiency of synthetic fertilizers via modifiable chemical structures and engineered, biodegradable coatings which respond to plant rhizosphere signaling molecules, could precisely supply nutrients to crops, and thus, largely reduce ammonium (NH_4) losses and GHG emissions during fertilizer application.[375]

Smart livestock production systems could be achieved through better livestock production structures, such as a slight switch from monogastric to ruminant animals to reduce GHG emissions, due to better food waste recycling and less concentrated feed requirement of ruminant animals compared to monogastric animals.[376] Spatial planning of livestock production is necessary in a few large countries with unevenly distributed livestock production, to close the nutrient recycling loop between crop and livestock production, and to reduce the demand for synthetic fertilizers as well as related energy use and emissions.[377]

Smart adjustment of the crop and livestock production structure is necessary since GHG emissions from livestock production systems were twice that from crop production.[368,378] Adjusting food production according to the EAT-Lancet diet will considerably reduce GHG emissions,[379] such as choices towards more plant-based diets. New farming technologies, such as food waste-based insect production as food for humans or feed for livestock,[380,381] natural gas-based microbial protein production,[382] and cultured meat,[383] with no competition for land and demand of natural resources, also provides sound mitigation potentials.

ADAPTATION TO CLIMATE CHANGE

Terrestrial and freshwater ecosystem-based management

Terrestrial and freshwater ecosystems, from the tropics to the frozen land of the polar regions, are also markedly threatened by climate change.[384,385] Thus, management measures are pressing and should adapt to climate change to prevent disastrous environmental and social-economic consequences.[386,387] One option for significantly increasing the resilience of vulnerable terrestrial ecosystems is ecosystem-based management (EbM)—an approach that manages ecosystems and their associated functions to reduce a range of climate change risks to people, biodiversity, and ecosystem services with multiple co-benefits (Fig. 6).[388,389] As a nature-based solution to climate change, EbM is increasingly being recognized by governments and academia as an effective measure to provide considerable co-benefits relating to climate change adaptation and terrestrial ecosystem conservation.[387,390] For instance, Scheiter and Savadogo[391] indicated that effective ecosystem management can mitigate vegetation shifts induced by climate change in West Africa.

In recent years, substantial progress in EbM has been observed across the world with various terrestrial and freshwater ecosystems, especially forests[392,393] and lakes.[130,131] The promising EbM measures for natural and managed forests include comprehensive conservation and restoration, optimal rotation strategies, diversifying tree species and compositions, and alleviating increased risks from diseases and wildfires.[388,394] Studies of lakes have revealed that many of the symptoms of climate warming as similar to those of eutrophication occurring as a result of excessive nutrient input, which means that the negative effects of warming can be partly mitigated by reducing the nutrient input from the lake catchments.[130,131] Such measures may also result in lower GHG release from lakes.[395] Thus, supportive public policies and novel technologies, together with effective EbM measures may enhance the resilience and stability of terrestrial and freshwater ecosystems to adapt to climate change.[3,396,397]

Despite great progress in recent years, there are still large gaps and challenges in managing terrestrial and freshwater ecosystems for climate change adaptation.[385,389] For example, most terrestrial EbM measures are fragmented, small-scaled, sector-specific, designed to respond to immediate and near-term risks, and focused more on planning rather than implementation.[388,394] Additionally, terrestrial and freshwater EbM measures are unequally distributed worldwide, and gaps are partially driven by widening disparities between the estimated costs of measures and the actual financial support.[394,398] Furthermore, EbM measures are vulnerable to climate change impacts, with effectiveness declining and even reaching their limits with increasing global warming. Ecosystems that have already reached or surpassed their management and adaptation limits might include some drylands and polar and mountain ecosystems.[384,389] Therefore, in the implementation of terrestrial and freshwater EbM measures, it is necessary to fully consider not only the feasibility and effectiveness of the measures but also their limiting factors and conditions to avoid maladaptation.

Coastline protection and combating sea level rise

Coastline protection and rising sea levels are important issues affecting many coastal communities and ecosystems. Sea level rise projections for 2100 vary depending on different scenarios of GHG emissions and ice sheet dynamics. According to some sources: The National Climate Assessment reports that the global sea level has risen by about 0.24 m since 1880 and is projected to rise another 0.3-1.2 m by 2100. Kopp et al.[399] predicted a very likely (90% probability) global sea level rise of 0.5-1.2 m under representative concentration pathway (RCP) 8.5, 0.4-0.9 m under RCP 4.5, and 0.3-0.8 m under RCP 2.6 between the years 2000 and 2100.

Sea level rise can have serious impacts such as flooding, erosion, saltwater intrusion, habitat loss, infrastructure damage, displacement, and increased vulnerability to storms.[400,401] Therefore, it is important to take action to reduce emissions and adapt to changing conditions.[402] There are different strategies to protect coasts from sea level rises, such as hard engineering (e.g., concrete seawalls, levees, and dikes) or soft engineering (e.g., nature-based solutions, living shorelines, and beach nourishment) (Fig. 6). Recent studies suggest that nature-based solutions can be as effective as concrete seawalls at protecting against sea-level rise while providing extra benefits such as habitat creation, carbon sequestration, and recreation.[403-405]

Nature-based solutions are approaches that use natural processes and ecosystems to address environmental and social challenges such as climate change, biodiversity loss, disaster risk reduction, food security, water management, and human well-being.[406] The nature-based solutions for sea level rise and coastal protection include: 1) Conserving coastal wetlands: Coastal wetlands and mangroves are periodically flooded by saltwater. They can buffer wave energy, trap sediments, reduce erosion, and provide habitat for wildlife,[407,408] 2) Restoring beaches: Beaches are sandy shorelines that can absorb wave impacts, prevent flooding, and support recreation and tourism. They can be restored by adding sand or vegetation to replenish eroded areas, 3) Creating oyster reefs: Oysters are bivalve mollusks that form reefs by attaching to hard substrates. They can reduce wave height, stabilize shorelines, filter water quality, and enhance fisheries, and 4) Restoring mangroves: Mangroves are trees and shrubs that grow in tropical and subtropical coastal areas. They can protect coasts from storm surges, sequester CO_2,[409] prevent saltwater intrusion, and host diverse species.[410-412]

These nature-based solutions can offer multiple benefits such as reducing GHG emissions,[413,414] enhancing biodiversity conservation, improving human health and well-being, and creating jobs, and livelihood opportunities. However, nature-based solutions also face some challenges such as a lack of funding, policy support, technical knowledge, and stakeholder engagement.[415,416] For example, many developing countries lack the financial resources to implement large-scale nature-based solutions projects.[417] In addition, policymakers may prioritize other issues over nature-based solutions or lack the technical knowledge to design effective policies. Moreover, stakeholders such as local communities or private sector actors may not be sufficiently engaged in the planning and implementation of nature-based solutions projects. Therefore, all people from different sectors must work together to address these challenges. Governments should provide funding and policy support for nature-based solutions while also engaging with stakeholders to ensure their participation in decision-making processes. Private sector actors should invest in nature-based solutions as part of their corporate social responsibility strategies while also exploring business opportunities in this field. Civil society organizations should raise awareness about the benefits of nature-based solutions and advocate for their inclusion in policy agendas.

Another important pathway of climate change adaptation is the transformation of the social-ecological system. In the Mekong Delta of Vietnam, for instance, the sea level rises together with other factors like increased groundwater use, hydro dam constructions, and less water in the Mekong itself have caused salt intrusions into the delta that are a risk to rice production. However, land use may change – in this case, for instance, from rice to rice-shrimp farming systems, which maintain both fertility of the soil, flexibility to future salt-water intrusions, and higher economic return, though also at higher investments.[418-420] In other areas, the response to climate change differs, as evidenced by the construction of sophisticated dams in the relatively level terrain of the Red River Delta. Hence, adaptation measures exist, but they are site-dependent, and do not only depend on the ecological but also socio-economical or -political settings.

Climate-smart agricultural practices and regenerative agriculture as instruments in a carbon economy

Climate-smart practices, such as crop residue management, reduced tillage, soil amendments (e.g., biochar), and cover crops aim to sequester soil carbon and reduce GHG emissions. A global meta-analysis with 3,049 paired measurements found that biochar applications most effectively increased SOC (39%) followed by cover crops (6%) and conservation tillage (5%).[307] Meta-analyses showed that soil carbon is also improved by no-tillage and other conservation measures,[421-424] but this improvement depends on the sampling depth and other environmental factors.[421,424] Crop yields may increase when soil carbon (organic matter) increases[425] and when conservation measures are implemented under certain conditions,[426] though this varies geographically.[423,426,427]

Despite these overall trends, each country, region, and each farm have specific soil, landscape, and climate conditions, and are subject to supply, trade, logistics, labor, and policy chains. Farmers have their own experiences, personal interests, and world view, and may be more or less inclined to adopt climate-smart practices and join climate mitigation and carbon-focused initiatives. Positive environmental co-benefits for crop and soil health and soil security are associated with the sequestration of carbon in soils.[428] Carbon and environmental education as well as public and private incentives are ways to sensitize unaware producers and consumers and convince undecided farmers to adopt climate-smart practices intended to accrue soil carbon. Before and beyond climate mitigation, the positive effects of soil carbon (organic matter) on nutrient retention and supply,[429] water retention,[430,431] biodiversity,[432] pollution control,[429] and erosion control[432] improve soil health and security[433] while increasing or sustaining crop yields[434,435] with benefits for the farmer and the environment.

Development of climate-resilient crops

Climate change significantly impacts plant agriculture and is a growing threat to global food security.[436] More food is needed to feed a growing world population, but there is not enough agricultural land to grow crops to produce the needed food.[437] Increasing food production on existing farmland is a critical component of efforts to reduce deforestation and preserve forests. By adopting sustainable farming practices, investing in precision agriculture technologies, promoting agroforestry practices, and developing new climate-resilient crop varieties, we can ensure a more secure food supply while protecting our planet's precious natural resources. The changing climate has led to more frequent and severe weather conditions such as heatwaves, droughts, and floods. These extreme weather conditions can cause crop failure, reduced yield, and reduced crop quality. It was estimated that every degree Celsius increase in temperature could lead to a 6% reduction in global wheat yields.[438] Other studies have shown similar impacts on crops such as maize, rice, and soybeans. The statistics highlight the urgency of developing climate change adaptation strategies for plant agriculture to ensure food security.

Heat tolerance is a critical agronomic trait for crops, particularly in the context of climate change. Rising temperatures can cause significant damage to crops affecting their growth and development, reducing their yield and quality, and exacerbating other stresses such as drought, pests, and diseases. Therefore, developing heat-tolerant crop varieties is crucial in mitigating the negative impacts of climate change on agriculture. Crop breeding efforts to develop heat-tolerant crop varieties focus on photosynthesis efficiency, antioxidant systems, and the ability to quickly repair damages caused by high temperatures in specific plant tissues such as leaves or reproductive organs.[439] In addition to heat tolerance, drought, and flooding are other significant stressors that affect plant agriculture. Drought can lead to reduced yields, crop failure, and decreased crop quality by reducing the amount of water available for plant growth. Conversely, flooding can cause root suffocation, soil erosion, nutrient leaching, and damage to crops. Therefore, developing crops that are tolerant to drought and flooding is also important in adapting to climate change. The development of climate-resilient crop varieties should be combined with soil quality and water management practices. Implementing conservation agriculture and drip irrigation techniques can significantly improve soil quality and water management practices. Conservation agriculture involves minimal soil disturbance, crop rotation, and cover crops to enhance soil health and reduce erosion. This technique also helps to increase the soil's ability to absorb water, which can mitigate the impact of extreme weather events such as heavy rainfall or drought. Drip irrigation is another effective method for managing water resources in agriculture. This technique delivers water directly to the roots of plants slowly and steadily, reducing water loss due to evaporation and runoff. By providing plants with the right amount of water at the right time, drip irrigation can improve crop yields and reduce the risk of water stress during periods of drought.

Another strategy for crop adaptation to climate change is increasing the fertilizer use efficiency of crops. This can be achieved through plant breeding and precision farming techniques such as variable rate fertilization that allow for more targeted and efficient use of fertilizers. Such efforts can reduce the amount of fossil fuels required to produce fertilizers and thus help to reduce GHG emissions. In conclusion, climate change has significant impacts on plant agriculture, and crop adaptation strategies are needed to ensure food security in the face of changing weather conditions.[436] Developing crop tolerance to heat, drought, and flooding, improving soil quality and water management practices, and increasing fertilizer use efficiency are some of the key strategies that plant agriculture can use to adapt to climate change. Plant breeding is traditionally a lengthy process since developing an improved crop variety often takes more than 10 years. Breeding for climate-resilient crops is especially challenging because projections of future climate and weather patterns exhibit much uncertainty.[440] To meet this challenge, breeding programs must adopt new approaches such as genome editing and genomic selection that can significantly accelerate crop breeding.[441] In addition, it is important to utilize the wide natural genetic diversity in landraces, wild relatives, and orphan crops, many of which possess climate resilience traits that have been lost in our main crops.[442]

Address and plan for environmental change

Plans for adapting and mitigating climate change-induced environmental problems should be combined with urgent applicable solutions/actions for reducing environmental pollution/degradation.[443,444] Addressing global issues related to climate change, such as the sustainable management of global warming and the induced/associated changes on soil health, air pollution, water, and food security, waste management, and finding alternative energy sources are the major challenges of the 21st century and needed to achieve the United Nations Sustainable Development Goals (UNSDGs).[445] Reducing climate change-induced environmental pollution aligns with the zero pollution vision for 2050 and is urgently required to decrease the levels of pollutants in air, water, and soil to mitigate the potential ecological and human health hazards associated with climate change.[446] These aims also meet the 2030 key targets to reduce pollution sources. These targets include improving air, water, and soil quality, aiming to reduce the number of premature deaths caused by pollution, and reducing the release into the environment, which will help strengthen the green and economic environmental growth and create a healthier, socially fairer planet.

Reducing pollutants in the air is important for human health and the environment. Therefore, we urgently need to control and reduce multi-pollutant emissions, decrease the concentrations of particulate matter in the air, regulate the use of small coal-fired boilers, accelerate desulfurization and de-nitrification, improve the quality of the fuels, and control urban dust including the release of brake and tire wear materials from traffic systems.[443,447-449]

Harnessing soil carbon sink capacity for adaptation and mitigation of climate change, reducing soil erosion and including it as a source for GHGs in the global carbon budget, enhancing the use efficiency of agro-ecosystems inputs, using global dry-lands, and restoring degraded soils are among the most important soil-centric options for addressing global issues.[450] Remediation of degraded soils and reducing GHG emissions from soils could be achieved via the application of organic amendments such as crop residue return and biochar.[445,451,452] Those actions could contribute to the mitigation of climate change-driven negative impacts and enhance the strategy of "producing more from less", which achieves the Sustainable Development Goals or the Agenda 2030.[450] Finally, coupling citizen science with advanced technologies such as remote sensing and sensor networks can provide more accurate information about pollution and environmental degradation in near real-time.[416,453-455] This approach can help researchers, policymakers, and the general public make informed decisions about planning for and addressing these environmental issues.

Efficient risk management of extreme weather events

Extreme weather events have become more frequent and severe in recent years due to climate change. From hurricanes and tornadoes to floods and wildfires, these disasters have caused significant damage to both human life and property.[456] Under climate anomalies, rainfall, and extreme weather that occur only once in decades have become more common. In 2020, massive floods occurred in China's Yangtze River basin, with precipitation exceeding that of the great floods in 1998, causing massive casualties and economic losses.[457] Only two years after a devastating flood, a rare and extremely severe drought hit the entire Yangtze River Basin in 2022.[458] This drought greatly negatively impacted various aspects of life in the region, including agriculture, transportation, and energy production.[459] This event highlights the vulnerability of regions that are heavily dependent on a single river system for their livelihoods. Similarly, floods in developed cities, such as Zhengzhou in China and Seoul in Korea, have become more common.[460,461] Due to the dense population and facilities in large cities, flood disasters tend to cause great economic losses. Sponge city construction to create water retention areas in urban construction design can assist in mitigating extreme climatic events. Meanwhile, coastal areas prone to more intense hurricanes require rethinking vulnerabilities and risk management. In the mountainous area, more attention should be directed toward geohazards induced by rising temperatures, such as snow avalanches and glacier lake outbursts.

Generally, we need to effectively consider the impacts of climate change on engineering construction and natural disaster risk assessment.[462] Considering and taking into account extreme events based on factor analysis is essential for effective risk management and decision-making.[463] By doing so, individuals and organizations can better prepare for potential disruptions and adapt to their impacts. Secondly, prevention and control measures are important means to protect life and property, and more space should be reserved to allow extreme weather.[464] In addition, efficient national early warning systems are important as unexpected extreme weather becomes frequent.[465] Meanwhile, for the residents, it is necessary to pay great attention to unusual weather and eco-disasters that impact the lives of people.[466] In short, more education is needed to raise public awareness of extreme weather and related natural hazards. By understanding the link between climate change and extreme weather, preparing for these events, and understanding the economic consequences, individuals and communities can take action to reduce their risk and adapt to the impacts of these events. In addition to raising awareness, leveraging existing technologies to track extreme weather is essential for reducing the effects of climate change (see Section 6.1). Real-time observations of weather patterns can help governments make informed decisions about disaster response efforts and infrastructure development.[467] Satellite platforms are an essential tool for monitoring global weather patterns. These platforms provide a comprehensive view of the Earth's atmosphere, allowing scientists to track weather systems as they develop. Ground-based monitoring stations also play a critical role in observing local weather conditions. These stations collect data on temperature, precipitation, wind speed, and other variables that are used to create accurate weather forecasts. Overall, the combination of raising public awareness and utilizing advanced technologies for monitoring extreme weather events is essential in developing effective solutions to mitigate the impacts of climate change.

Urban soil for adaptation to climate change

Given more than half of the population resides in cities, with this fraction likely to grow to between 60% and 92% by the end of the 21st century,[468] the state and functioning of soils in urban spaces are particularly important foci.[469] For millennia, soils have been deeply embedded in urban spaces and livelihoods,[470] but they now have increased importance in helping to combat the intensifying impacts of climate change.[471]

One of the ways by which urban soils can help mitigate climate change is to support the growth and functioning of urban green infrastructure (UGI). This refers to natural and semi-natural areas and features, including parks, green walls and roofs, street trees, rain gardens, and other vegetated spaces within urban areas, contributing to the swamp cities' concept for retaining water in the cities for irrigation purposes and cooling.[472] Whilst each of these UGI forms is designed to meet specific local priorities, they share a common dependency on urban soils. UGI can help to mitigate the impacts of climate change in multifarious ways such as capturing and storing carbon,[473] providing shading to regulate microclimate,[474] and ameliorating urban heat islands.[475] More indirectly, UGI can improve air quality [476] and reduce building energy use,[472] as well as foster more sustainable behavior patterns (e.g., facilitating greener transport options).[477]

In addition to UGI, urban soils provide essential resources to support urban agriculture. Urban food growing practices can bring about similar climate change mitigation benefits as UGI [478] but food cultivation within towns and cities can also strengthen an urban population's resilience to the multiscalar threats that climate change poses to global food supply chains.[479] From short-term and localized natural disasters induced by climate change to longer-term and global scales of land degradation, food-growing activities can help to supplement more traditional agriculture by spreading the risk of disruption to food supplies and adapting to future climate change.

As well as providing a medium for plant growth, the properties of urban soils can also directly mitigate the impacts of climate change. For example, in regions experiencing increasing precipitation intensity, urban soils, and retention spaces serve to reduce flood potential by infiltrating and storing water.[480] This is especially pertinent given the pervasiveness of impervious materials used within the urban grey infrastructure.[481]

A paradox remains to be resolved which involves facilitating urbanization in the future that requires more land to house more people, yet more land for agricultural food production will also be required to sustain these increasing urban populations.[470] Overall, adapting urban soils to climate change requires a multifaceted approach that addresses both structural and functional aspects of soil health. By implementing best practices in urban soil management and utilizing new technologies (such as the use of biochar as a soil amendment), cities can create more resilient and sustainable urban ecosystems that are better equipped to withstand the challenges of a changing climate.

Infrastructure transformation for adaptation to climate change

The current state of play. The impact of climate change on the natural, economic, political, and social environments is broad and pronounced. Human activities are a significant contributor to the cause of climate change;

Figure 6. Ecosystem-based management options for the adaptation to climate change in global systems.

they have altered the natural environments in all parts of the world through GHG emissions into the atmosphere.[482] Within the built environments, various types of green, blue, and grey infrastructures are designed and operated to provide important services for human safety, health, the environment, and economic development. Blue-green infrastructure refers to infrastructure aiming to restore the natural water cycle, while grey infrastructure refers to human-engineered approaches to water management such as pipes, stormwater treatment ponds, and hard surfaces. However, the United Nations Environment Programme highlighted that engineered grey infrastructures are responsible for 79% of all GHG emissions, and account for 88% of all adaptation costs.[483] These infrastructures are also affected by the physical impacts of climate variability in numerous ways.[484-486] For instance, the increased frequency and intensity of hydrometeorological hazard events such as floods, droughts, heatwaves, and wildfires are costing lives, disrupting economies, and setting back development progress that has taken years to establish.[487] Rübbelke & Vögele[484] analyzed the consequences of climate-change-related impacts on European critical infrastructures. In particular, they examined how the exchange of electricity between countries in Europe is threatened by climate change because of the higher risk of water supply shortages due to more frequent drought and heat-wave incidences. Similarly, the United Kingdom experiences a significant impact due to the natural variability of climate. This variability in natural environmental conditions can increase the frequency of severe weather events, such as flooding and heat waves, leading to increased urban infrastructure disruption.[488-490]

Changes in long-term trends (e.g., a rise in average temperatures, precipitation, sea level) along with the associated natural hazards (e.g., floods, droughts, heatwaves, landslides) can reduce the capacity or efficiency of infrastructure functionality and benefits. These increases and shifts can alter the design life of infrastructure and the effectiveness of its services. Therefore, failure to consider and plan for infrastructure transformation that can cope with climate change-related challenges could lead to increased disruption of a whole range of services that we rely on, such as heating, lighting, sanitation, and transportation and thereby hamper economic growth.[491] There is a growing need to transform how infrastructure is planned, implemented, and managed as urbanization, digitalization, and climate change increasingly impact the world. In such cases, existing built infrastructure may need to be retrofitted with nature-based interventions or managed differently to mitigate and adapt to climate change.[416,492] For example, infrastructure networks built with less vegetated surfaces or purely grey materials decreases evaporative cooling, and on the other hand, capping of previously pervious surface leads to increased runoff and an increased risk of flooding.[493,494] Furthermore, countries during the COP26 re-affirmed their commitments to climate action, including through the submission of their revised nationally determined contributions under the Paris Climate Agreement. Such actions advance mitigation and adaptation objectives set out in the agreement and can also protect and enhance progress towards related targets of the Sustainable Development Goals.[483]

Future development. Climate change poses a critical threat to the development of future infrastructure, especially in regions where poverty is prevalent and the key assets such as urban-built infrastructure are underdeveloped for meeting even the current needs let alone the needs in the future due to every growing urbanization.[495] Due to increases in GHG concentrations, increases in global average temperature are expected to be within the range of 1.1 °C to 5.4 °C at the end of the 21st century. Changes in the future projections of precipitation and storm will vary by season and region. Some regions may have less precipitation, some more precipitation, and some may have little or completely dry.[496] Therefore, precipitation extremes and the associated hazards often cause infrastructure damage, agricultural losses, and deterioration of freshwater and coastal water quality. For instance, decreased precipitation can lead to increased water pollution due to a drop in water flows; increased air and water temperatures lead to more rapid evaporation; and a sea level rise could affect both the availability and quality of water supply due to saltwater intrusion into groundwater aquifers and distribution networks.[488] Therefore, new/future infrastructure assets should be prioritized, planned, designed, built, and operated to account for the climate changes that may occur over their lifetimes. Scenario modeling studies demonstrate that the effectiveness of nature-based management strategies depends on future climate conditions, such as the extent of warming, and global wind speed.[497] For example, Wada et al.[498] demonstrated that the most cost-effective methods for forest restoration must consider the variation of wildfire risk and water availability under current and future climate change scenarios. Meanwhile, Krauss et al.[499] reported that the extent to which mangroves adapt to the rise in sea level through soil accretion and hence the protection of coastal communities depends on the rate of sea-level rise under future climate change scenarios. Similarly, Langridge et al.[500] identified where and to what extent nature-based interventions can protect engineered coastal defenses, coastal populations, and farmland from coastal flooding and erosion in the changing climate.

From traditional infrastructure to climate-resilient infrastructure. Infrastructure networks are assets, interdependent, and long-lived across sectors. Decisions made now about the design, location, and operation of these assets will determine their longer-term resilience to the impacts of climate change.[501] Improving resilience in this area is important to climate adaptation and mitigation, particularly since adequate, reliable infrastructure underpins future development. The continued global trend towards increasing urbanization requires a rethink of how cities and metropolitan regions are built and operated to remain functional in the coming decades. Cities produce more than 70% of the global CO_2 emissions.[502] Thus, climate change-responsive management of urban systems is key in our efforts to reduce CO_2 emissions markedly.[503] As the impact of climate change becomes increasingly apparent, cities worldwide recognize the need to adapt their infrastructure to mitigate its effects. This will require significant changes to complex urban infrastructure, which will take time and require careful planning. Retrofitting existing infrastructure will also be necessary to make it more resilient to the impacts of climate change. In the meantime, cities must be prepared to handle the amplified stresses and shocks exerted by the environment at all spatial scales. Ideally, changes in urban infrastructure must aim to improve the capacity for mitigation and adaptation simultaneously to address the challenges posed by climate change (Fig. 6). By doing so, cities can become more sustainable and resilient for current and future generations.[504] Recent research has found that expanding Urban Green Infrastructure is the most effective tool to achieve this.[505] Especially trees play a major role in reducing land surface temperatures of cities by up to 12 K.[506] Urban trees also help to reduce the risk of flooding by absorbing stormwater[507,508] and provide a large number of other co-benefits that assist in climate change adaptation.[509] However, increasing surface albedo[510,511] and replacing impervious with pervious surfaces[512] are additional proven techniques to mitigate the thermal impacts of overheating and associated loss of human lives in cities.[513] NBS will play a key role in this transformative process (see Section 4.1). However, in our expanding and densifying cities, these NBS must not only cope with the existing stressors like pollution and disturbance but they must be designed to cope with the climate extremes they are designed to mitigate, including storm surges, extreme temperatures, and drought.[514] It thus becomes inevitable that holistic concepts like that of regenerative cities are implemented.[515] NBS will survive and thrive in regenerative cities because these cities address resilience not only at the street or precinct scale but help transform their entire metabolism, lessen their regional impact, and reduce their contribution to global climate change.[516]

When embedded in infrastructure development, climate resilience can protect investment returns, support business continuity, and meet regulatory requirements.[501,517] Therefore, climate-resilient infrastructure should be planned, designed, built, and operated in a way that anticipates, prepares for, and adapts to changing climate conditions. The future planning to design and develop regenerative infrastructure should consider protecting key biodiversity regions, maintaining ecological connectivity, and considering holistic benefits to human and environmental health.[518]

Nature-based solutions (NBS) or natural climate solutions are part of the response to limiting climate change and could also help address the interlinked crisis of global biodiversity losses.[519-521] Natural climate solutions, involve conserving, protecting, restoring, or better managing ecosystems to remove CO_2 from the atmosphere. For example, allowing forests to regrow, restoring coastal wetlands and freshwaters, and switching to restorative agricultural practices that support healthy soils, such as cover crop rotation. These ecosystems reduce climate change by enhancing their ability to sequester CO_2 in plants, soils, and sediments and once more become 'net sinks' of carbon (meaning they store more carbon than they emit). They also provide a wide range of other important benefits, such as cleaner air and water, natural hazard management, economic benefits, and increased biodiversity.[522] Many studies explored the important function of NBS, that is, the network of green and blue space in a city can play a key role in adapting them against climate change-induced natural hazards[487,493,521,523] and climate resilience of urban energy systems.[524,525]

Climate-resilient infrastructure can improve service provision reliability, increase asset life and protect asset returns.[500] Building climate-resilient infrastructure involves approaches that restore, protect, or enhance natural systems. Some examples of climate-resilient natural infrastructures include: (1) avoiding emissions through protecting landscapes where deforestation and land-use change are restricted; (2) restoring ecosystems, such as drained peatlands, to enhance carbon sequestration; (3) improving degraded habitats by bringing ecological diversity into landscapes dominated by singular species; (4) improving management practices of farmed land such that emissions are reduced and sequestration of carbon is maximized; (5) allowing waterways to meander along their natural courses to reduce flood risk; and (6) better-integrating nature into urban areas and agricultural landscapes. Protection, restoration, and enhancement of natural habitats to defend infrastructures against the impacts of climate change are practical and cost-effective approaches that can be and are implemented in many regions of the world. However, decision-makers, planners, architects, and engineers need to collaborate and work together to support these efforts, particularly in the area where familiarity with traditional grey-built infrastructure may lead to skepticism about the role of NBS and natural infrastructure. Moreover, infrastructure resilient to climate change could help the achievement of the goals of the Paris Agreement, while at the same time supporting efforts to achieve a number of the Sustainable Development Goals and enable the implementation of the Sendai Framework for Disaster Risk Reduction.[525-527]

CARBON QUANTIFICATION, MODELING, AND PRICING

The role of space technology and remote sensing in the fight against climate change

Cost-effective assessment of land-based carbon sequestration and reduction of GHG emissions using remote sensor technology. Measuring soil carbon changes over time requires field and laboratory methods that are accurate, reliable, and reproducible. Some methods are established in academia, industry, and the service sector, including chemical oxidation,[528] high-temperature combustions,[529], and carbon analyzers.[530] The soil bulk density is measured for carbon stock assessment, typically by the core method,[531] from undisturbed samples. Field sampling, especially for subsoil sampling, is costly and soil carbon laboratory methods have a high cost per sample.

Proximal soil sensing of soil reflectance in the visible (VIS, ~400-800 nm), near-infrared (NIR, ~800-2500 nm), and mid-infrared (MIR, ~2500-25,000 nm) electromagnetic wave ranges offer an alternative for traditional laboratory soil carbon assessment that is fast and cheap per sample.[532-534] The accuracy of VIS-NIR-MIR spectral carbon measurements and their applicability for different soils and carbon fractions have been demonstrated in various geographic regions.[535-543] Open soil spectral libraries, such as Soil Spectroscopy for the Greater Good,[544] operationalization in the industry,[545,546] and the development of portable field instruments,[547,548] have facilitated reliable soil carbon assessment.

The cost reduction of soil carbon assessment and monitoring is critical for making carbon offset projects economically feasible and boosting the carbon market in the agriculture sector. VIS-NIR-MIR spectroscopy expedites and reduces the costs of soil carbon measurements allowing denser and more frequent surveys to monitor soil carbon sequestration within fields. The transition of adopting cost-effective soil carbon sensing technology and AI spectral modeling in the carbon economy by aggregators and registries that operate carbon crediting programs is still in its infancy as most carbon quantification protocols and verification standards (e.g., Verified Carbon Standard, Gold Standard, South Pole, Climate Action Reserve) rely on traditional laboratory-based soil carbon analytics. Few carbon aggregators (e.g., CarbonTerra) and registries (e.g., GHG Registry) stand out as early adopters of cost-effective sensor-driven carbon monitoring approach for carbon crediting, supported by ample evidence of the high accuracy and robustness of spectral-based AI soil carbon estimates.

Using satellite observations and spatial analysis to mitigate and adapt to climate change. Satellite observation and space analysis technology have become increasingly important tools for observing climate change phenomena, strengthening climate change response, and providing early warning.[3] These technologies allow scientists to monitor changes in the Earth's atmosphere, oceans, and land surfaces with unprecedented accuracy and detail. Satellites equipped with sensors that can measure temperature, precipitation, sea level, vegetation cover, and other environmental variables provide data that can be used to track changes in the Earth's climate over time. This information is critical for understanding the causes and effects of climate change and developing strategies to mitigate its impacts. In addition to monitoring changes in the Earth's environment, satellite observation and space analysis technologies also play a vital role in disaster response and risk reduction. By providing real-time data on weather patterns, natural disasters such as hurricanes, floods, and wildfires can be anticipated and prepared more effectively. They also allow for rapid response efforts following disasters, enabling rescue teams to locate survivors and assess damage quickly. With the improvement toward finer-grained spatial-temporal resolution and accuracy of satellite observations, new sensors, and intelligent information extraction and analysis technology, the quality, and accuracy of data products are continuously improved. As a result of these advancements, data products are becoming more reliable and useful for a variety of applications such as climate modeling, natural resource management, and disaster response. The increased accuracy and precision of satellite observations also allow for better monitoring of environmental changes over time, which is crucial for understanding how human activities affect our planet. Specifically, the main functions of earth observation and spatial analysis are reflected in three aspects:

(1) Reducing disaster costs by acquiring near real-time data on climate change-related disasters. The extreme disasters caused by climate change are increasing. The frequency and intensity of floods,[549] droughts,[550] hurricanes,[551] heat waves,[552] and wildfires[553] have increased, resulting in an increasing number of affected people and economic losses.[554] Satellite observation can realize early detection and forecast of these disasters, analyze their changes, predict their trends, and provide information on the extent, frequency, and intensity of disasters for their timely mitigation.

(2) Early warning of long-term impacts of climate change. In addition to short-term extreme weather, climate change will also bring many irreversible long-term impacts, which may drastically change human life. Through long-term observation of glacier area and mass, it was found that the accelerated melting of temperate glaciers, which are called the tower of water, led to the imbalance of water resources in arid areas[555,556] as well as in river ecosystems and also their use in transportation. By observing changes in the thickness of the ice sheet and the state of snow melt, it has been found that the ablation of the polar ice sheet is accelerating and is predicted to lead to a significant rise in global sea levels,[557] resulting in the disappearance of small island countries and the inundation of coastal areas. By monitoring ocean temperatures with thermal infrared images, it has been found that the ocean is warming rapidly, causing irreversible damage to marine corals, mangroves, and other ecosystems.[558,559]

(3) Provide basic data support for the global carbon cycle. The continuous accumulation of GHGs is the root cause of climate change. Sentinel-2 satellite observations can provide global GHG concentration data, including CO_2, CH_4, N_2O, and other GHGs.[560] The Sentinel-2 mission is primarily designed for land monitoring, whereas Sentinel-4, -5, and 5P are dedicated to atmospheric monitoring. The Sentinel-4 mission is a geostationary mission that continuously monitors Europe's atmosphere for air quality, ozone, and ultraviolet (UV) radiation.[561] The Sentinel-5 and 5P missions are low Earth orbit missions that focus on measuring a range of atmospheric gases such as carbon monoxide (CO), CH_4, and N_2O.[562] In addition to the Sentinel missions, China's FengYun and GaoFen series of satellites also play an important role in Earth observation. The FengYun-series satellites are used for weather forecasting, climate monitoring, and environmental management.[563,564] The GaoFen-series satellites are used for Earth observation, including land surveying, mapping, and disaster monitoring.[565,566] In addition, various satellite observations from multispectral and microwave passive and active sensors can provide global distributions of various vegetation structural parameters (leaf area index, vegetation height, biomass), providing support for the estimation of the global terrestrial ecosystem carbon budget.[567,568]

Monitoring the impact of climate on the land surface carbon sink from global satellite observations. In particular, satellite observations have been used to monitor changes in forest carbon stocks, which represent a major component of the carbon sink on land surfaces. Global observations have been used to monitor "greening" from optical vegetation indices such as the Normalized Difference Vegetation Index (NDVI),[569,570] associated with the increased photosynthetic activity of vegetation. However, greening does not mean an increase in aboveground carbon stocks (AGC); for example, herbaceous vegetation may replace trees after fires, which is associated with an increase in NDVI but a decrease in AGC.[571] Optical observations are therefore affected by saturation effects, limiting their ability to monitor AGC, particularly in dense forests, which are the largest contributors to global vegetation carbon stocks.[572] Radar (active microwave instruments, primarily in the L-, C-, and X-bands) has also been used to monitor AGC, but the observed radar backscatter is affected by complex structural/geometric effects of soil and vegetation, as well as saturation (at ~ 50-100 tons/ha).[573] To date, the most promising results in monitoring annual AGC changes at the continental scale, albeit at coarse spatial resolution (~25 km), have been obtained from passive L-band microwave observations (~20 cm wavelength), which exhibit weak saturation effects even in dense forests. These observations, through L-band vegetation optical depth (L-VOD), could reveal the large-scale impact of climate on vegetation carbon stocks (e.g., drought mortality during El Nino events in the tropics,[574] fire in boreal regions,[571], etc.) and associated recovery of AGC (e.g., AGC recovery in Australia after 2020 fires[575]).

Light Detection and Ranging (LiDAR) observations, a remote sensing technology that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth, allow to measure canopy height (as an indicator of AGC), also have great potential to monitor the impact of climate on AGC. But observations are sparse (e.g., a 25 m footprint for the Global Ecosystem Dynamics Investigation (GEDI) by the National Aeronautics and Space Administration (NASA) space instrument),[576] limiting the possibility of obtaining frequent and global monitoring. Recently, promising new remote sensing methods have emerged to overcome the limitations of sparse LiDAR data. These methods involve applying AI (primarily deep learning, DL) to high-resolution radar/optical observations (both in space and time) to monitor key forest features. DL model learning is based on very large datasets, constructed from manual mapping of individual tree crowns, aerial or satellite GEDI observations of tree heights, etc. Notable recent applications include mapping (1) individual trees and their carbon stock in the Sahel (~10 billion trees),[577] and Rwanda,[578] (2) global forest height at 30 m and 10 m resolution,[579] (3) canopy cover, height, and aboveground biomass maps in Europe at high resolution.[580,581]

Integrated assessment models of climate change

Integrated modeling approaches are profoundly important in addressing global climate change impacts and adaptation and mitigation strategies. Various factors are integrated to facilitate comprehensive assessments: (1) environmental, social, and economic data mining and harmonization, (2) technologies (e.g., proximal sensing, remote sensing, field measurements), and (3) multi-model or multi-methods. Data-driven intelligent models, stochastic, hybrid, and mechanistic (process-based) simulation models have been used to quantify terrestrial carbon and GHG emissions and estimate uncertainties. These carbon quantities are then coupled with valuation and economic models to assess carbon credits, carbon taxes, or other valuation scores (e.g., ecosystem services) that hold economic and social values in voluntary or mandatory carbon markets.

AI and data-driven modeling of carbon sequestration and GHG emissions. Artificial intelligence and data-driven approaches to predict soil carbon contents, stocks, pools, sequestration, and soil processes including soil respiration and GHG emissions as well as soil health have been used widely at the field, regional and global scales.[582] AI is concerned with building intelligent entities (machines) that can compute how to act effectively and safely in a wide variety of novel situations.[583] Machine learning AI refers to machines and systems designed to provide solutions to specific problems by learning (training) from experience supplied by data and algorithms, and then applying the gained knowledge to effectively solve the problems.[582,583] For instance, artificial neural networks (ANNs) are composed of nodes and discrete layers, connections, and directions of data propagation,[584] and thus, are well suited for training DP AI algorithms that are composed of multiple processing layers to learn representations of data with multiple levels of abstraction.[584]

Pedometrics uses sensor technology and AI algorithms extensively for cost-effective and rapid sensing of soil carbon, [582] and modeling that guides climate and carbon-smart agricultural management considering site-specific climatic, crop, and environmental conditions.[585] A collection of AI machine learning approaches for assessing soil carbon and other soil properties,[586] soil carbon sequestration, and soil respiration to quantify GHG emissions,[587] as well as digital soil quantification, are available. In a global study, Random Forest AI models provided superior results in estimating heterotrophic respiration when compared to 10 different mechanistic terrestrial ecosystem simulation models.[588] Data-driven AI approaches combine site-specific soil carbon measurements, soil proximal sensing data, remote sensing and geospatial data of topography, land use/land cover, geology, and climate to derive information and solutions at fine spatial resolution (pixel size), and temporal frequency (daily to weekly).[582,589,590] Soil proximal sensors and remote sensing technologies allow the developing digital twins of soil and terrestrial carbon evolution trending toward near-real time.

To achieve a net zero carbon economy, spectral-informed AI carbon modeling provides cost-effective strategies for rapid quantification of soil carbon sequestration to mitigate global climate change. These data-driven AI soil and terrestrial carbon models built on data hypercubes interpreted by machines provide distinct advantages compared to human understanding of ecosystem processes engrained in simulation models. The latter is an undertaking that has been hampered by the complexity of soil ecosystems and uncertainties in developing model algorithms and structures to accurately represent the underlying variability and interactions among biogeochemical, microbial, hydrological, climatic, and other ecosystem processes. In contrast, data-driven AI models are simpler, more flexible, and allow the identification of the main drivers of processes, such as soil carbon sequestration (‘gray boxes’). In addition, they benefit from the myriad of data types, formats, and resolutions they can handle to create spatially and temporally continuous digital twins of soil properties, functions, and processes, including carbon change and GHG emissions.

How to simulate climate change scenarios for the future. More than 30 years ago, a FACE (free-air CO_2 enrichment) system was developed to mimic elevated CO_2 under future climate.[591] The FACE system enabled the air above open-field plots to be enriched with CO_2 for the entire growing season.[592] The FACE system is used to assess the “actual” responses of plants in a future high-CO_2 world.[593,594] Numerous FACE experiments have already been conducted on many species. This spans a wide range of plant functional types, including crops, legumes, grasses, trees, shrubs, and forbs.[591,595] However, the CO_2 amplitudes in these FACE systems are higher than under natural conditions, due to the difficulty of controlling elevated CO_2 concentrations in turbulent air.[596] The fluctuations of CO_2 in the FACE system may decrease plant photosynthesis, biomass, and yield, thus underestimating the CO_2 fertilization effect on plant growth.[596] In addition, current FACE experiments mainly focus on IPCC mid-range emission scenarios that suggest a CO_2 increase of 200-350 ppm by 2100.[593,597] However, in the worst-case scenarios (IPCC RCP8.5), these mid-range CO_2 levels will be surpassed earlier than expected. Thus, the FACE technology must also be improved to reduce the range of CO_2 fluctuations and simulate higher CO_2 levels.

Under future climate change, elevated CO_2 is associated with an increase in global surface temperature. Global surface warming includes warming of surface water, soil warming, air warming, and plant warming, that is, whole-ecosystem warming. Due to the logistical complexity, high-energy requirements, and expense, most free-air controlled temperature enhancement experiments to date have focused on heating either soil or water, air or plant. For instance, Rich et al.[598] and Noyce et al.[599] used an infrared canopy warming system combined with a soil warming system to increase the whole-ecosystem temperature in a forest and grassland. More whole-ecosystem warming experiments need to be conducted in a variety of ecosystems. In addition, the magnitude of warming in these free-air controlled temperature enhancement experiments is limited and usually below 3.5 ºC.[598-602] As plant responses to multiple elevated temperatures are nonlinear, higher warming levels also need to be simulated using free-air controlled temperature enhancement systems.

To simulate drought conditions, rainout shelters can be constructed to intercept a certain percentage of incoming precipitation.[603] These shelters can be made from various materials such as polyvinyl chloride (PVC) pipes, wood or metal frames, and clear plastic sheeting. The size and shape of the shelter will depend on the scale of the experiment and the type of plants being studied. Roots that intercept a certain percentage of incoming precipitation can be used to simulate drought conditions.[604] This can be achieved by placing barriers such as plastic sheets or root barriers at different depths in the soil. These barriers will prevent some of the water from reaching the roots of the plants, simulating drought conditions. In addition to rainout shelters, other methods can also be used to simulate drought conditions such as withholding water from plants or using soil with low water-holding capacity.[605] These methods can be used in combination with rainout shelters for more accurate results.

Economics of climate change

Climate adaptation and mitigation through voluntary vs mandatory carbon markets. Carbon markets form a large and integral part of climate policy.[606] The mandatory (regulated, compliance) carbon market refers to the economy that is regulated by national and international treaties setting rules and targets for reducing the carbon footprint of committed countries by sequestering carbon and reducing GHG emissions. The Kyoto Protocol which entered into force in 2006[607] and its successors under the United Nations Framework Convention on Climate Change proposed a cap and trade mechanism, where the cap sets the maximum allowed emissions per country and industry sector, and the trade enables companies and countries to trade GHG emission allowances, encouraging industries to reduce GHG emissions (‘avoidance’) and purchase external carbon offset credits from land-based sequestered carbon through management beyond business-as-usual (‘additionality’). The voluntary market allows companies and individuals to voluntarily trade carbon credits. The private sector mainly governs this market and is more informal and flexible than the mandatory one, with multiple standards, definitions, and prices for carbon credits and mechanisms for project monitoring, reporting, and verification (MRV).[608]

Both carbon markets open the opportunity for farmers to produce and sell carbon offset credits through projects that embrace climate-smart agriculture. The aim is to sequester soil carbon (additionality) and reduce GHG emissions (avoidance) while sustaining agricultural production and profit, with the latter expectedly boosted by carbon credit sales. Under the MRV framework, a well-conducted, well-documented climate-smart project is the first step to producing, approving, and selling carbon credits. A positive carbon offset must be achieved and verified by a third-party company for carbon credit approval and trading.[609] Out of seven evaluated negative emission technologies, SOC sequestration ranked highest with up to 5 $GtCO_2\ yr^{-1}$ along with afforestation and reforestation (0.5-5 $GtCO_2\ yr^{-1}$) for sustainable carbon sequestration.[610] However, the low prices of carbon credits *versus* the high costs of carbon/project MRV, and the commitment to permanence (for land-based carbon storage of typically 100 years) to avoid the reversal of carbon storage impose barriers to adopting carbon offset projects. This calls for reframing MRV standards, protocols, and governance frameworks.[611] In time, climate-smart agriculture promotes carbon sequestration and storage,

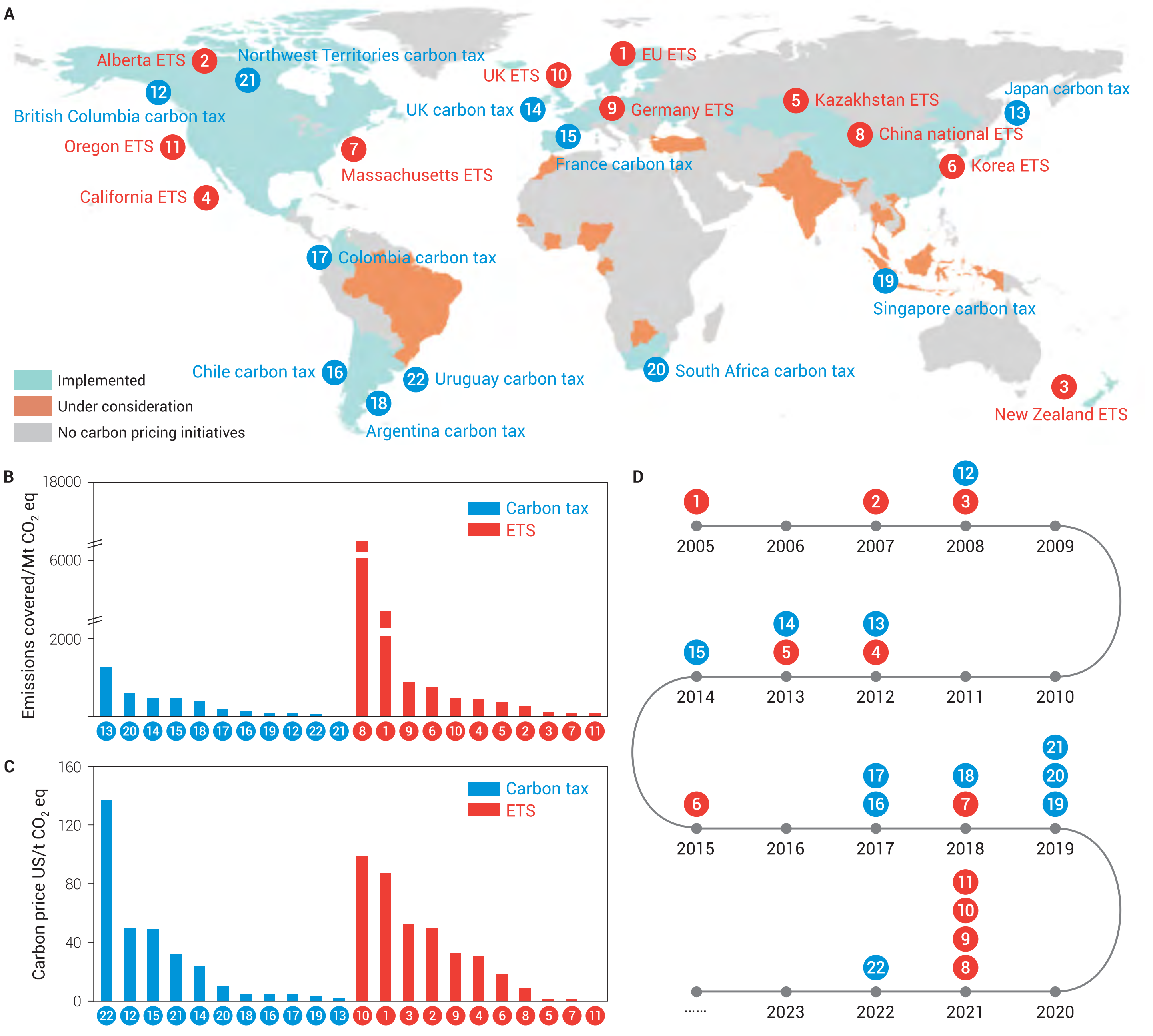


Figure 7. The status of carbon pricing initiatives worldwide A. Map of the geographical distribution of carbon pricing initiatives; B. Greenhouse gas (GHG) emissions covered (2018) for 11 implemented Emissions Trading Systems (ETS) and 11 implemented Carbon Tax; C. Carbon price (2018) for 11 implemented Emissions Trading Systems (ETS) and 11 implemented Carbon Tax; D. Year of implementation for 11 implemented ETS and 11 implemented Carbon Tax. Data sources: Word Bank.[615]

while proximal and remote sensing assessments of soil and terrestrial carbon reduce costs. Subsequently, profitable MRV projects improve the additionality and avoidance of GHG emissions. Beyond carbon sequestration for climate change mitigation, climate-smart agriculture produces multiple co-benefits ranging from soil ecosystem services to soil security, with local to global positive impacts.

Carbon tax and emissions trading system. Carbon pricing, as an approach to spur climate action, shifts consumption and investment patterns and makes contributions to economic development compatible with climate change mitigation (Fig. 7). The general idea of carbon pricing is to charge emitters or to offer incentives for emission reduction.[612,613] It captures the external costs of carbon emissions and effectively shifts the responsibility of paying for climate change damage from the public to the GHG emitters.[614]

There are various forms of carbon pricing instruments. Two main forms are carbon tax and emissions trading system (ETS). The former is a price-based mechanism, while the latter is a quantity-based mechanism.[616] The carbon tax imposes a fixed fee per unit of carbon emission.[617] The carbon price could be directly controlled to manipulate the reduction level of carbon emissions by disincentivizing GHG emission-intensive productions. It is a cost-effective measure since only emitters capable of reducing emissions at a cost below the tax will choose to do so.

ETS, also termed a cap-and-trade system, is a tradable-permit system for carbon emissions. This quantity-based mechanism works by imposing a quota on emission permits issued to participants (i.e., enterprises, industries, and countries), and then allowing participants to trade these permits in the market.[618] The advantage of ETS is that it can directly control the emission reduction level under carbon price uncertainties. Participants covered by the ETS have the flexibility of trading permits to reach the lowest cost possible for themselves and society. Participants with lower emission reduction costs could sell their excess permits, while participants with higher emission reduction costs could buy permits to avoid emission reduction.[619] Thus, ETS caps the total amount emitted at a level exactly equal to the number of permits issued. Under this mechanism, the carbon price is determined by the balance between the demand for total emissions for the production of goods and services and the available emissions permits allocated.

Carbon pricing instruments have been booming around the world.[620] Both carbon pricing mechanisms have their advantages, and many studies have compared their efficiency. Weitzman's pioneering work indicated that the relative slopes of the marginal cost and benefit functions determine which is more sufficient. If the slope of the marginal cost function is greater than the absolute value of the slope of the marginal benefit function, a price-based mechanism is more efficient. Otherwise, a quantity-based mechanism is preferred.[621] Many researchers argue that carbon tax has practical and economic advantages due to ease of administration and price certainty,[622] but IT may not be socially acceptable in some countries. Nobel Prize-winning economist Nordhaus pointed out the superiority of the price-based mechanism after comparing carbon pricing mechanisms from multiple angles.[623] The Canadian province of British Columbia has levied a carbon tax on fossil fuels combusted for electricity, transportation, and heating since 2008.[613] By comparison, ETSs are preferred by many countries or regions as they provide more certainty over emissions levels. As of 2021, there are 33 ETSs in operation globally. These ETSs cover carbon emissions in various sectors such as electricity, industry, aviation, and construction. The European Union Emissions Trading System (EU ETS) is the largest and oldest ETS in the world. It covers more than 11,000 power stations and manufacturing plants across 31 countries. The EU ETS has been in operation since 2005 and has undergone several reforms to improve its efficiency, currently covering about 45% of EU GHG emissions.[624] China has the largest carbon market in the world, covering more than 4 billion tonnes of CO_2 emissions annually.[625] China's ETS was launched in 2017 and initially covered only the power sector.[626] However, it is expected to expand to other sectors such as cement, steel, and aluminum. Other notable ETSs include the Regional Greenhouse Gas Initiative (RGGI) in the United States, which covers power plants in ten Northeastern states, and the Western Climate Initiative (WCI), which is a joint effort between California and Quebec covering multiple sectors.

A new approach has also been considered, combining elements of the price-based mechanism (e.g., carbon tax) and the quantity-based mechanism (e.g., ETS). This hybrid approach uses the initial allocation of tradable permits to set quantity targets but allows extra permits to be purchased at a fixed fee.[627] It improves efficiency significantly compared to quantity-based and price-based mechanisms.

Despite all advantages of carbon pricing, there are still drawbacks to be overcome, such as (1) the lack of LCA analyses in determining carbon prices, the full carbon footprint which includes production and transport costs is usually not included in the prices[628] and (2) pricing carbon emissions is a relatively straightforward process compared to measuring land-based carbon sequestration. While carbon pricing involves putting a price on each ton of CO_2 emitted, measuring SOC gains requires extensive and accurate measurement techniques, which are often challenging and expensive in case traditional methods are used instead of cost-effective AI modeling and sensor-driven modeling of carbon. One concern is the avoidance of carbon leakages, for example, which may result from transporting high C-rich materials from one site to another, thus resulting in a lack of C sequestration in other regions. And finally, soils sequester SOC likely most efficiently when previous SOC losses were large, such as in degraded arable land.[280] However, incentivizing farmers who have degraded soils the most can also lead to unfair competition, giving them an advantage over other farmers practicing sustainable agriculture. In search of a solution, Paustian et al.[629] suggested the use of moving averages, which consider past successes in SOC storage.

Behavioral and cultural education to help mitigate and adapt to climate change

The important role that education plays in dealing with climate change has been admitted by the United Nations Framework Convention on Climate Change since 1992,[630] further emphasized by the Bonn Declaration,[631] and promoted by the efforts from multiple international organizations.[632] While technical and financial support undoubtedly matter to combat the changing climate, broader behavioral, cultural, and ideological shifts are also critical.[633] This is where education acts in climate actions.

Integrating climate change education into education systems, both formally and informally, is one of the most effective ways to respond to climate issues, particularly in terms of mitigation and adaptation.[634] Education can inform the public that, as conscious consumers and responsible citizens, they have a responsibility to shift away from carbon-intensive and energy-inefficient consumption patterns and lifestyles to promote sustainability.[635] Beyond the essential role of education in individual behavior change for mitigation, education is also an integral component of adaptive capacity.[636] By equipping people with the knowledge about responding to specific climate shocks and providing skills required to make informed decisions on adjusting individual lives and social and economic systems, education helps increase the general adaptation capacity by reducing vulnerability and increasing resilience.[635,637] Furthermore, the multiplier effect of education helps enhance the ' bottom-up' solutions to the climate crisis that elites cannot deal with. Education multiplier effect implies that households and communities can also benefit from climate and environmental competency and literacy. Thus, education creates an inexhaustible resource of local capabilities and solutions because the information and knowledge gained on climate change mitigation and adaptation by individuals can be delivered to a wider population and future generations.[634]

Climate change education is underpinned by transformations at multiple levels, both individually and collectively.[634] Therefore, it primarily focuses on personal and collective actions' role in tackling climate issues, from behavioral change to cultural and ideological shifts. Climate change education can equip individuals with the knowledge, skills, and sense of urgency necessary to take action and make an impact on their communities and societies. Individual-level actions include adjusting consumption patterns and lifestyles towards green and sustainable ones, such as using energy-efficient household appliances and taking public transportation.[638] At the collective level, it involves multilevel cooperation to ensure producers and governments take greater responsibility for addressing climate change.[634]

Merely possessing environmental knowledge and awareness does not naturally bring about pro-environmental behavior.[639] We also need to vote against media fake news and misinformation about climate change as well as profit-driven publications, reviews, and lobbying questioning climate change. Conceptual shifts in approach to climate change education are needed to facilitate behavioral change. Climate change education should move beyond being based solely on cognitive and scientific knowledge and instead involve learners more in the emotional dimension of the issue.[640,641] Instead of being limited to what people already know or do not yet know, climate change education should respond to the current views and beliefs of the target population to create emotional connections between various experiences and information about climate change, thereby triggering affect-driven behavioral change.[640] This is in line with behavioral economics emphasis on "nudges", in which climate change education influences the decision-making of consumers or citizens without changing either objective payoffs or incentives.[642]

The vital role that education plays in facilitating individual and collective behavioral change for mitigation, as well as the improvement of the general adaptation capacity, makes it indispensable in tackling climate issues and worth increased attention worldwide.

Climate change mitigation and lifestyle change

Resident lifestyles have played an important role in driving global and local GHG emissions on both the production and demand sides.[643-645] Although production-based low-carbon strategies have been seen as the main solution to climate change mitigation, demand-side mitigation options on household lifestyle changes can provide the necessary leeway to accomplish climate goals[646,647] and to maintain UN Sustainable Development Goals (SDGs).[648] Several international bodies and countries have already incorporated lifestyle changes into their long-term carbon mitigation strategies.[356,644,648,649]

Connecting household lifestyle change and climate change mitigation needs knowledge from various disciplines. There are promising multi- and trans-disciplinary frameworks that can identify and characterize the demand-side or lifestyle-based actions for mitigating climate change.[649,650] Some disciplines tend to interpret household behaviors qualitatively based on surveys,[651] literature studies,[652] and expert judgment,[653] for example, using public transport instead of driving a private car for travel purposes. Other disciplines use quantitative methodologies to assess the outcome of behavior options, which can be well connected to coupling analysis and other economic models. For example, turning the room thermostat down 1 ℃ can save a certain amount of household energy use.[654,655] Several systematic conceptual frameworks have recently been developed to facilitate transdisciplinary collaboration. For instance, the well-established "Avoid-Shift-Improve" framework classifies behavioral choices and captures interactions between these choices.[648,649,656,657]

In terms of categories of behavioral options, there are four principal domains: food,[658-660] mobility,[655,661-664] housing,[665-668] and other consumption.[649,669,670] Despite a large number of published studies, most assessments were often carried out with a relatively narrow focus on one of the major domains. Only very few studies considered multiple behavioral options, and their approach was to discuss different types of options separately, rather than considering the changes synergistically.[651,671,672]

Our review of regional studies shows that most of them mainly focused on developed countries.[651,671,672] Assessments of behavioral change to reduce household carbon emissions in developing and emerging economies are still lacking.

Given the potential for laying out short-term and behavior-oriented mitigation pathways, various choices of green consumption are incorporated into and combined with other modeling frameworks to quantify their potential environmental impacts. Assessment approaches, such as LCA, input-output (IO) analysis, and integrated assessment model (IAM), are widely used. While LCA provides an appropriate process-specific approach, it fails to capture the system-wide impacts of climate problems.[673] The IO framework of household consumption, especially multi-regional IO, offers a solution for evaluating the mitigation potentials throughout the supply chain.[651,665,671,674] Wood et al.[674] formalized an approach that models reductions and shifts in demand rebound effects, changes in production recipes, and reductions in environmental intensity. However, the shortcoming of IO frameworks is the inability to consider the dynamic change in technology over a longer time frame. Furthermore, it is possible to soft-couple lifestyle-oriented measures into technology-rich dynamic models, such as IAMs, to project environmental impacts under future mitigation scenarios. One example is the WILIAM ("Within limits") Integrated Assessment Model (IAM), developed in the scope of LOCOMOTION, whose economic module is based on a dynamic Multi-Regional Input Output (MRIO) model that has been extended by final endogenous demand.[675] WILIAM can shift household behaviors towards more or less carbon-friendly consumption patterns, providing possibilities to reveal mitigation pathways from both production and consumption perspectives. However, there are still challenges to integrating demand-side policy interventions into most IAMs as they are often designed for production-side technologies and processes, with aggregated sectoral and regional categories.[649,655,676] There is a growing recognition of the importance of covering more detailed representations of consumer behaviors in IAMs.[677]

GLOBAL IMPLICATIONS AND FUTURE PERSPECTIVES

Over the past 150 years, global systems have evolved rapidly in response to the needs of a growing and prosperous world population. However, this rapid development has partly come at the cost of overexploiting natural resources and disrupting biogeochemical cycles. In particular, the use of fossil fuels for energy production has exacerbated climate change with more complex feedback loops in our Earth system than that predicted by rising global average temperatures. Thus, action is needed to transform local and global food and socio-ecological systems to better mitigate and adapt to climate change. Here, we can rely on new scientific and technological advances from various fields of research. Also, theories and policies exist to combat climate change, yet, within current global development systems, there are still significant obstacles to overcome in adapting to and reducing the effects of climate change.

First, there is a persistent and critical challenge of achieving a higher quality of life and economic growth while reducing the negative impact of energy consumption on the environment. In 2022, fossil fuels provided 81% of the world's energy, despite the need to combat climate change, and energy-related CO_2 emissions continue to rise. Given that the enormous potential of global renewable energy sources could meet global energy demand, it is still possible to reduce emissions in the energy and transport sector and close the gap between climate change promises and actions. Additional efforts are needed from country to country to increase the share of clean and renewable energy sources in the global energy mix.

Second, to effectively feed the growing population, agriculture is developing rapidly, and its contribution to global GHG emissions is also increasing as a result of the production and use of chemical fertilizers and other agricultural management practices. Agriculture currently accounts for 19-29% of total GHG emissions globally, and this percentage could increase significantly as countries seek to increase food production. If managed well, however, agriculture could become one of the centers for combating climate change. In this regard, reductions in emissions from fertilizer and livestock systems are necessary to achieve carbon-neutral agriculture. This calls for effective management of soils and crop-livestock production systems, recycling the agricultural waste in agroecosystems, and improving the features of bio/organic fertilizers. In addition, we must be aware that changes in transportation, wastewater treatment, and dietary preferences can be advantageous for climate change mitigation.

Third, environmental degradation and pollution create new challenges in our quest to adapt to and mitigate climate change. The ongoing loss of ecosystem carbon, its sequestration potential, and ecosystem services leave an unnecessary debt to future generations. In this regard, collaborative efforts centered on our current and future demands are needed, irrespective of global political or economic tensions. In the end, addressing climate change and environmental degradation will require sustained efforts from all sectors of the global community. A sustainable future for ourselves and future generations is only possible if we collaborate and act swiftly to address the complex issues that imperil our planet and way of life.

REFERENCES

1. Piguet, E. (2022). Linking climate change, environmental degradation, and migration: An update after 10 years. Wiley Interdiscip. Rev. Clim. Change **13**: e746.
2. Lubchenco, J., Heather, T., and Eli, F. (2022). Accounting for nature on earth day 2022. The White House.
3. Wang, F., Harindintwali, J.D., Yuan, Z., et al. (2021). Technologies and perspectives for achieving carbon neutrality. The Innovation *2*, 100180, 10.1016/j.xinn.2021.100180.
4. EPA (2020). Sources of greenhouse gas emissions. Environmental Protection Agency.
5. NOAA (2022). 2022 was world's 6th-warmest year on record. Antarctic sea ice coverage melted to near-record lows. National Oceanic and Atmospheric Administration.
6. Canadell, J.G., Meyer, C.P., Cook, G.D., et al. (2021). Multi-decadal increase of forest burned area in Australia is linked to climate change. Nat. Commun. **12**: 6921. DOI: 10.1038/s41467-021-27225-4.
7. Marlon, J.R., Bartlein, P.J., Gavin, D.G., et al. (2012). Long-term perspective on wildfires in the western USA. Proc. Natl. Acad. Sci. USA **109**: E535–E543. DOI: 10.1073/pnas.1119351109.
8. Perkins, S. (2022). How much of the Earth's ice is melting. New and old techniques combine to paint a sobering picture. Proc. Natl. Acad. Sci. USA **119**: e2213762119.
9. Gudmundsson, L., Boulange, J., Do, H.X., et al. (2021). Globally observed trends in mean and extreme river flow attributed to climate change. Science **371**: 1159–1162. DOI: 10.1126/science.aba3996.
10. Sun, Y., Zhang, X.B., Ding, Y.H., et al. (2022). Understanding human influence on climate change in China. Natl. Sci. Rev. **9**: nwab113. DOI: 10.1093/nsr/nwab113.
11. Meza, I., Rezaei, E.E., Siebert, S., et al. (2021). Drought risk for agricultural systems in South Africa: Drivers, spatial patterns, and implications for drought risk management. Sci. Total Environ. **799**: 149505. DOI: 10.1016/j.scitotenv.2021.149505.
12. Roman-Palacios, C., and Wiens, J.J. (2020). Recent responses to climate change reveal the drivers of species extinction and survival. Proc. Natl. Acad. Sci. U.S.A. **117**: 4211–4217. DOI: 10.1073/pnas.1913007117.
13. Ford, J., Zavaleta-Cortijo, C., Ainembabazi, T., et al. (2022). Interactions between climate and COVID-19. Lancet Planet. Health **6**: E825–E833. DOI: 10.1016/S2542-5196(22)00174-7.
14. Heavens, N.G., Ward, D.S., and Natalie, M.M. (2013). Studying and projecting climate change with earth system models. Nat. Educ. Knowl. **4**: 4.
15. Voosen, P. (2018). Science insurgents plot a climate model driven by artificial intelligence. Science.

16. Shaikh Farzaneh, K., Aysin, D.-H., Michael, H., and Elnaz, T. (2021). Can public awareness, knowledge and engagement improve climate change adaptation policies? Discover Sustain. *2*.
17. Prakash, A., and Bernauer, T. (2020). Survey research in environmental politics: why it is important and what the challenges are introduction. Env. Polit. **29**: 1127–1134. DOI: 10.1080/09644016.2020.1789337.
18. Schmid, N., Beaton, C., Kern, F., et al. (2021). Elite vs. mass politics of sustainability transitions. Environ. Innov. Soc. Transit. **41**: 67–70.
19. UNCC (2021). The Paris agreement What is the Paris agreement? United Nations Climate Change.
20. Fuhr, H. (2021). The rise of the Global South and the rise in carbon emissions. Third World Q. **42**: 2724–2746. DOI: 10.1080/01436597.2021.1954901.
21. Jin, Y., Hu, S., Zhang, Z., et al. (2022). The path to carbon neutrality in China: a paradigm shift in fossil resource utilization. Res. Chem. Mater. **1**: 129–135.
22. Marquardt, J., Fünfgeld, A., and Elsässer, J.P. (2023). Institutionalizing climate change mitigation in the Global South: current trends and future research. Earth Syst. Gov. **15**: 100163. DOI: 10.1016/j.esg.2022.100163.
23. IPCC (2022). Climate change 2022: Mitigation of climate change. Mitigation pathways compatible with long-term goals. Intergovernmental Panel on Climate Change.
24. Ratwatte, P., Wehling, H., Phalkey, R., and Weston, D. (2023). Prioritising climate change mitigation behaviours and exploring public health co-benefits: a delphi study. Int. J. Environ. Res. Public Health **20**: 5094. DOI: 10.3390/ijerph20065094.
25. HERRING, D., and LINDSEY, R. (2020). Hasn't earth warmed and cooled naturally throughout history? NOAA Climate.gov.
26. Forster, P., V. Ramaswamy, P. Artaxo, et al. (2007). Changes in atmospheric constituents and in radiative forcing. (Cambridge University Press)L.
27. EPA (2023). Causes of climate change. United States Environmental Protection Agency.
28. Friedlingstein, P., O'Sullivan, M., Jones, M.W., et al. (2022). Global carbon budget 2022. Earth Syst. Sci. Data **14**: 4811–4900. DOI: 10.5194/essd-14-4811-2022.
29. Liu, Z., Deng, Z., Davis, S., and Ciais, P. (2023). Monitoring global carbon emissions in 2022. Nat. Rev. Earth Environ. **4**: 205–206. DOI: 10.1038/s43017-023-00406-z.
30. Cui, C., Guan, D., Wang, D., et al. (2022). Global mitigation efforts cannot neglect emerging emitters. Natl. Sci. Rev. **9**: nwac223. DOI: 10.1093/nsr/nwac223.
31. Keeling, C.D., Piper, S.C., Bacastow, R.B., et al. (2001). Exchanges of atmospheric CO_2 and $^{13}CO_2$ with the terrestrial biosphere and oceans from 1978 to 2000. Global Aspects. UC San Diego: Scripps Institution of Oceanography *88*.
32. Lüthi, D., Le Floch, M., Bereiter, B., et al. (2008). High-resolution carbon dioxide concentration record 650,000–800,000 years before present. Nature **453**: 379–382. DOI: 10.1038/nature06949.
33. Waters, C.N., Zalasiewicz, J., Summerhayes, C., et al. (2016). The Anthropocene is functionally and stratigraphically distinct from the Holocene. Science **351**: aad2622. DOI: 10.1126/science.aad2622.
34. Steffen, W., Rockstrom, J., Richardson, K., et al. (2018). Trajectories of the Earth System in the Anthropocene. Proc. Natl. Acad. Sci. U.S.A. **115**: 8252–8259. DOI: 10.1073/pnas.1810141115.
35. Crutzen, P.J. (2002). Geology of mankind. Nature **415**: 23–23. DOI: 10.1038/415023a.
36. Cowie, R.H., Bouchet, P., and Fontaine, B. (2022). The Sixth Mass Extinction: fact, fiction or speculation. Biol. Rev. Camb. Philos. Soc. **97**: 640–663. DOI: 10.1111/brv.12816.
37. Isbell, F., Balvanera, P., Mori, A.S., et al. (2023). Expert perspectives on global biodiversity loss and its drivers and impacts on people. Front. Ecol. Environ. **21**: 94–103. DOI: 10.1002/fee.2536.
38. Gulev, S.K., Thorne, P.W., Ahn, J., et al. (2021). In climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. In changing state of the climate system, Masson-Delmott, P.Z. V., A. Pirani, et al., eds. (Cambridge University Press), 287–422.
39. Jungclaus, J.H., Bard, E., Baroni, M., et al. (2017). The PMIP4 contribution to CMIP6 – Part 3: the last millennium, scientific objective, and experimental design for the PMIP4 past1000 simulations. Geosci. Model Dev. **10**: 4005–4033. DOI: 10.5194/gmd-10-4005-2017.
40. Goldblatt, C., and Zahnle, K.J. (2011). Faint young sun paradox remains. Nature **474**: E3–E4.
41. Feulner, G. (2012). The faint young sun problem. Rev. Geophys. **50**: RG2006.
42. Hay, W.W. (1996). Tectonics and climate. Geol. Rundsch. **85**: 409–437. DOI: 10.1007/BF02369000.
43. Smith, A.G. (1999). Tectonic boundary conditions for climate reconstructions. In Oxford Monographs on geology and geophysics, T.J. CROWLEY, and K.C. BURKE, eds. (Oxford University Press), pp. 599-606.
44. Ruddiman, W.F. (2012). Tectonic uplift and climate change (Springer; Softcover reprint of the original 1st ed. 1997 edition)L.
45. Marshall, L.R., Maters, E.C., Schmidt, A., et al. (2022). Volcanic effects on climate: recent advances and future avenues. Bull. Volcanol. **84**: 54. DOI: 10.1007/s00445-022-01559-3.
46. Robock, A. (2000). Volcanic eruptions and climate. Rev. Geophys. **38**: 191–219. DOI: 10.1029/1998RG000054.
47. Hays, J.D., Imbrie, J., and Shackleton, N.J. (1976). Variations in the earth's orbit: pacemaker of the ice ages. Science **194**: 1121–1132. DOI: 10.1126/science.194.4270.1121.
48. Laskar, J., Robutel, P., Joutel, F., et al. (2004). A long-term numerical solution for the insolation quantities of the earth. Astron. Astrophys. **428**: 261–285. DOI: 10.1051/0004-6361:20041335.
49. Zachos, J., Pagani, M., Sloan, L., et al. (2001). Trends, rhythms, and aberrations in global climate 65 Ma to present. Science **292**: 686–693. DOI: 10.1126/science.1059412.
50. Li, J., and Fang, X. (1999). Uplift of the Tibetan Plateau and environmental changes. Chin. Sci. Bull. **44**: 2117–2124. DOI: 10.1007/BF03182692.
51. Wu, F., Fang, X., Yang, Y., et al. (2022). Reorganization of Asian climate in relation to Tibetan Plateau uplift. Nat. Rev. Earth Environ. **3**: 684–700. DOI: 10.1038/s43017-022-00331-7.
52. Ruddiman, W.F., and Kutzbach, J.E. (1991). Plateau uplift and climatic change. Sci. Am. **264**: 66–72.
53. Hollis, C.J., Dunkley Jones, T., Anagnostou, E., et al. (2019). The DeepMIP contribution to PMIP4: methodologies for selection, compilation and analysis of latest Paleocene and early Eocene climate proxy data, incorporating version 0.1 of the DeepMIP database. Geosci. Model Dev. *12*, 3149-3206.
54. Cox, G.M., Halverson, G.P., Stevenson, R.K., et al. (2016). Continental flood basalt weathering as a trigger for Neoproterozoic Snowball Earth. Earth Planet. Sci. Lett. **446**: 89–99. DOI: 10.1016/j.epsl.2016.04.016.
55. Brantley, S.L., Shaughnessy, A., Lebedeva, M.I., and Balashov, V.N. (2023). How temperature-dependent silicate weathering acts as Earth's geological thermostat. Science **379**: 382–389. DOI: 10.1126/science.add2922.
56. Dessert, C., Dupré, B., François, L.M., et al. (2001). Erosion of Deccan Traps determined by river geochemistry: impact on the global climate and the ^{87}Sr/^{86}Sr ratio of seawater. Earth Planet. Sci. Lett. **188**: 459–474. DOI: 10.1016/S0012-821X(01)00317-X.
57. Black, B.A., Neely, R.R., Lamarque, J.-F., et al. (2018). Systemic swings in end-Permian climate from Siberian Traps carbon and sulfur outgassing. Nat. Geosci. **11**: 949–954. DOI: 10.1038/s41561-018-0261-y.
58. Burgess, S.D., and Bowring, S.A. (2015). High-precision geochronology confirms voluminous magmatism before, during, and after Earth's most severe extinction. Sci. Adv. **1**: e1500470. DOI: 10.1126/sciadv.1500470.
59. Hoffman, P.F. (1999). The break-up of Rodinia, birth of Gondwana, true polar wander and the snowball Earth. J. Afr. Earth Sci. **28**: 17–33. DOI: 10.1016/S0899-5362(99)00018-4.
60. Claussen, M. (2009). Late Quaternary vegetation-climate feedbacks. Clim. Past **5**: 203–216. DOI: 10.5194/cp-5-203-2009.
61. Curry, J.A., Schramm, J.L., and Ebert, E.E. (1995). Sea ice-albedo climate feedback mechanism. J. Clim. **8**: 240–247. DOI: 10.1175/1520-0442(1995)008<0240:SIACFM>2.0.CO;2.
62. Goosse, H., Kay, J.E., Armour, K.C., et al. (2018). Quantifying climate feedbacks in polar regions. Nat. Commun. **9**: 1919. DOI: 10.1038/s41467-018-04173-0.
63. Pepin, N., Bradley, R.S., Diaz, H.F., et al. (2015). Elevation-dependent warming in mountain regions of the world. Nat. Clim. Change **5**: 424–430. DOI: 10.1038/nclimate2563.
64. Yang, F., Kumar, A., Wang, W., et al. (2001). Snow–albedo feedback and seasonal climate variability over North America. J. Clim. **14**: 4245–4248. DOI: 10.1175/1520-0442(2001)014<4245:SAFASC>2.0.CO;2.
65. Cess, R.D. (2005). Water vapor feedback in climate models. Science **310**: 795–796. DOI: 10.1126/science.1119258.
66. Dessler, A.E., Zhang, Z., and Yang, P. (2008). Water-vapor climate feedback inferred from climate fluctuations, 2003–2008. Geophys. Res. Lett. **35**: L20704. DOI: 10.1029/2008GL035333.
67. Schädel, C., Bader, M.K.F., Schuur, E.A.G., et al. (2016). Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. Nat. Clim. Change **6**: 950–953. DOI: 10.1038/nclimate3054.
68. Dean, J.F., Middelburg, J.J., Röckmann, T., et al. (2018). Methane feedbacks to the global climate system in a warmer world. Rev. Geophys. **56**: 207–250. DOI: 10.1002/2017RG000559.
69. Walker, X.J., Baltzer, J.L., Cumming, S.G., et al. (2019). Increasing wildfires threaten historic carbon sink of boreal forest soils. Nature **572**: 520–523. DOI: 10.1038/s41586-019-1474-y.
70. Mack, M.C., Bret-Harte, M.S., Hollingsworth, T.N., et al. (2011). Carbon loss from an unprecedented Arctic tundra wildfire. Nature **475**: 489–492. DOI: 10.1038/nature10283.
71. Moritz, M.A., Parisien, M.-A., Batllori, E., et al. (2012). Climate change and disruptions to global fire activity. Ecosphere **3**: 49.
72. Liu, Z., Notaro, M., Kutzbach, J., and Liu, N. (2006). Assessing global vegetation–climate feedbacks from observations. J. Clim. **19**: 787–814. DOI: 10.1175/JCLI3658.1.
73. Turner, S.K. (2018). Constraints on the onset duration of the Paleocene–Eocene Thermal Maximum. Philos. Trans. R. Soc., A **376**: 20170082. DOI: 10.1098/rsta.2017.0082.
74. Gutjahr, M., Ridgwell, A., Sexton, P.F., et al. (2017). Very large release of mostly volcanic carbon during the Palaeocene-Eocene Thermal Maximum. Nature **548**: 573–577. DOI: 10.1038/nature23646.
75. Zeebe, R.E., Ridgwell, A., and Zachos, J.C. (2016). Anthropogenic carbon release rate

unprecedented during the past 66 million years. Nat. Geosci. **9**: 325–329. DOI: 10.1038/ngeo2681.

76. Anagnostou, E., John, E.H., Babila, T.L., et al. (2020). Proxy evidence for state-dependence of climate sensitivity in the Eocene greenhouse. Nat. Commun. **11**: 4436. DOI: 10.1038/s41467-020-17887-x.
77. Cheng, H., Zhang, H., Spotl, C., et al. (2020). Timing and structure of the Younger Dryas event and its underlying climate dynamics. Proc. Natl. Acad. Sci. U.S.A. **117**: 23408–23417. DOI: 10.1073/pnas.2007869117.
78. Condron, A., and Winsor, P. (2012). Meltwater routing and the Younger Dryas. Proc. Natl. Acad. Sci. U.S.A. **109**: 19928–19933. DOI: 10.1073/pnas.1207381109.
79. Carlson, A. (2013). The Younger Dryas climate event. In The Encyclopedia of Quaternary Science, E. S.A., ed. (Elsevier), 126-134.
80. Ezer, T. (2013). Sea level rise, spatially uneven and temporally unsteady: Why the U. S. East Coast, the global tide gauge record, and the global altimeter data show different trends. Geophys. Res. Lett. **40**: 5439–5444.
81. Caesar, L., Rahmstorf, S., Robinson, A.V., et al. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. Nature **556**: 191–196. DOI: 10.1038/s41586-018-0006-5.
82. Lee, J.-Y., Marotzke, J., Bala, G., et al. (2021). Scenario-based projections and near-term information. In climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. In Future Global Climate, Masson-Delmott, P.Z. V., A. Pirani, et al., eds. (Cambridge University Press), 553–672.
83. Manabe, S., and Wetherald, R.T. (1967). Thermal equilibrium of the atmosphere with a given distribution of relative humidity. J. Atmos. Sci **24**: 241–259. DOI: 10.1175/1520-0469(1967)024<0241:TEOTAW>2.0.CO;2.
84. Hasselmann, K. (1976). Stochastic climate models: Part I. Theory. Tellus A: Dynamic Meteorology and Oceanography.
85. Castelvecchi, D., and Gaind, N. (2021). Climate modellers and theorist of complex systems share physics Nobel. Nature, **598**: 246–247.
86. IPCC (2021). Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergove. Intergovernmental Panel on Climate Change.
87. Graedel, T.E., and Crutzen, P.J. (1993). Atmospheric change: an earth system perspective Nature, 367, 695.
88. Isaksen, I.S.A., Granier, C., Myhre, G., et al. (2009). Atmospheric composition change: climate–chemistry interactions. Atmos. Environ. **43**: 5138–5192. DOI: 10.1016/j.atmosenv.2009.08.003.
89. Zittis, G., Almazroui, M., Alpert, P., et al. (2022). Climate change and weather extremes in the Eastern Mediterranean and Middle East. Rev. Geophys. **60**: e2021RG000762.
90. Diaz, J.H. (2013). Recognizing and reducing the threats to human health and environmental ecosystems from stratospheric ozone depletion. In Climate Vulnerability, R.A. Pielke, ed. (Academic Press), 17-38.
91. Crutzen, P.J. (1970). The influence of nitrogen oxides on the atmospheric ozone content. Q. J. R. Meteorol. Soc. **96**: 320–325. DOI: 10.1002/qj.49709640815.
92. Molina, M.J., and Rowland, F.S. (1974). Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone. Nature **249**: 810–812. DOI: 10.1038/249810a0.
93. Barnes, P.W., Williamson, C.E., Lucas, R.M., et al. (2019). Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future. Nat. Sustain. **2**: 569–579. DOI: 10.1038/s41893-019-0314-2.
94. Feng, Z., Xu, Y., Kobayashi, K., et al. (2022). Ozone pollution threatens the production of major staple crops in East Asia. Nat. Food **3**: 47–56. DOI: 10.1038/s43016-021-00422-6.
95. Mukherjee, A., and Agrawal, M. (2017). World air particulate matter: Sources, distribution and health effects. Environ. Chem. Lett. **15**: 283–309. DOI: 10.1007/s10311-017-0611-9.
96. EPA (2022). Climate change impacts on air quality. United States Environmental Protection Agency.
97. Brasseur, G.P. (2009). Implications of climate change for air quality. World Meteorological Organization (WMO) Bulletin **58**: 10.
98. Pinder, R.W., Davidson, E.A., Goodale, C.L., et al. (2012). Climate change impacts of US reactive nitrogen. Proc. Natl. Acad. Sci. USA **109**: 7671–7675. DOI: 10.1073/pnas.1114243109.
99. Shi, Y., Cui, S., Ju, X., et al. (2015). Impacts of reactive nitrogen on climate change in China. Sci. Rep. **5**: 8118. DOI: 10.1038/srep08118.
100. Wang, C., Jeong, G.R., and Mahowald, N. (2009). Particulate absorption of solar radiation: Anthropogenic aerosols vs. dust. Atmos. Chem. Phys. **9**: 3935–3945. DOI: 10.5194/acp-9-3935-2009.
101. de Wit, C.A., Vorkamp, K., and Muir, D. (2022). Influence of climate change on persistent organic pollutants and chemicals of emerging concern in the Arctic: state of knowledge and recommendations for future research. Environ. Sci.: Processes Impacts **24**: 1530–1543. DOI: 10.1039/D1EM00531F.
102. Friedlingstein, P., Jones, M., O'Sullivan, M., et al. (2021). Global carbon budget 2021. Earth Syst. Sci. Data **14**: 1917–2005.
103. Lal, R. (2008). Carbon sequestration. Philos. Trans. R. Soc., B **363**: 815–830. DOI: 10.1098/rstb.2007.2185.
104. Lehmann, J., Hansel, C.M., Kaiser, C., et al. (2020). Persistence of soil organic carbon caused by functional complexity. Nat. Geosci. **13**: 529–534. DOI: 10.1038/s41561-020-0612-3.
105. Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. Science **304**: 1623–1627. DOI: 10.1126/science.1097396.
106. Rengel, Z. (2011). Soil pH, soil health and climate change. In soil health and climate change, B.P. Singh, A.L. Cowie, and K.Y. Chan, eds. (Springer Berlin Heidelberg), 69-85.
107. Davidson, E.A., and Janssens, I.A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature **440**: 165–173. DOI: 10.1038/nature04514.
108. Wickland, K.P., and Neff, J.C. (2008). Decomposition of soil organic matter from boreal black spruce forest: environmental and chemical controls. Biogeochemistry **87**: 29–47. DOI: 10.1007/s10533-007-9166-3.
109. Schuur, E.A.G., McGuire, A.D., Schädel, C., et al. (2015). Climate change and the permafrost carbon feedback. Nature **520**: 171–179. DOI: 10.1038/nature14338.
110. Melillo, J.M., Frey, S.D., DeAngelis, K.M., et al. (2017). Long-term pattern and magnitude of soil carbon feedback to the climate system in a warming world. Science **358**: 101–104. DOI: 10.1126/science.aan2874.
111. Zhang, J., Kuang, L., Mou, Z., et al. (2022). Ten years of warming increased plant-derived carbon accumulation in an East Asian monsoon forest. Plant Soil **481**: 349–365. DOI: 10.1007/s11104-022-05642-8.
112. Verbrigghe, N., Leblans, N.I.W., Sigurdsson, B.D., et al. (2022). Soil carbon loss in warmed subarctic grasslands is rapid and restricted to topsoil. Biogeosciences **19**: 3381–3393. DOI: 10.5194/bg-19-3381-2022.
113. Soong, J.L., Castanha, C., Pries, C.E.H., et al. (2021). Five years of whole-soil warming led to loss of subsoil carbon stocks and increased CO2 efflux. Science Adv. **7**: eabd1343. DOI: 10.1126/sciadv.abd1343.
114. Jia, J., Cao, Z., Liu, C., et al. (2019). Climate warming alters subsoil but not topsoil carbon dynamics in alpine grassland. Global Change Biol. **25**: 4383–4393. DOI: 10.1111/gcb.14823.
115. Wang, H., Liu, H., Cao, G., et al. (2020). Alpine grassland plants grow earlier and faster but biomass remains unchanged over 35 years of climate change. Ecol. Lett. **23**: 701–710. DOI: 10.1111/ele.13474.
116. Feng, X., Simpson, A.J., Wilson, K.P., et al. (2008). Increased cuticular carbon sequestration and lignin oxidation in response to soil warming. Nat. Geosci. **1**: 836–839. DOI: 10.1038/ngeo361.
117. Fenner, N., and Freeman, C. (2011). Drought-induced carbon loss in peatlands. Nat. Geosci. **4**: 895–900. DOI: 10.1038/ngeo1323.
118. Meyer, N., Welp, G., and Amelung, W. (2018). The temperature sensitivity (Q10) of soil respiration: controlling factors and spatial prediction at regional scale based on environmental soil classes. Global Biogeochem. Cycles **32**: 306–323. DOI: 10.1002/2017GB005644.
119. Zhou, T., Shi, P., Hui, D., and Luo, Y. (2009). Global pattern of temperature sensitivity of soil heterotrophic respiration (Q10) and its implications for carbon-climate feedback. J. Geophys. Res.: Biogeosci. ***114***.
120. Fierer, N., Colman, B.P., Schimel, J.P., and Jackson, R.B. (2006). Predicting the temperature dependence of microbial respiration in soil: a continental-scale analysis. Global Biogeochem. Cy. **20**: 1–10.
121. Terrer, C., Jackson, R.B., Prentice, I.C., et al. (2019). Nitrogen and phosphorus constrain the CO_2 fertilization of global plant biomass. Nat. Clim. Change **9**: 684–689. DOI: 10.1038/s41558-019-0545-2.
122. Vitousek, P.M., Porder, S., Houlton, B.Z., and Chadwick, O.A. (2010). Terrestrial phosphorus limitation: Mechanisms, implications, and nitrogen-phosphorus interactions. Ecol Appl **20**: 5–15. DOI: 10.1890/08-0127.1.
123. Bauters, M., Janssens, I.A., Wasner, D., et al. (2022). Increasing calcium scarcity along Afrotropical forest succession. Nat. Ecol. Evol. **6**: 1122–1131. DOI: 10.1038/s41559-022-01810-2.
124. Batterman, S.A., Hedin, L.O., van Breugel, M., et al. (2013). Key role of symbiotic dinitrogen fixation in tropical forest secondary succession. Nature **502**: 224–227. DOI: 10.1038/nature12525.
125. Craine, J.M., Morrow, C., and Fierer, N. (2007). Microbial nitrogen limitation increases decomposition. Ecology **88**: 2105–2113. DOI: 10.1890/06-1847.1.
126. Meyer, N., Welp, G., Rodionov, A., et al. (2018). Nitrogen and phosphorus supply controls soil organic carbon mineralization in tropical topsoil and subsoil. Soil Biol. Biochem. **119**: 152–161. DOI: 10.1016/j.soilbio.2018.01.024.
127. Wrage, N., Velthof, G.L., van Beusichem, M.L., and Oenema, O. (2001). Role of nitrifier denitrification in the production of nitrous oxide. Soil Biol. Biochem. **33**: 1723–1732. DOI: 10.1016/S0038-0717(01)00096-7.
128. Griffis, T.J., Chen, Z., Baker, J.M., et al. (2017). Nitrous oxide emissions are enhanced in a warmer and wetter world. Proc. Natl. Acad. Sci. USA **114**: 12081–12085. DOI: 10.1073/pnas.1704552114.
129. Stocker, B.D., Roth, R., Joos, F., et al. (2013). Multiple greenhouse-gas feedbacks from the land biosphere under future climate change scenarios. Nat. Clim. Change **3**: 666–672. DOI: 10.1038/nclimate1864.
130. Moss, B., Kosten, S., Meerhoff, M., et al. (2011). Allied attack: climate change and nutrient pollution. Inland Waters **18**: 101–105.
131. Jeppesen, E., Kronvang, B., Meerhoff, M., et al. (2009). Climate change effects on runoff, catchment phosphorus loading and lake ecological state, and potential adaptations. J. Environ. Qual. **38**: 1930–1941. DOI: 10.2134/jeq2008.0113.
132. Steinhäuser, K.G., Von Gleich, A., Große Ophoff, M., and Körner, W. (2022). The necessity of a global binding framework for sustainable management of

chemicals and materials—interactions with climate and biodiversity. Sustainable Chem. **3**: 205–237. DOI: 10.3390/suschem3020014.

133. Sigmund, G., Ågerstrand, M., Antonelli, A., et al. (2023). Addressing chemical pollution in biodiversity research. Global Change Biol.
134. Ma, C.-S., Zhang, W., Peng, Y., et al. (2021). Climate warming promotes pesticide resistance through expanding overwintering range of a global pest. Nat. Commun. **12**: 5351. DOI: 10.1038/s41467-021-25505-7.
135. Jansson, J.K., and Wu, R. (2022). Soil viral diversity, ecology and climate change. Nat. Rev. Microbiol. **21**: 296–311.
136. Nielsen, U.N., Wall, D.H., and Six, J. (2015). Soil biodiversity and the environment. Annu. Rev. Env. Resour. **40**: 63–90. DOI: 10.1146/annurev-environ-102014-021257.
137. Cavicchioli, R., Ripple, W.J., Timmis, K.N., et al. (2019). Scientists' warning to humanity: Microorganisms and climate change. Nat. Rev. Microbiol. **17**: 569–586. DOI: 10.1038/s41579-019-0222-5.
138. Jansson, J.K., and Hofmockel, K.S. (2020). Soil microbiomes and climate change. Nat. Rev. Microbiol. **18**: 35–46. DOI: 10.1038/s41579-019-0265-7.
139. Spence, A.R., and Tingley, M.W. (2020). The challenge of novel abiotic conditions for species undergoing climate - induced range shifts. Ecography **43**: 1571–1590. DOI: 10.1111/ecog.05170.
140. Kästner, M., Miltner, A., Thiele-Bruhn, S., and Liang, C. (2021). Microbial necromass in soils—linking microbes to soil processes and carbon turnover. Front. Environ. Sci. *9*.
141. Nations, U. (2020). UN world water development report 2020.
142. WMO (2020). World meteorological day focus on climate change and water. WMO.
143. Srivastava, S., Mehta, L., and Naess, L.O. (2022). Increased attention to water is key to adaptation. Nat. Clim. Change **12**: 113–114. DOI: 10.1038/s41558-022-01277-w.
144. Woolway, R.I., Kraemer, B.M., Lenters, J.D., et al. (2020). Global lake responses to climate change. Nat. Rev. Earth Environ. **1**: 388–403. DOI: 10.1038/s43017-020-0067-5.
145. Grossiord, C., Buckley, T.N., Cernusak, L.A., et al. (2020). Plant responses to rising vapor pressure deficit. New Phytol. **226**: 1550–1566. DOI: 10.1111/nph.16485.
146. Pokhrel, Y., Felfelani, F., Satoh, Y., et al. (2021). Global terrestrial water storage and drought severity under climate change. Nat. Clim. Change **11**: 226–233. DOI: 10.1038/s41558-020-00972-w.
147. Piao, S., Ciais, P., Huang, Y., et al. (2010). The impacts of climate change on water resources and agriculture in China. Nature **467**: 43–51. DOI: 10.1038/nature09364.
148. Dai, A. (2013). Increasing drought under global warming in observations and models. Nat. Clim. Change **3**: 52–58. DOI: 10.1038/nclimate1633.
149. Trenberth, K.E. (2011). Changes in precipitation with climate change. Clim. Res. **47**: 123–138. DOI: 10.3354/cr00953.
150. HU, Y.L., JI, G.X., LI, J.H., et al. (2022). Interpretation of IPCC AR6: terrestrial and freshwater ecosystems and their services. Clim. Chang. Res. **18**: 395–404.
151. Nations, U. (2022). The Sustainable Development Goals Report 2022. United Nations Statistics Divisi.
152. Orth, R., and Destouni, G. (2018). Drought reduces blue-water fluxes more strongly than green-water fluxes in Europe. Nat. Commun. **9**: 3602. DOI: 10.1038/s41467-018-06013-7.
153. Li, X., Long, D., Scanlon, B.R., et al. (2022). Climate change threatens terrestrial water storage over the Tibetan Plateau. Nat. Clim. Change **12**: 801–807. DOI: 10.1038/s41558-022-01443-0.
154. Mengistu, D., Bewket, W., Dosio, A., and Panitz, H.J. (2021). Climate change impacts on water resources in the Upper Blue Nile (Abay) River Basin, Ethiopia. J. Hydrol. **592**: 125614. DOI: 10.1016/j.jhydrol.2020.125614.
155. Anurag, H., and Ng, G.H.C. (2022). Assessing future climate change impacts on groundwater recharge in Minnesota. J. Hydrol. **612**: 128112. DOI: 10.1016/j.jhydrol.2022.128112.
156. Øygarden, L., Deelstra, J., Lagzdins, A., et al. (2014). Climate change and the potential effects on runoff and nitrogen losses in the Nordic–Baltic region. Agric., Ecosyst. Environ. **198**: 114–126. DOI: 10.1016/j.agee.2014.06.025.
157. Kløve, B., Ala-Aho, P., Bertrand, G., et al. (2014). Climate change impacts on groundwater and dependent ecosystems. J. Hydrol. **518**: 250–266. DOI: 10.1016/j.jhydrol.2013.06.037.
158. Wang, J.W., Huang, J.T., Fang, T., et al. (2021). Relationship of underground water level and climate in Northwest China's inland basins under the global climate change: Taking the Golmud River Catchment as an example. China Geol. **4**: 402–409.
159. Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., et al. (2007). Coral reefs under rapid climate change and ocean acidification. Science **318**: 1737–1742. DOI: 10.1126/science.1152509.
160. Orton, J.H. (1920). Sea-temperature, breeding and distribution in marine animals. J. Mar. Biol. Assoc. U. K. **12**: 339–366. DOI: 10.1017/S0025315400000102.
161. Huisman, J., Codd, G.A., Paerl, H.W., et al. (2018). Cyanobacterial blooms. Nat.Rev. Microbiol. **16**: 471–483. DOI: 10.1038/s41579-018-0040-1.
162. Trainer, V.L., Moore, S.K., Hallegraeff, G., et al. (2020). Pelagic harmful algal blooms and climate change: Lessons from nature's experiments with extremes. Harmful Algae **91**: 101591. DOI: 10.1016/j.hal.2019.03.009.
163. Woolway, R.I., Jennings, E., Shatwell, T., et al. (2021). Lake heatwaves under climate change. Nature **589**: 402–407. DOI: 10.1038/s41586-020-03119-1.
164. Ilarri, M., Souza, A.T., Dias, E., and Antunes, C. (2022). Influence of climate change and extreme weather events on an estuarine fish community. Sci. Total Environ. **827**: 154190. DOI: 10.1016/j.scitotenv.2022.154190.
165. Xi, Y., Peng, S., Ciais, P., and Chen, Y. (2021). Future impacts of climate change on inland Ramsar wetlands. Nat. Clim. Change **11**: 45–51. DOI: 10.1038/s41558-020-00942-2.
166. Knapp, A.K., Ciais, P., and Smith, M.D. (2017). Reconciling inconsistencies in precipitation–productivity relationships: implications for climate change. New Phytol. **214**: 41–47. DOI: 10.1111/nph.14381.
167. Westerling, A.L., and Bryant, B.P. (2008). Climate change and wildfire in California. Clim. Change **87**: 231–249. DOI: 10.1007/s10584-007-9363-z.
168. Mimura, N. (2013). Sea-level rise caused by climate change and its implications for society. Proc. Jpn. Acad. Ser. B Phys. Biol. Sci. **89**: 281–301. DOI: 10.2183/pjab.89.281.
169. Mukherji, A. (2022). Climate change: put water at the heart of solutions. Nature **605**: 195. DOI: 10.1038/d41586-022-01273-2.
170. Vitasse, Y., Ursenbacher, S., Klein, G., et al. (2021). Phenological and elevational shifts of plants, animals and fungi under climate change in the European Alps. Biol. Rev. **96**: 1816–1835. DOI: 10.1111/brv.12727.
171. Berner, L.T., and Goetz, S.J. (2022). Satellite observations document trends consistent with a boreal forest biome shift. Global Change Biol. **28**: 3275–3292. DOI: 10.1111/gcb.16121.
172. Piao, S., Liu, Q., Chen, A., et al. (2019). Plant phenology and global climate change: Current progresses and challenges. Global Change Biol. **25**: 1922–1940. DOI: 10.1111/gcb.14619.
173. Stöcklin, J., and Körner, C. (1999). Recruitment and mortality of pinus sylvestris near the nordic treeline: the role of climatic change and herbivory. Ecol. Bull. 168-177.
174. Mamet, S.D., Brown, C.D., Trant, A.J., and Laroque, C.P. (2019). Shifting global Larix distributions: northern expansion and southern retraction as species respond to changing climate. J. Biogeogr. **46**: 30–44. DOI: 10.1111/jbi.13465.
175. Beck, P.S.A., Juday, G.P., Alix, C., et al. (2011). Changes in forest productivity across Alaska consistent with biome shift. Ecol. Lett **14**: 373–379. DOI: 10.1111/j.1461-0248.2011.01598.x.
176. Jezkova, T., and Wiens, J.J. (2016). Rates of change in climatic niches in plant and animal populations are much slower than projected climate change. Proc. R. Soc. B **283**: 20162104. DOI: 10.1098/rspb.2016.2104.
177. Cleland, E.E., Chuine, I., Menzel, A., et al. (2007). Shifting plant phenology in response to global change. Trends Ecol. Evol. **22**: 357–365. DOI: 10.1016/j.tree.2007.04.003.
178. MENZEL, A., SPARKS, T.H., ESTRELLA, N., et al. (2006). European phenological response to climate change matches the warming pattern. Global Change Biol. **12**: 1969–1976. DOI: 10.1111/j.1365-2486.2006.01193.x.
179. Gill, A.L., Gallinat, A.S., Sanders-DeMott, R., et al. (2015). Changes in autumn senescence in northern hemisphere deciduous trees: a meta-analysis of autumn phenology studies. Ann. Bot. **116**: 875–888. DOI: 10.1093/aob/mcv055.
180. Fu, Y.H., Geng, X., Hao, F., et al. (2019). Shortened temperature-relevant period of spring leaf-out in temperate-zone trees. Global Change Biol. **25**: 4282–4290. DOI: 10.1111/gcb.14782.
181. Zhu, Z., Piao, S., Myneni, R.B., et al. (2016). Greening of the Earth and its drivers. Nat. Clim. Change **6**: 791–795. DOI: 10.1038/nclimate3004.
182. Piao, S., Liu, Z., Wang, T., et al. (2017). Weakening temperature control on the interannual variations of spring carbon uptake across northern lands. Nat. Clim. Change **7**: 359–363. DOI: 10.1038/nclimate3277.
183. Baltzer, J.L., Day, N.J., Walker, X.J., et al. (2021). Increasing fire and the decline of fire adapted black spruce in the boreal forest. Proc. Natl. Acad. Sci. USA **118**: e2024872118. DOI: 10.1073/pnas.2024872118.
184. Barber, V.A., Juday, G.P., and Finney, B.P. (2000). Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature **405**: 668–673. DOI: 10.1038/35015049.
185. Allen, C.D., Macalady, A.K., Chenchouni, H., et al. (2010). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. **259**: 660–684. DOI: 10.1016/j.foreco.2009.09.001.
186. Aleixo, I., Norris, D., Hemerik, L., et al. (2019). Amazonian rainforest tree mortality driven by climate and functional traits. Nat. Clim. Change **9**: 384–388. DOI: 10.1038/s41558-019-0458-0.
187. Mitton, J.B., and Ferrenberg, S.M. (2012). Mountain Pine Beetle Develops an Unprecedented Summer Generation in Response to Climate Warming. Proc. Am. Soc. Zool. **179**: E163–E171.
188. Skendžić, S., Zovko, M., Živković, I.P., et al. (2021). The impact of climate change on agricultural insect pests. Insects **12**: 440. DOI: 10.3390/insects12050440.
189. Hock, R., Bliss, A., Marzeion, B.E.N., et al. (2019). GlacierMIP – a model intercomparison of global-scale glacier mass-balance models and projections. J. Glaciol. **65**: 453–467. DOI: 10.1017/jog.2019.22.
190. Fox-Kemper, B., Hewitt, H.T., Xiao, C., et al. (2021). Ocean, cryosphere and sea level change. In Masson-Delmotte, P.Z. V., A. Pirani, , S.L. Connors, et al., eds. In climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. CUP.
191. Bamber, J.L., Westaway, R.M., Marzeion, B., and Wouters, B. (2018). The land ice contribution to sea level during the satellite era. Environ. Res. Lett. **13**: 063008. DOI: 10.1088/1748-9326/aac2f0.
192. The IMBIE Team (2018). Mass balance of the Antarctic Ice Sheet from 1992 to 2017. Nature *558*, 219-222.
193. Mudryk, L., Santolaria-Otín, M., Krinner, G., et al. (2020). Historical Northern

Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. The Cryosphere **14**: 2495–2514. DOI: 10.5194/tc-14-2495-2020.
194. Yue, S., Che, T., Dai, L., et al. (2022). Characteristics of snow depth and snow phenology in the high latitudes and high altitudes of the northern hemisphere from 1988 to 2018. Remote Sens. **14**: 5057. DOI: 10.3390/rs14195037.
195. Biskaborn, B.K., Smith, S.L., Noetzli, J., et al. (2019). Permafrost is warming at a global scale. Nat. Commun. **10**: 264. DOI: 10.1038/s41467-018-08240-4.
196. Liu, Y., Cobb, K.M., Song, H., et al. (2017). Recent enhancement of central Pacific El Niño variability relative to last eight centuries. Nat. Commun. **8**: 15386. DOI: 10.1038/ncomms15386.
197. Cao, B., Zhang, T., Peng, X., et al. (2018). Thermal characteristics and recent changes of permafrost in the upper reaches of the Heihe River Basin, Western China. J. Geophys. Res.: Atmos. **123**: 7935–7949.
198. Zhao, L., Zou, D., Hu, G., et al. (2020). Changing climate and the permafrost environment on the Qinghai-Tibet (Xizang) plateau. Permafr. **31**: 396–405.
199. Noetzli J, Christiansen H., Deline P., et al. (2019). Permafrost thermal state [in "State of the climate in 2018"]. Bull. Am. Meteorol. Soc. **100**: S21–S22.
200. Streletskiy, D.A., Sherstiukov, A.B., Frauenfeld, O.W., and Nelson, F.E. (2015). Changes in the 1963–2013 shallow ground thermal regime in Russian permafrost regions. Environ. Res.Lett. **10**: 125005. DOI: 10.1088/1748-9326/10/12/125005.
201. Andersen J. K., Andreassen L.M., Baker E.H., et al. (2020). The Arctic: terrestrial ermafrost [in "state of the climate in 2019"]. Bull. Am. Meteorol. Soc. **101**: S265–S269.
202. Romanovsky, V.E. et al. (2020). The Arctic: Terrestrial Permafrost [in "State of the Climate in 2019"]. Bulletin of the American Meteorological Society **101**: S265–S269.
203. Stammerjohn, S.E., Martinson, D.G., Smith, R.C., et al. (2008). Trends in Antarctic annual sea ice retreat and advance and their relation to El Nino–Southern Oscillation and Southern Annular Mode variability. J.Geophys.Res.: Oceans **113**: C03S90.
204. Turner, J., Lu, H., White, I., et al. (2016). Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. Nature **535**: 411–415. DOI: 10.1038/nature18645.
205. Evans, S.G., and Delaney, K.B. (2015). Chapter 16 - Catastrophic Mass Flows in the Mountain Glacial Environment. In Snow and Ice-Related Hazards, Risks, and Disasters, J.F. Shroder, W. Haeberli, and C. Whiteman, eds. (Academic Press), 563-606.
206. Coe, J.A., Bessette-Kirton, E.K., and Geertsema, M. (2017). Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery. Landslides **15**: 393–407.
207. Allen, S.K., Cox, S.C., and Owens, I.F. (2011). Rock avalanches and other landslides in the central southern alps of New Zealand: a regional study considering possible climate change impacts. Landslides **8**: 33–48. DOI: 10.1007/s10346-010-0222-z.
208. Ballesteros-Cánovas, J.A., Trappmann, D., Madrigal-González, J., et al. (2018). Climate warming enhances snow avalanche risk in the western himalayas. Proc. Natl. Acad. Sci. USA **115**: 3410–3415. DOI: 10.1073/pnas.1716913115.
209. Taylor, C., Robinson, T.R., Dunning, S., et al. (2023). Glacial lake outburst floods threaten millions globally. Nat. Commun. **14**: 487. DOI: 10.1038/s41467-023-36033-x.
210. Hock, R., G. Rasul, C. Adler, et al. (2019): High mountain areas. In: IPCC special report on the ocean and cryosphere in a Changing climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 131–202.
211. Hodson, A.J. (2014). Understanding the dynamics of black carbon and associated contaminants in glacial systems. WIREs. Water **1**: 141–149. DOI: 10.1002/wat2.1016.
212. You, J., Qin, X., Ranjitkar, S., et al. (2018). Response to climate change of montane herbaceous plants in the genus Rhodiola predicted by ecological niche modelling. Sci. Rep. **8**: 5879. DOI: 10.1038/s41598-018-24360-9.
213. Yang, Y., Hopping, K., Wang, G., et al. (2018). Permafrost and drought regulate vulnerability of Tibetan Plateau grasslands to warming. Ecosphere **9**: e02233.
214. Williams, C.M., Henry, H.A.L., and Sinclair, B.J. (2015). Cold truths: how winter drivesresponses of terrestrial organisms to climate change. Biol. Rev. **90**: 214–235.
215. He, X., Burgess, K.S., Gao, L.M., and Li, D.Z. (2019). Distributional responses to climate change for alpine species of Cyananthus and Primula endemic to the Himalaya-Hengduan Mountains. Plant Divers. **41**: 26–32. DOI: 10.1016/j.pld.2019.01.004.
216. Zimova, M., Mills, L.S., and Nowak, J.J. (2016). High fitness costs of climate change-induced camouflage mismatch. Ecol. Lett. **19**: 299–307. DOI: 10.1111/ele.12568.
217. Panetta, A.M., Stanton, M.L., and Harte, J. (2018). Climate warming drives local extinction: Evidence from observation and experimentation. Sci. Adv. **4**: eaaq1819. DOI: 10.1126/sciadv.aaq1819.
218. Gentili, R., Baroni, C., Caccianiga, M., et al. (2015). Potential warm-stage microrefugia for alpine plants: Feedback between geomorphological and biological processes. Ecol. Complex. **21**: 87–99. DOI: 10.1016/j.ecocom.2014.11.006.
219. Xiao, C.-D., Wang, S.-J., and Qin, D.-H. (2015). A preliminary study of cryosphere service function and value evaluation. Advances in climate change research **6**: 181–187. DOI: 10.1016/j.accre.2015.11.004.
220. Steiger, R., Scott, D., Abegg, B., et al. (2017). A critical review of climate change risk for ski tourism. Curr. Issues Tour. **22**: 1343–1379.
221. Hagenstad, M., E.A. Burakowski, and Hill, R. (2018). Economic contributions of winter sports in a changing climate. Protect Our Winters, Boulder, CO, USA.
222. Tschakert, P., Ellis, N.R., Anderson, C., et al. (2019). One thousand ways to experience loss: a systematic analysis of climate-related intangible harm from around the world. Glob. Environ. Change. **55**: 58–72. DOI: 10.1016/j.gloenvcha.2018.11.006.
223. Konchar, K.M., Staver, B., Salick, J., et al. (2015). Adapting in the shadow of annapurna: a climate tipping point. J. Ethnobiol. **35**: 449–471. DOI: 10.2993/0278-0771-35.3.449.
224. Becken, S., Lama, A.K., and Espiner, S. (2013). The cultural context of climate change impacts: perceptions among community members in the Annapurna Conservation Area, Nepal. Environ. Dev. **8**: 22–37. DOI: 10.1016/j.envdev.2013.05.007.
225. Steinhäuser, K.G., Von Gleich, A., Große Ophoff, M., and Körner, W. (2022). The necessity of a global binding framework for sustainable management of chemicals and materials -Interactions with climate and biodiversity. Sustainable Chem. **3**: 205–237. DOI: 10.3390/suschem3020014.
226. Carlsson, P., Christensen, J., Borgå, K., et al. (2017). Influence of climate change on transport, levels, and effects of contaminants in northern areas – part 2. planning and coordination: Lars-Otto Reiersen, Janet Pawlak Production management: Janet Pawlak Technical production and layout.
227. Li, M., Gazang, C., Ge, H., et al. (2021). The atmospheric travel distance of persistent organic pollutants-revisit and application in climate change impact on long-rang transport potential. Atmos. Res. **255**: 105558. DOI: 10.1016/j.atmosres.2021.105558.
228. Wang, X., Sun, D., and Yao, T. (2016). Climate change and global cycling of persistent organic pollutants: a critical review. Sci. China: Earth Sci. **59**: 1899–1911.
229. Zhang, Y., Granger, S.J., Semenov, M.A., et al. (2022). Diffuse water pollution during recent extreme wet-weather in the UK: environmental damage costs and insight into the future. J. Cleaner Prod. **338**: 130633. DOI: 10.1016/j.jclepro.2022.130633.
230. Deutsch, C.A., Tewksbury, J.J., Tigchelaar, M., et al. (2018). Increase in crop losses to insect pests in a warming climate. Sci. **361**: 916–919. DOI: 10.1126/science.aat3466.
231. Crawford, S.E., Brinkmann, M., Ouellet, J.D., et al. (2022). Remobilization of pollutants during extreme flood events poses severe risks to human and environmental health. J. Hazard. Mater. **421**: 126691. DOI: 10.1016/j.jhazmat.2021.126691.
232. Perera, F., and Nadeau, K. (2022). Climate Change, Fossil-Fuel Pollution, and Children's Health. N. Engl. J. Med. **386**: 2303–2314. DOI: 10.1056/NEJMra2117706.
233. Xu, R.B., Yu, P., Abramson, M.J., et al. (2020). Wildfires, global climate change, and human health. N. Engl. J. Med. **383**: 2173–2181. DOI: 10.1056/NEJMsr2028985.
234. Guo, Y., Gasparrini, A., Armstrong, B.G., et al. (2017). Heat wave and mortality: a multicountry, multicommunity study. Environ. Health Perspect. **125**: 087006. DOI: 10.1289/EHP1026.
235. McDermott-Levy, R., Scolio, M., Shakya, K.M., and Moore, C.H. (2021). Factors that influence climate change-related mortality in the United States: an integrative review. Int. J. Environ. Res. Public Health **18**: 8220. DOI: 10.3390/ijerph18158220.
236. Green, H., Bailey, J., Schwarz, L., et al. (2019). Impact of heat on mortality and morbidity in low and middle income countries: a review of the epidemiological evidence and considerations for future research. Environ. Res. **171**: 80–91. DOI: 10.1016/j.envres.2019.01.010.
237. Weilnhammer, V., Schmid, J., Mittermeier, I., et al. (2021). Extreme weather events in europe and their health consequences - a systematic review. Int. J. Hyg. Environ. Health **233**: 113688. DOI: 10.1016/j.ijheh.2021.113688.
238. Poursafa, P., Keikha, M., and Kelishadi, R. (2015). Systematic review on adverse birth outcomes of climate change. J. Res. Med. Sci. **20**: 397–402.
239. Bekkar, B., Pacheco, S., Basu, R., and DeNicola, N. (2020). Association of air pollution and heat exposure with preterm birth, low birth weight, and stillbirth in the US: a systematic review. JAMA Netw Open **3**: e208243. DOI: 10.1001/jamanetworkopen.2020.8243.
240. Liu, J., Varghese, B.M., Hansen, A., et al. (2021). Is there an association between hot weather and poor mental health outcomes. A systematic review and meta-analysis. Environ Int **153**: 106533.
241. Cianconi, P., Betro, S., and Janiri, L. (2020). The impact of climate change on mental health: a systematic descriptive review. Front. Psychiatry **11**: 74.
242. Yang, J., Yin, P., Sun, J., et al. (2019). Heatwave and mortality in 31 major Chinese cities: definition, vulnerability and implications. Sci. Total Environ. **649**: 695–702. DOI: 10.1016/j.scitotenv.2018.08.332.
243. Guo, Y.M., Zhang, Y.W., Yu, P., et al. (2023). Strategies to reduce the health impacts of heat exposure. In Heat Exposure and Human Health in the Context of Climate Change, 293-322.
244. Liu, J., Varghese, B.M., Hansen, A., et al. (2022). Heat exposure and cardiovascular health outcomes: a systematic review and meta-analysis. Lancet Planet. Health **6**: e484–e495. DOI: 10.1016/S2542-5196(22)00117-6.
245. Cheng, J., Xu, Z., Bambrick, H., et al. (2019). Cardiorespiratory effects of heatwaves: a systematic review and meta-analysis of global epidemiological evidence. Environ. Res. **177**: 108610. DOI: 10.1016/j.envres.2019.108610.
246. Zhang, Y., Hajat, S., Zhao, L., et al. (2022). The burden of heatwave-related preterm births and associated human capital losses in China. Nat. Commun. **13**: 7565. DOI: 10.1038/s41467-022-35008-8.
247. Finlay, S.E., Moffat, A., Gazzard, R., et al. (2012). Health impacts of wildfires. PLoS Curr. ***4***, e4f959951cce959952c.
248. Reid, C.E., Brauer, M., Johnston, F.H., et al. (2016). Critical review of health impacts of

wildfire smoke exposure. Environ. Health Perspect. **124**: 1334–1343. DOI: 10.1289/ehp.1409277.
249. Yang, F., Gao, Y., Zhao, H., et al. (2021). Revealing the distribution characteristics of antibiotic resistance genes and bacterial communities in animal-aerosol-human in a chicken farm: from One-Health perspective. Ecotoxicol. Environ. Saf. **224**: 112687. DOI: 10.1016/j.ecoenv.2021.112687.
250. Amjad, S., Chojecki, D., Osornio-Vargas, A., and Ospina, M.B. (2021). Wildfire exposure during pregnancy and the risk of adverse birth outcomes: a systematic review. Environ. Int. **156**: 106644. DOI: 10.1016/j.envint.2021.106644.
251. Belleville, G., Ouellet, M.C., and Morin, C.M. (2019). Post-Traumatic stress among evacuees from the 2016 Fort McMurray Wildfires: exploration of psychological and sleep symptoms three months after the evacuation. Int. J. Environ. Res. Public Health **16**: 1604. DOI: 10.3390/ijerph16091604.
252. Bryant, R.A., Gibbs, L., Gallagher, H.C., et al. (2018). Longitudinal study of changing psychological outcomes following the Victorian Black Saturday bushfires. Aust. N. Z. J. Psychiat **52**: 542–551. DOI: 10.1177/0004867417714337.
253. Dosa, D.M., Skarha, J., Peterson, L.J., et al. (2020). Association between exposure to hurricane irma and mortality and mospitalization in florida nursing home residents. Jama. Netw. Open **3**: e2019460. DOI: 10.1001/jamanetworkopen.2020.19460.
254. Watkins, D.J., Torres Zayas, H.R., Vélez Vega, C.M., et al. (2020). Investigating the impact of Hurricane Maria on an ongoing birth cohort in Puerto Rico. Popul. Environ. **42**: 95–111. DOI: 10.1007/s11111-020-00345-7.
255. Schwartz, R.M., Gillezeau, C.N., Liu, B., et al. (2017). Longitudinal impact of hurricane sandy exposure on Mental Health Symptoms. Int. J. Environ. Res. Public Health **14**: 957. DOI: 10.3390/ijerph14090957.
256. Lenane, Z., Peacock, E., Joyce, C., et al. (2019). Association of post-traumatic stress disorder symptoms following hurricane katrina with incident cardiovascular disease events among older adults with hypertension. Am. J. Geriatr. Psychiatry **27**: 310–321. DOI: 10.1016/j.jagp.2018.11.006.
257. Brown, M.R.G., Agyapong, V., Greenshaw, A.J., et al. (2019). After the Fort McMurray wildfire there are significant increases in mental health symptoms in grade 7-12 students compared to controls. BMC Psychiatry **19**: 97. DOI: 10.1186/s12888-019-2074-y.
258. Benmarhnia, T., Deguen, S., Kaufman, J.S., and Smargiassi, A. (2015). Vulnerability to heat-related mortality a systematic review,meta-analysis, and meta-regression analysis. Epidemiology **26**: 781–793. DOI: 10.1097/EDE.0000000000000375.
259. Romanello, M., McGushin, A., Di Napoli, C., et al. (2021). The 2021 report of the Lancet Countdown on health and climate change: code red for a healthy future. Lancet **398**: 1619–1662. DOI: 10.1016/S0140-6736(21)01787-6.
260. Xu, R., Zhao, Q., Coelho, M., et al. (2020). Socioeconomic inequality in vulnerability to all-cause and cause-specific hospitalisation associated with temperature variability: A time-series study in 1814 Brazilian cities. Lancet Planet. Health **4**: e566–e576. DOI: 10.1016/S2542-5196(20)30251-5.
261. Burrows, M.T., Bates, A.E., Costello, M.J., et al. (2019). Ocean community warming responses explained by thermal affinities and temperature gradients. Nat. Clim. Chang. **9**: 959–963. DOI: 10.1038/s41558-019-0631-5.
262. Chaudhary, C., Richardson, A.J., Schoeman, D.S., and Costello, M.J. (2021). Global warming is causing a more pronounced dip in marine species richness around the equator. Proc. Natl. Acad. Sci. USA **118**: e2015094118. DOI: 10.1073/pnas.2015094118.
263. Gordó-Vilaseca, C., Stephenson, F., Coll, M., et al. (2023). Three decades of increasing fish biodiversity across the northeast Atlantic and the Arctic Ocean. Proc. Natl. Acad. Sci. **120**: e2120869120. DOI: 10.1073/pnas.2120869120.
264. Manes, S., Costello, M.J., Beckett, H., et al. (2021). Endemism increases species' climate change risk in areas of global biodiversity importance. Biol. Conserv **257**: 109070. DOI: 10.1016/j.biocon.2021.109070.
265. Costello, M.J. (2022). Biodiversity conservation through protected areas supports healthy ecosystems and resilience to climate change and other disturbances. In Imperiled: The Encyclopedia of Conservation, D.A. DellaSala, and M.I. Goldstein, eds. 423-429.
266. Zhao, Q., Huang, H., Costello, M.J., and Chu, J. (2023). Climate change projections show shrinking deep-water ecosystems with implications for biodiversity and aquaculture in the Northwest Pacific. Sci. Total Environ. **861**: 160505. DOI: 10.1016/j.scitotenv.2022.160505.
267. Lavin, C.P., Gordó-Vilaseca, C., Costello, M.J., et al. (2022). Warm and cold temperatures limit the maximum body length of teleost fishes across a latitudinal gradient in Norwegian waters. Environ. Biol. Fishes **105**: 1415–1429. DOI: 10.1007/s10641-022-01270-4.
268. Lavin, C.P., Gordó-Vilaseca, C., Stephenson, F., et al. (2022). Warmer temperature decreases the maximum length of six species of marine fishes, crustacean, and squid in New Zealand. Environ. Biol. Fishes **105**: 1431–1446. DOI: 10.1007/s10641-022-01251-7.
269. Costello, M.J., M.M. Vale, W. Kiessling, et al. (2022). Cross-chapter paper 1: biodiversity hotspots. In climate change 2022: Impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change, H.-O. Pörtner, D.C. Roberts, M. Tignor, et al., eds. 2123–2161.
270. Mackintosh, A., Hill, G., Costello, M., et al. (2023). Modeling Aquaculture Suitability in a Climate Change Future. Oceanography, **36**: 8–8.
271. Lawrence, J., B. Mackey, F. Chiew, et al. (2022). Australasia. In: climate change 2022: Impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. In H.-O. Pörtner, D.C. Roberts, M. Tignor, et al., eds.
272. Pörtner, H.-O., D.C. Roberts, H. Adams, et al. (2022). Technical summary. In: climate change 2022: impacts, adaptation, and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. In H.-O. Pörtner, D.C. Roberts, M. Tignor, et al., eds.
273. Costello, M.J. (2022). Threats to marine species and habitats, and how banning seabed trawling supports the global biodiversity framework. In Imperiled: the encyclopedia of conservation, D.A. DellaSala, and M.I. Goldstein, eds. 633-639.
274. Costello, M.J. (2022). Restoring biodiversity and living with nature (Based Solutions). In imperiled: the encyclopedia of conservation, D.A. DellaSala, and M.I. Goldstein, eds. 7-14.
275. Costello, M.J., Webb, J.T., Provoost, P., and Appeltans, W. (2022). New knowledge on and threats to marine biodiversity. In: state of the ocean report, pilot edition. IOC Technical Series IOC-UNESCO.
276. Costello, Mark J. (2015). Biodiversity: The known, unknown, and rates of extinction. Curr. Biol. **25**: R368–R371. DOI: 10.1016/j.cub.2015.03.051.
277. Costello, M.J. (2022). Climate Change is not the biggest threat to freshwater biodiversity. In Imperiled: the encyclopedia of conservation, D.A. DellaSala, and M.I. Goldstein, eds. 623-632.
278. Leadley, P., Obura, D., Archer, E., et al. (2022). Actions needed to achieve ambitious objectives of net gains in natural ecosystem area by 2030 and beyond. PLOS Sustainability and Transformation **1**: e0000040. DOI: 10.1371/journal.pstr.0000040.
279. Kocsis, Á.T., Zhao, Q., Costello, M.J., and Kiessling, W. (2021). Not all biodiversity rich spots are climate refugia. Biogeosciences **18**: 6567–6578. DOI: 10.5194/bg-18-6567-2021.
280. Amelung, W., Bossio, D., de Vries, W., et al. (2020). Towards a global-scale soil climate mitigation strategy. Nat. Commun. **11**: 5427. DOI: 10.1038/s41467-020-18887-7.
281. Yu, Z., Loisel, J., Brosseau, D.P., et al. (2010). Global peatland dynamics since the Last Glacial Maximum. Geophys. Res. Lett. *37*.
282. Scharlemann, J.P.W., Tanner, E.V.J., Hiederer, R., and Kapos, V. (2014). Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Manag. **5**: 81–91. DOI: 10.4155/cmt.13.77.
283. Schimmel, H., and Amelung, W. (2022). Organic soils. In Reference Module in Earth Systems and Environmental Sciences.
284. Frolking, S., Talbot, J., Jones, M.C., et al. (2011). Peatlands in the Earth's 21st century climate system. Environ. Rev. **19**: 371–396. DOI: 10.1139/a11-014.
285. Leifeld, J., Wüst-Galley, C., and Page, S. (2019). Intact and managed peatland soils as a source and sink of GHGs from 1850 to 2100. Nat. Clim. Chang. **9**: 945–947. DOI: 10.1038/s41558-019-0615-5.
286. Knox, S.H., Sturtevant, C., Matthes, J.H., et al. (2015). Agricultural peatland restoration: effects of land-use change on greenhouse gas (CO_2 and CH_4) fluxes in the Sacramento-San Joaquin Delta. G. C. Biology **21**: 750–765. DOI: 10.1111/gcb.12745.
287. Paustian, K., Lehmann, J., Ogle, S., et al. (2016). Climate-smart soils. Nature **532**: 49–57. DOI: 10.1038/nature17174.
288. Lu, N., Tian, H.Q., Fu, B.J., et al. (2022). Biophysical and economic constraints on China's natural climate solutions. Nat. Clim. Chang. **12**: 847. DOI: 10.1038/s41558-022-01432-3.
289. Fargione, J.E., Bassett, S., Boucher, T., et al. (2018). Natural climate solutions for the United States. Sci. Adv. **4**: eaat1869. DOI: 10.1126/sciadv.aat1869.
290. Pan, Y.D., Birdsey, R.A., Fang, J.Y., et al. (2011). A large and persistent carbon sink in the world's forests. Science **333**: 988–993. DOI: 10.1126/science.1201609.
291. Grassi, G., House, J., Dentener, F., et al. (2017). The key role of forests in meeting climate targets requires science for credible mitigation. Nat. Clim. Chang. **7**: 220–+. DOI: 10.1038/nclimate3227.
292. Ruseva, T.B. (2023). The governance of forest carbon in a subnational climate mitigation system: insights from a network of action situations approach. Sustain. Sci. **18**: 59–78. DOI: 10.1007/s11625-022-01262-4.
293. Morecroft, M.D., Duffield, S., Harley, M., et al. (2019). Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. Science *366*, 1329-+, eaaw9256.
294. Anderegg, W.R.L., Trugman, A.T., Badgley, G., et al. (2020). Climate-driven risks to the climate mitigation potential of forests. Science **368**: eaaz7005. DOI: 10.1126/science.aaz7005.
295. Rana, P., and Varshney, L.R. (2023). Exploring limits to tree planting as a natural climate solution. J. Clean. Prod. **384**: 135566. DOI: 10.1016/j.jclepro.2022.135566.
296. Fleischman, F., Basant, S., Chhatre, A., et al. (2020). Pitfalls of tree planting show why we need people-centered natural climate solutions. Bioscience **70**: 947–950.
297. Strassburg, B.B.N., Iribarrem, A., Beyer, H.L., et al. (2020). Global priority areas for ecosystem restoration. Nature **586**: 724–729. DOI: 10.1038/s41586-020-2784-9.
298. Doelman, J.C., and Stehfest, E. (2022). The risks of overstating the climate benefits of ecosystem restoration. Nature **609**: E1–E3. DOI: 10.1038/s41586-022-04881-0.
299. Elias, M., Kandel, M., Mansourian, S., et al. (2022). Ten people-centered rules for socially sustainable ecosystem restoration. Restor. Ecol. **30**: e13574.
300. Wu, X., Lu, Y., Zhang, J., et al. (2023). Adapting ecosystem restoration for sustainable development in a changing world. The Innovation *4*, 100375, 10.1016/j.xinn.2023.100375.

301. IPCC (2019). Climate change 2019: Synthesis report contribution of working groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change.
302. Tian, D., Zhang, Y., Mu, Y., et al. (2020). Effect of N fertilizer types on N_2O and NO emissions under drip fertigation from an agricultural field in the North China Plain. Sci. Total Environ. **715**: 136903. DOI: 10.1016/j.scitotenv.2020.136903.
303. Saunois, M., Bousquet, P., Poulter, B., et al. (2016). The global methane budget 2000–2012. Earth Syst. Sci. Data **8**: 697–751. DOI: 10.5194/essd-8-697-2016.
304. Tao, F., Palosuo, T., Valkama, E., and Mäkipää, R. (2019). Cropland soils in China have a large potential for carbon sequestration based on literature survey. Soil and Tillage Res. **186**: 70–78. DOI: 10.1016/j.still.2018.10.009.
305. Hobley, E.U., Honermeier, B., Don, A., et al. (2018). Decoupling of subsoil carbon and nitrogen dynamics after long-term crop rotation and fertilization. Agr. Ecosyst. Environ. **265**: 363–373. DOI: 10.1016/j.agee.2018.06.021.
306. Liu, J., Jiang, B.S., Shen, J.L., et al. (2021). Contrasting effects of straw and straw-derived biochar applications on soil carbon accumulation and nitrogen use efficiency in double-rice cropping systems. Agr. Ecosyst. Environ. **311**: 107286. DOI: 10.1016/j.agee.2020.107286.
307. Bai, X., Huang, Y., Ren, W., et al. (2019). Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. Global Change Biol. **25**: 2591–2606. DOI: 10.1111/gcb.14658.
308. Xia, L., Cao, L., Yang, Y., et al. (2023). Integrated biochar solutions can achieve carbon-neutral staple crop production. Nature Food **4**: 236–246. DOI: 10.1038/s43016-023-00694-0.
309. Wang, H., Wang, S., Yu, Q., et al. (2020). No tillage increases soil organic carbon storage and decreases carbon dioxide emission in the crop residue-returned farming system. J. Environ. Manage **261**: 110261. DOI: 10.1016/j.jenvman.2020.110261.
310. Six, J., Feller, C., Denef, K., et al. (2002). Soil organic matter, biota and aggregation in temperate and tropical soils - Effects of no-tillage. Agronomie **22**: 755–775. DOI: 10.1051/agro:2002043.
311. Cai, A., Han, T., Ren, T., et al. (2022). Declines in soil carbon storage under no tillage can be alleviated in the long run. Geoderma **425**: 116028. DOI: 10.1016/j.geoderma.2022.116028.
312. Yang, Y., Ti, J., Zou, J., et al. (2023). Optimizing crop rotation increases soil carbon and reduces GHG emissions without sacrificing yields. Agr. Ecosyst. Environ. *342*. 108220.
313. Shen, H., Shiratori, Y., Ohta, S., et al. (2021). Mitigating N2O emissions from agricultural soils with fungivorous mites. ISME J. **15**: 2427–2439. DOI: 10.1038/s41396-021-00948-4.
314. Cai, S., Zhao, X., Pittelkow, C.M., et al. (2023). Optimal nitrogen rate strategy for sustainable rice production in China. Nature **615**: 73–79. DOI: 10.1038/s41586-022-05678-x.
315. Rees, R.M., Maire, J., Florence, A., et al. (2020). Mitigating nitrous oxide emissions from agricultural soils by precision management. Front Agric Sci Eng **7**: 75–80. DOI: 10.15302/J-FASE-2019294.
316. Cui, X.Q., Zhou, F., Ciais, P., et al. (2021). Global mapping of crop-specific emission factors highlights hotspots of nitrous oxide mitigation. Nature Food **2**: 886–+. DOI: 10.1038/s43016-021-00384-9.
317. Recio, J., Alvarez, J.M., Rodriguez-Quijano, M., and Vallejo, A. (2019). Nitrification inhibitor DMPSA mitigated N2O emission and promoted NO sink in rainfed wheat. Environ。 Pollut **245**: 199–207. DOI: 10.1016/j.envpol.2018.10.135.
318. Recio, J., Montoya, M., Ginés, C., et al. (2020). Joint mitigation of NH3 and N2O emissions by using two synthetic inhibitors in an irrigated cropping soil. Geoderma **373**: 114423。. DOI: 10.1016/j.geoderma.2020.114423.
319. Bakken, L.R., and Frostegård, Å. (2020). Emerging options for mitigating N2O emissions from food production by manipulating the soil microbiota. Curr. Opin. Environ. Sustain. **47**: 89–94. DOI: 10.1016/j.cosust.2020.08.010.
320. Shen, H., Shiratori, Y., Ohta, S., et al. (2021). Mitigating N2O emissions from agricultural soils with fungivorous mites. ISME J.l **15**: 2427–2439. DOI: 10.1038/s41396-021-00948-4.
321. Storer, K., Coggan, A., Ineson, P., and Hodge, A. (2018). Arbuscular mycorrhizal fungi reduce nitrous oxide emissions from N2O hotspots. New Phytol. **220**: 1285–1295. DOI: 10.1111/nph.14931.
322. Hiya, H.J., Ali, M.A., Baten, M.A., and Barman, S.C. (2020). Effect of water saving irrigation management practices on rice productivity and methane emission from paddy field. J. Geosci.Environ. Prot. **8**: 182–196.
323. Iqbal, M.F., Zhang, Y., Kong, P., et al. (2023). High-yielding nitrate transporter cultivars also mitigate methane and nitrous oxide emissions in paddy. Front. Plant Sci. *14*. 1133643.
324. Wang, C., Liu, J., Shen, J., et al. (2018). Effects of biochar amendment on net greenhouse gas emissions and soil fertility in a double rice cropping system: A 4-year field experiment. Agric., Ecosyst. Environ. **262**: 83–96. DOI: 10.1016/j.agee.2018.04.017.
325. Yagi, K., Sriphirom, P., Cha-un, N., et al. (2020). Potential and promisingness of technical options for mitigating greenhouse gas emissions from rice cultivation in Southeast Asian countries. Soil Sci. Plant Nutr. **66**: 37–49. DOI: 10.1080/00380768.2019.1683890.
326. Scholz, V.V., Meckenstock, R.U., Nielsen, L.P., and Risgaard-Petersen, N. (2020). Cable bacteria reduce methane emissions from rice-vegetated soils. Nat. Commun. **11**: 1878. DOI: 10.1038/s41467-020-15812-w.
327. Rani, V., Bhatia, A., and Kaushik, R. (2021). Inoculation of plant growth promoting-methane utilizing bacteria in different N-fertilizer regime influences methane emission and crop growth of flooded paddy. Sci. Total Environ. **775**: 145826. DOI: 10.1016/j.scitotenv.2021.145826.
328. Davamani, V., Parameswari, E., and Arulmani, S. (2020). Mitigation of methane gas emissions in flooded paddy soil through the utilization of methanotrophs. Sci. Total Environ. **726**: 138570. DOI: 10.1016/j.scitotenv.2020.138570.
329. Fan, L.C., Dippold, M.A., Ge, T.D., et al. (2020). Anaerobic oxidation of methane in paddy soil: Role of electron acceptors and fertilization in mitigating CH4 fluxes. Soil Biol. Biochem. **141**: 107685. DOI: 10.1016/j.soilbio.2019.107685.
330. Clark, M.A., Domingo, N.G.G., Colgan, K., et al. (2020). Global food system emissions could preclude achieving the 1.5 degrees and 2 degrees C climate change targets. Science *370*, 705–+.
331. Clark, S. (2020). Organic Farming and Climate Change: The Need for Innovation. Sustainability **12**: 7012. DOI: 10.3390/su12177012.
332. Reganold, J.P., and Wachter, J.M. (2016). Organic agriculture in the twenty-first century. Nat. Plants **2**: 15221. DOI: 10.1038/nplants.2015.221.
333. Renwick, L.L.R., Deen, W., Silva, L., et al. (2021). Long-term crop rotation diversification enhances maize drought resistance through soil organic matter. Environ. Res. Lett. **16**: 084067. DOI: 10.1088/1748-9326/ac1468.
334. Rollan, À., Hernández-Matías, A., and Real, J. (2019). Organic farming favours bird communities and their resilience to climate change in Mediterranean vineyards. Agric. Ecosyst. Environ. **269**: 107–115. DOI: 10.1016/j.agee.2018.09.029.
335. Małgorzata, H., Jolanta, K., and Magdalena, J. (2022). Reducing Carbon Footprint of Agriculture. Can Organic Farming Help to Mitigate Climate Change? Agriculture **12**: 1383.
336. Šarauskis, E., Romaneckas, K., Kumhála, F., and Kriaučiūnienė, Z. (2018). Energy use and carbon emission of conventional and organic sugar beet farming. J. Clean Prod. **201**: 428–438. DOI: 10.1016/j.jclepro.2018.08.077.
337. Cooper, J., Baranski, M., Stewart, G., et al. (2016). Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. Agron. Sustain. Dev. **36**: 22. DOI: 10.1007/s13593-016-0354-1.
338. Zani, C.F., Lopez-Capel, E., Abbott, G.D., et al. (2022). Effects of integrating grass-clover leys with livestock into arable crop rotations on soil carbon stocks and particulate and mineral-associated soil organic matter fractions in conventional and organic systems. Soil Use Manag. **38**: 448–465. DOI: 10.1111/sum.12754.
339. Skinner, C., Gattinger, A., Krauss, M., et al. (2019). The impact of long-term organic farming on soil-derived greenhouse gas emissions. Sci. Rep. **9**: 1702. DOI: 10.1038/s41598-018-38207-w.
340. Gangopadhyay, S., Banerjee, R., Batabyal, S., et al. (2022). Carbon sequestration and greenhouse gas emissions for different rice cultivation practices. Sustain. Prod. Consump. **34**: 90–104. DOI: 10.1016/j.spc.2022.09.001.
341. Skinner, C., Gattinger, A., Krauss, M., et al. (2019). The impact of long-term organic farming on soil-derived greenhouse gas emissions. Sci. Rep. **9**: 1702. DOI: 10.1038/s41598-018-38207-w.
342. Costa, C., Wollenberg, E., Benitez, M., et al. (2022). Roadmap for achieving net-zero emissions in global food systems by 2050. Sci. Rep. **12**: 15064. DOI: 10.1038/s41598-022-18601-1.
343. Miksa, O., Chen, X., Baležentienė, L., et al. (2020). Ecological challenges in life cycle assessment and carbon budget of organic and conventional agroecosystems: A case from Lithuania. Sci. Total Environ. **714**: 136850. DOI: 10.1016/j.scitotenv.2020.136850.
344. Longlong, X., Liang, C., Yi, Y., et al. (2023). Integrated biochar solutions can achieve carbon-neutral staple crop production. Nature Food. **4**: 236–246. DOI: 10.1038/s43016-023-00694-0.
345. Chiriacò, M.V., Grossi, G., Castaldi, S., and Valentini, R. (2017). The contribution to climate change of the organic versus conventional wheat farming: A case study on the carbon footprint of wholemeal bread production in Italy. J. Clean. Prod. **153**: 309–319. DOI: 10.1016/j.jclepro.2017.03.111.
346. El Chami, D. (2020). Towards Sustainable Organic Farming Systems. Sustainability. **12**: 9832. DOI: 10.3390/su12239832.
347. Tutuncu, A.N. (2020). Fossil Fuels: A technical overview. In The Oxford Handbook of Energy Politics, K.J. Hancock, and J.E. Allison, eds. (Oxford University Press). 22-41.
348. NRC. (2010). Hidden costs of energy: unpriced consequences of energy production and use (The National Academies Press).
349. Bian, Z., Inyang, H.I., Daniels, J.L., et al. (2010). Environmental issues from coal mining and their solutions. Min. Sci. Technol. **20**: 215–223.
350. Clay, K., Jha, A., Muller, N., and Walsh, R. (2019). External costs of transporting petroleum products: Evidence from shipments of crude oil from North Dakota by pipelines and rail. The Energy J. **40**: 55–72.
351. Kaygusuz, K. (2007). Energy for sustainable development: Key issues and challenges. Energy Sources **2**: 73–83. DOI: 10.1080/15567240500402560.
352. Rubin, E.M. (2008). Genomics of cellulosic biofuels. Nature **454**: 841–845. DOI: 10.1038/nature07190.
353. Gibb, D., Ledanois, N., Ranalder, L., et al. (2022). Renewables 2022 global status report+ Renewable energy data in perspective+ Press releases+ Regional fact sheets+ Country fact sheets.
354. Yang, Z., Zhang, J., Kintner-Meyer, M.C.W., et al. (2011). Electrochemical Energy Storage for Green Grid. Chem. Rev. **111**: 3577–3613. DOI: 10.1021/cr100290v.

355. IEA (2022). Carbon capture, utilisation and storage - fuels & technologies. Int. J. Energy Res.
356. IPCC (2018). Global warming of 1.5 °C: an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change.
357. CAEP (2021). The annual report of CCUS in China-The Chinese CCUS pathway. Chinese Academy of Environmental planning.
358. IEA (2020). Energy technology perspectives: special report on carbon capture utilisation and storage CCUS in clean energy transitions. International Energy Agency.
359. Rogelj, J., Popp, A., Calvin, K.V., et al. (2018). Scenarios towards limiting global mean temperature increase below 1.5 °C. Nat. Clim. Chang. *8*, 325-332.
360. Shahbaz, M., AlNouss, A., Ghiat, I., et al. (2021). A comprehensive review of biomass based thermochemical conversion technologies integrated with CO2 capture and utilisation within BECCS networks. Resour, Conserv. Recycl. **173**: 105734. DOI: 10.1016/j.resconrec.2021.105734.
361. Sagues, W.J., Jameel, H., Sanchez, D.L., and Park, S. (2020). Prospects for bioenergy with carbon capture & storage (BECCS) in the United States pulp and paper industry. Energy Environ. Sci. **13**: 2243–2261. DOI: 10.1039/D0EE01107J.
362. Xing, X., Wang, R., Bauer, N., et al. (2021). Spatially explicit analysis identifies significant potential for bioenergy with carbon capture and storage in China. Nat. Commun. **12**: 3159. DOI: 10.1038/s41467-021-23282-x.
363. Smith, P., Davis, S.J., Creutzig, F., et al. (2015). Biophysical and economic limits to negative CO2 emissions. Nat. Clim. Chang. **6**: 42–50.
364. Hanssen, S.V., Steinmann, Z.J.N., Daioglou, V., et al. (2022). Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity. Glob. Chang. Biol. Bioenergy. **14**: 307–321. DOI: 10.1111/gcbb.12911.
365. Fajardy, M., Morris, J., Gurgel, A., et al. (2021). The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5 °C or 2 °C world. Glob. Environ. Change. *68*, 102262.
366. Stenzel, F., Gerten, D., Werner, C., and Jägermeyr, J. (2019). Freshwater requirements of large-scale bioenergy plantations for limiting global warming to 1.5 °C. Environ. Res. Lett. *14*, 084001.
367. Li, W., Ciais, P., Han, M., et al. (2021). Bioenergy crops for low warming targets require half of the present agricultural fertilizer use. Environ. Sci. Technol. **55**: 10654–10661. DOI: 10.1021/acs.est.1c02238.
368. Crippa, M., Solazzo, E., Guizzardi, D., et al. (2021). Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food **2**: 198–209. DOI: 10.1038/s43016-021-00225-9.
369. Yang, J., Zhou, Q., and Zhang, J. (2017). Moderate wetting and drying increases rice yield and reduces water use, grain arsenic level, and methane emission. Crop. J. **5**: 151–158. DOI: 10.1016/j.cj.2016.06.002.
370. Wang, Z., Yin, Y., Wang, Y., et al. (2022). Integrating crop redistribution and improved management towards meeting China's food demand with lower environmental costs. Nature Food **3**: 1031–1039. DOI: 10.1038/s43016-022-00646-0.
371. Vaughan, A. (2021). COP26: 105 countries pledge to cut methane emissions by 30 per cent.
372. Clark, M., Springmann, M., Rayner, M., et al. (2022). Estimating the environmental impacts of 57,000 food products. Proc. Natl. Acad. Sci. U. S. A. **119**: e2120584119. DOI: 10.1073/pnas.2120584119.
373. Gerten, D., Heck, V., Jägermeyr, J., et al. (2020). Feeding ten billion people is possible within four terrestrial planetary boundaries. Nat. Sustain. **3**: 200–208. DOI: 10.1038/s41893-019-0465-1.
374. Hickey, L.T., N. Hafeez, A., Robinson, H., et al. (2019). Breeding crops to feed 10 billion. Nat. Biotechnol. **37**: 744–754. DOI: 10.1038/s41587-019-0152-9.
375. Lam, S.K., Wille, U., Hu, H.-W., et al. (2022). Next-generation enhanced-efficiency fertilizers for sustained food security. Nature Food **3**: 575–580. DOI: 10.1038/s43016-022-00542-7.
376. Cheng, L., Zhang, X., Reis, S., et al. (2022). A 12% switch from monogastric to ruminant livestock production can reduce emissions and boost crop production for 525 million people. Nature Food **3**: 1040–1051. DOI: 10.1038/s43016-022-00661-1.
377. Bai, Z., Fan, X., Jin, X., et al. (2022). Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population. Nature Food **3**: 152–160. DOI: 10.1038/s43016-021-00453-z.
378. Xu, X., Sharma, P., Shu, S., et al. (2021). Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nature Food **2**: 724–732. DOI: 10.1038/s43016-021-00358-x.
379. Clark, M.A., Domingo, N.G.G., Colgan, K., et al. (2020). Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science *370*, 705-708.
380. van Huis, A., and Gasco, L. (2023). Insects as feed for livestock production. Science **379**: 138–139. DOI: 10.1126/science.adc9165.
381. Hazarika, A.K., and Kalita, U. (2023). Human consumption of insects. Science **379**: 140–141. DOI: 10.1126/science.abp8819.
382. Humpenoder, F., Bodirsky, B.L., Weindl, I., et al. (2022). Projected environmental benefits of replacing beef with microbial protein. Nature **605**: 90–96. DOI: 10.1038/s41586-022-04629-w.
383. Lynch, J., and Pierrehumbert, R. (2019). Climate impacts of cultured meat and beef cattle. Front. Sustain. Food Syst. **3**: 5. DOI: 10.3389/fsufs.2019.00005.
384. Li, T., Chen, Y.Z., Han, L.J., et al. (2021). Shortened duration and reduced area of frozen soil in the Northern Hemisphere. The Innovation *2*, 100146, 10.1016/j.xinn.2021.100146.
385. Malhi, Y., Franklin, J., Seddon, N., et al. (2020). Climate change and ecosystems: Threats, opportunities and solutions. Philos Trans. R. Soc. Lond B. Biol. Sci. **375**: 20190104. DOI: 10.1098/rstb.2019.0104.
386. Li, D., Wu, S., Liu, L., et al. (2018). Vulnerability of the global terrestrial ecosystems to climate change. Glob. Chang. Biol. **24**: 4095–4106. DOI: 10.1111/gcb.14327.
387. Reside, A.E., Butt, N., and Adams, V.M. (2018). Adapting systematic conservation planning for climate change. Biodiversity Conserv. **27**: 1–29. DOI: 10.1007/s10531-017-1442-5.
388. Mills, A.J., Tan, D., Manji, A.K., et al. (2020). Ecosystem - based adaptation to climate change: Lessons learned from a pioneering project spanning Mauritania, Nepal, the Seychelles, and China. Plants, People, Planet **2**: 587–597. DOI: 10.1002/ppp3.10126.
389. Chanza, N., and Musakwa, W. (2021). Indigenous practices of ecosystem management in a changing climate: Prospects for ecosystem-based adaptation. Environ. Sci. Policy **126**: 142–151. DOI: 10.1016/j.envsci.2021.10.005.
390. Manes, S., Vale, M.M., Malecha, A., and Pires, A.P.F. (2022). Nature-based solutions promote climate change adaptation safeguarding ecosystem services. Ecosyst. Serv. **55**: 101439. DOI: 10.1016/j.ecoser.2022.101439.
391. Scheiter, S., and Savadogo, P. (2016). Ecosystem management can mitigate vegetation shifts induced by climate change in West Africa. Ecol. Modell. **332**: 19–27. DOI: 10.1016/j.ecolmodel.2016.03.022.
392. Cameron, D.R., Marvin, D.C., Remucal, J.M., and Passero, M.C. (2017). Ecosystem management and land conservation can substantially contribute to California's climate mitigation goals. Proc. Natl. Acad. Sci. U. S. A. **114**: 12833–12838. DOI: 10.1073/pnas.1707811114.
393. Trivino, M., Moran-Ordonez, A., Eyvindson, K., et al. (2022). Future supply of boreal forest ecosystem services is driven by management rather than by climate change. Glob. Chang. Biol. **29**: 1484–1500.
394. IPCC (2022). Climate change 2022: impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change.
395. Davidson, T.A., Audet, J., Jeppesen, E., et al. (2018). Synergy between nutrients and warming enhances methane ebullition from experimental lakes. Nat. Clim. Change **8**: 156–160. DOI: 10.1038/s41558-017-0063-z.
396. Zhu, Y., Wang, D., Smith, P., et al. (2022). What can the glasgow declaration on forests bring to global emission reduction? The Innovation *3*, 100307, 10.1016/j.xinn.2022.100307.
397. Jeppesen, E., Søndergaard, M., Lauridsen, T.L., et al. (2012). Chapter 6 - Biomanipulation as a restoration tool to combat eutrophication: recent advances and future challenges. In Adv. Ecol. Res., G. Woodward, U. Jacob, and E.J. O'Gorman, eds. AP, 411-488.
398. Timilsina, G.R. (2021). Financing climate change adaptation: International initiatives. Sustainability **13**: 6515. DOI: 10.3390/su13126515.
399. Kopp, R.E., Horton, R.M., Little, C.M., et al. (2014). Probabilistic 21st and 22nd century sea - level projections at a global network of tide - gauge sites. Earths Future **2**: 383–406. DOI: 10.1002/2014EF000239.
400. Church, J.A., Clark, P.U., Cazenave, A., et al. (2013). Sea level change. In climate change 2013 – the physical science basis: working group I contribution to the fifth assessment report of the intergovernmental panel on climate change, C. Intergovernmental Panel on Climate, ed. (Cambridge University Press), 1137-1216.
401. De Dominicis, M., Wolf, J., Jevrejeva, S., et al. (2020). Future interactions between sea level rise, tides, and storm surges in the world's largest urban area. Geophys. Res. Lett. *47*.
402. Valiela, I., Lloret, J., Bowyer, T., et al. (2018). Transient coastal landscapes: Rising sea level threatens salt marshes. Sci. Total Environ. *640-641*, 1148-1156.
403. Macreadie, P.I., Costa, M.D.P., Atwood, T.B., et al. (2021). Blue carbon as a natural climate solution. Nat. Rev. Earth Environ. **2**: 826–839. DOI: 10.1038/s43017-021-00224-1.
404. Jankowska, E., Pelc, R., Alvarez, J., et al. (2022). Climate benefits from establishing marine protected areas targeted at blue carbon solutions. Proc. Natl. Acad. Sci. U. S. A. **119**: e2121705119. DOI: 10.1073/pnas.2121705119.
405. Miles, L., Agra, R., Sandeep, et al. (2021). Nature-based solutions for climate change mitigation. United Nations Environment Programme.
406. Griscom, B.W., Adams, J., Ellis, P.W., et al. (2017). Natural climate solutions. Proc. Natl. Acad. Sci. U. S. A. **114**: 11645–11650. DOI: 10.1073/pnas.1710465114.
407. Schuerch, M., Spencer, T., Temmerman, S., et al. (2018). Future response of global coastal wetlands to sea-level rise. Nature **561**: 231–234. DOI: 10.1038/s41586-018-0476-5.
408. Kirwan, M.L., and Megonigal, J.P. (2013). Tidal wetland stability in the face of human impacts and sea-level rise. Nature **504**: 53–60. DOI: 10.1038/nature12856.
409. Wang, F., Lu, X., Sanders, C.J., and Tang, J. (2019). Tidal wetland resilience to sea level rise increases their carbon sequestration capacity in United States. Nat. Commun. **10**: 5434. DOI: 10.1038/s41467-019-13294-z.
410. Saintilan, N., Khan, N.S., Ashe, E., et al. (2020). Thresholds of mangrove survival under rapid sea level rise. Science **368**: 1118–1121. DOI: 10.1126/science.aba2656.
411. Saintilan, N., Kovalenko, K.E., Guntenspergen, G., et al. (2022). Constraints on the

adjustment of tidal marshes to accelerating sea level rise. Science **377**: 523–527. DOI: 10.1126/science.abo7872.

412. Rogers, K., Kelleway, J.J., Saintilan, N., et al. (2019). Wetland carbon storage controlled by millennial-scale variation in relative sea-level rise. Nature **567**: 91–95. DOI: 10.1038/s41586-019-0951-7.
413. Wang, F., Eagle, M., Kroeger, K.D., et al. (2021). Plant biomass and rates of carbon dioxide uptake are enhanced by successful restoration of tidal connectivity in salt marshes. Sci. Total Environ. **750**: 141566. DOI: 10.1016/j.scitotenv.2020.141566.
414. Wang, F., Sanders, C.J., Santos, I.R., et al. (2021). Global blue carbon accumulation in tidal wetlands increases with climate change. Natl. Sci. Rev. **8**: nwaa296. DOI: 10.1093/nsr/nwaa296.
415. Kumar, P., Debele, S.E., Sahani, J., et al. (2021). Nature-based solutions efficiency evaluation against natural hazards: Modelling methods, advantages and limitations. Sci. Total Environ. **784**: 147058. DOI: 10.1016/j.scitotenv.2021.147058.
416. Kumar, P., Debele, S.E., Sahani, J., et al. (2021). An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. Earth-Sci. Rev. **217**: 103603. DOI: 10.1016/j.earscirev.2021.103603.
417. Atteridge, A., Bhatpuria, D., Macura, B., et al. (2022). Assessing finance for nature-based solutions to climate change. Stockholm Environment Institute.
418. Kruse, J., Koch, M., Khoi, C.M., et al. (2020). Land use change from permanent rice to alternating rice-shrimp or permanent shrimp in the coastal Mekong Delta, Vietnam: Changes in the nutrient status and binding forms. Sci. Total Environ. **703**: 134758. DOI: 10.1016/j.scitotenv.2019.134758.
419. Renaud, F.G., Le, T.T.H., Lindener, C., et al. (2015). Resilience and shifts in agro-ecosystems facing increasing sea-level rise and salinity intrusion in Ben Tre Province, Mekong Delta. Clim. Change **133**: 69–84. DOI: 10.1007/s10584-014-1113-4.
420. Smajgl, A., Toan, T.Q., Nhan, D.K., et al. (2015). Responding to rising sea levels in the Mekong Delta. Nat. Clim. Change **5**: 167–174. DOI: 10.1038/nclimate2469.
421. Hashimi, R., Kaneko, N., and Komatsuzaki, M. (2023). Impact of no-tillage on soil quality and crop yield in Asia: a meta-analysis. Land Degrad. Dev. **34**: 1004–1018. DOI: 10.1002/ldr.4512.
422. Crystal-Ornelas, R., Thapa, R., and Tully, K.L. (2021). Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: A meta-analysis. Agric., Ecosyst. Environ. **312**: 107356. DOI: 10.1016/j.agee.2021.107356.
423. Jordon, M.W., Willis, K.J., Bürkner, P.-C., et al. (2022). Temperate Regenerative Agriculture practices increase soil carbon but not crop yield—a meta-analysis. Environ. Res. Lett. **17**: 093001. DOI: 10.1088/1748-9326/ac8609.
424. Luo, Z., Wang, E., and Sun, O.J. (2010). Can no-tillage stimulate carbon sequestration in agricultural soils. A meta-analysis of paired experiments. Agric. Ecosyst. Environ. **139**: 224–231. DOI: 10.1016/j.agee.2010.08.006.
425. Oldfield, E.E., Bradford, M.A., and Wood, S.A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. Soil **5**: 15–32. DOI: 10.5194/soil-5-15-2019.
426. Pittelkow, C.M., Liang, X., Linquist, B.A., et al. (2015). Productivity limits and potentials of the principles of conservation agriculture. Nature **517**: 365–368. DOI: 10.1038/nature13809.
427. Lal, R. (2020). Soil organic matter content and crop yield. J. Soil Water Conserv. **75**: 27A. DOI: 10.2489/jswc.75.2.27A.
428. Mizuta, K., Grunwald, S., and Phillips, M.A. (2018). New Soil Index Development and Integration with Econometric Theory. Soil Sci. Soc. Am. J. **82**: 1017–1032. DOI: 10.2136/sssaj2017.11.0378.
429. Gerke, J. (2022). The Central Role of Soil Organic Matter in Soil Fertility and Carbon Storage. Soil Syst. **6**: 33. DOI: 10.3390/soilsystems6020033.
430. Ankenbauer, K.J., and Loheide II, S.P. (2017). The effects of soil organic matter on soil water retention and plant water use in a meadow of the Sierra Nevada, CA. Hydrol. Processes **31**: 891–901. DOI: 10.1002/hyp.11070.
431. Emerson, W. (1995). Water-retention, organic-C and soil texture. Soil Res. **33**: 241–251. DOI: 10.1071/SR9950241.
432. IES. (2015). Soil threats in Europe (Joint Research Centre, Institute for Environment and Sustainability)L.
433. Karlen, D.L., and Rice, C.W. (2015). Soil degradation: will humankind ever learn. Sustainability **7**: 12490–12501. DOI: 10.3390/su70912490.
434. Lorenz, K., Lal, R., and Ehlers, K. (2019). Soil organic carbon stock as an indicator for monitoring land and soil degradation in relation to United Nations' Sustainable Development Goals. Land Degrad. Dev. **30**: 824–838. DOI: 10.1002/ldr.3270.
435. Oelofse, M., Markussen, B., Knudsen, L., et al. (2015). Do soil organic carbon levels affect potential yields and nitrogen use efficiency. An analysis of winter wheat and spring barley field trials. Eur. J. Agron. **66**: 62–73.
436. Wheeler, T., and von Braun, J. (2013). Climate change impacts on global food security. Science **341**: 508–513. DOI: 10.1126/science.1239402.
437. Fedoroff, N.V., Battisti, D.S., Beachy, R.N., et al. (2010). Radically rethinking agriculture for the 21st century. Science **327**: 833–834. DOI: 10.1126/science.1186834.
438. Asseng, S., Ewert, F., Martre, P., et al. (2015). Rising temperatures reduce global wheat production. Nat. Clim. Change **5**: 143–147. DOI: 10.1038/nclimate2470.
439. Zhu, J.K. (2016). Abiotic stress signaling and responses in plants. Cell **167**: 313–324. DOI: 10.1016/j.cell.2016.08.029.
440. Xiong, W., Reynolds, M., and Xu, Y. (2022). Climate change challenges plant breeding. Curr. Opin. Plant Biol. **70**: 102308. DOI: 10.1016/j.pbi.2022.102308.
441. Zhan, X., Lu, Y., Zhu, J.K., and Botella, J.R. (2021). Genome editing for plant research and crop improvement. J Integr Plant Biol **63**: 3–33. DOI: 10.1111/jipb.13063.
442. Zhang, H., Li, Y., and Zhu, J.-K. (2018). Developing naturally stress-resistant crops for a sustainable agriculture. Nat. Plants **4**: 989–996. DOI: 10.1038/s41477-018-0309-4.
443. Galimova, T., Ram, M., and Breyer, C. (2022). Mitigation of air pollution and corresponding impacts during a global energy transition towards 100% renewable energy system by 2050. Energy Rep. **8**: 14124–14143. DOI: 10.1016/j.egyr.2022.10.343.
444. Donatti, C.I., Andrade, A., Cohen-Shacham, E., et al. (2022). Ensuring that nature-based solutions for climate mitigation address multiple global challenges. One Earth **5**: 493–504. DOI: 10.1016/j.oneear.2022.04.010.
445. Shaheen, S.M., Antoniadis, V., Shahid, M., et al. (2022). Sustainable applications of rice feedstock in agro-environmental and construction sectors: a global perspective. Renewable Sustainable Energy Rev. **153**: 111791. DOI: 10.1016/j.rser.2021.111791.
446. Kumar, R., V. Nguyen, T., J.S., et al. (2023). Towards realizing the EU 2050 zero pollution vision for nitrogen export. EGU General Assembly.
447. Khreis, H., Sanchez, K.A., Foster, M., et al. (2023). Urban policy interventions to reduce traffic-related emissions and air pollution: A systematic evidence map. ENVIRON INT. **172**: 107805. DOI: 10.1016/j.envint.2023.107805.
448. Jiang, P., Khishgee, S., Alimujiang, A., and Dong, H. (2020). Cost-effective approaches for reducing carbon and air pollution emissions in the power industry in China. J. Environ. Manage. **264**: 110452. DOI: 10.1016/j.jenvman.2020.110452.
449. Breuer, J.L., Samsun, R.C., Stolten, D., and Peters, R. (2021). How to reduce the greenhouse gas emissions and air pollution caused by light and heavy duty vehicles with battery-electric, fuel cell-electric and catenary trucks. ENVIRON INT. **152**: 106474. DOI: 10.1016/j.envint.2021.106474.
450. Lal, R. (2020). Managing soils for resolving the conflict between agriculture and nature: the hard talk. Eur J Soil Sci. **71**: 1–9. DOI: 10.1111/ejss.12857.
451. Palansooriya, K.N., Shaheen, S.M., Chen, S.S., et al. (2020). Soil amendments for immobilization of potentially toxic elements in contaminated soils: a critical review. Environ. int. **134**: 105046. DOI: 10.1016/j.envint.2019.105046.
452. El-Naggar, A., El-Naggar, A.H., Shaheen, S.M., et al. (2019). Biochar composition-dependent impacts on soil nutrient release, carbon mineralization, and potential environmental risk: a review. J. Environ. Manage. **241**: 458–467. DOI: 10.1016/j.jenvman.2019.02.044.
453. Li, J., Pei, Y., Zhao, S., et al. (2020). A Review of Remote Sensing for Environmental Monitoring in China. Remote Sens. **12**: 1130. DOI: 10.3390/rs12071130.
454. Moiroux-Arvis, L., Royer, L., Sarramia, D., et al. (2023). ConnecSenS, a Versatile IoT Platform for Environment Monitoring: bring Water to Cloud. Sensors **23**: 2896. DOI: 10.3390/s23062896.
455. Manshur, T., Luiu, C., Avis, W.R., et al. (2023). A citizen science approach for air quality monitoring in a Kenyan informal development. City and Environment Interactions **19**: 100105. DOI: 10.1016/j.cacint.2023.100105.
456. Cui, P., Peng, J., Shi, P., et al. (2021). Scientific challenges of research on natural hazards and disaster risk. Geography and Sustainability **2**: 216–223. DOI: 10.1016/j.geosus.2021.09.001.
457. Wei, K., Ouyang, C., Duan, H., et al. (2020). Reflections on the Catastrophic 2020 Yangtze River basin flooding in Southern China. The Innovation *1*, 100038, 10.1016/j.xinn.2020.100038.
458. Jiang, W., Niu, Z., Wang, L., et al. (2022). Impacts of drought and climatic factors on vegetation dynamics in the Yellow River Basin and Yangtze River Basin, China. Remote Sens. *14*.
459. Ma, M., Qu, Y., Lyu, J., et al. (2022). The 2022 extreme drought in the Yangtze River Basin: Characteristics, causes and response strategies. River **1**: 162–171. DOI: 10.1002/rvr2.23.
460. Kim, J., Lee, J., Hwang, S., and Kang, J. (2022). Urban flood adaptation and optimization for net-zero: Case study of Dongjak-gu, Seoul. J. hydrol. reg. stud. **41**: 101110. DOI: 10.1016/j.ejrh.2022.101110.
461. Zheng, Q., Shen, S.L., Zhou, A., and Lyu, H.M. (2022). Inundation risk assessment based on G-DEMATEL-AHP and its application to Zhengzhou flooding disaster. Sustain. cities. soc. **86**: 104138. DOI: 10.1016/j.scs.2022.104138.
462. Simpson, N.P., Mach, K.J., Constable, A., et al. (2021). A framework for complex climate change risk assessment. One Earth **4**: 489–501. DOI: 10.1016/j.oneear.2021.03.005.
463. IPCC (2012). Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change In C.B., V. Barros, T.F. Stocker, et al., eds.
464. Poumadere, M., Mays, C., Le Mer, S., and Blong, R. (2005). The 2003 heat wave in France: dangerous climate change here and now. RISK ANAL. **25**: 1483–1494. DOI: 10.1111/j.1539-6924.2005.00694.x.
465. Luther, J., Hainsworth, A., Tang, X., et al. (2017). World Meteorological Organization (WMO)—concerted international efforts for advancing multi-hazard early warning systems. In K. Sassa, M. Mikoš, and Y. Yin, eds. Advancing culture of living with landslides. Springer International Publishing.
466. Owusu, S., Wright, G., and Arthur, S. (2015). Public attitudes towards flooding and property-level flood protection measures. Nat. Hazards **77**: 1963–1978. DOI: 10.1007/s11069-015-1686-x.

467. Dwivedi, Y.K., Hughes, L., Kar, A.K., et al. (2022). Climate change and COP26: are digital technologies and information management part of the problem or the solution. An editorial reflection and call to action. Int. J. Inf. Manage. **63**: 102456.
468. Jiang, L.W., and O'Neill, B.C. (2017). Global urbanization projections for the Shared Socioeconomic Pathways. Global Environ. Change-Human Policy Dim. **42**: 193–199. DOI: 10.1016/j.gloenvcha.2015.03.008.
469. Barthel, S., Isendahl, C., Vis, B.N., et al. (2019). Global urbanization and food production in direct competition for land: Leverage places to mitigate impacts on SDG2 and on the Earth System. Anthr. Rev. **6**: 71–97.
470. Evans, D.L., Vis, B.N., Dunning, N.P., et al. (2021). Buried solutions: how Maya urban life substantiates soil connectivity. Geoderma **387**: 114925. DOI: 10.1016/j.geoderma.2020.114925.
471. O'Riordan, R., Davies, J., Stevens, C., et al. (2021). The ecosystem services of urban soils: a review. Geoderma **395**: 115076. DOI: 10.1016/j.geoderma.2021.115076.
472. De la Sota, C., Ruffato-Ferreira, V.J., Ruiz-Garcia, L., and Alvarez, S. (2019). Urban green infrastructure as a strategy of climate change mitigation. A case study in northern Spain. Urban For. Urban Gree. **40**: 145–151.
473. Vasenev, V., and Kuzyakov, Y. (2018). Urban soils as hot spots of anthropogenic carbon accumulation: Review of stocks, mechanisms and driving factors. Land Degrad. Dev. **29**: 1607–1622. DOI: 10.1002/ldr.2944.
474. Wang, Y., Bakker, F., de Groot, R., et al. (2015). Effects of urban green infrastructure (UGI) on local outdoor microclimate during the growing season. Environ. Monit. Assess **187**: 732. DOI: 10.1007/s10661-015-4943-2.
475. Marando, F., Heris, M.P., Zulian, G., et al. (2022). Urban heat island mitigation by green infrastructure in European Functional Urban Areas. Sustain. Cities Soc. **77**: 103564. DOI: 10.1016/j.scs.2021.103564.
476. Yao, Y.B., Wang, Y.F., Ni, Z.B., et al. (2022). Improving air quality in Guangzhou with urban green infrastructure planning: an i-Tree Eco model study. J. Clean. Prod. **369**: 133372. DOI: 10.1016/j.jclepro.2022.133372.
477. Molla, M. (2015). The Value of Urban Green Infrastructure and Its Environmental Response in Urban Ecosystem: a Literature Review. Int. J. Environ. Sci. **4**: 4–183.
478. Evans, D.L., Falagan, N., Hardman, C.A., et al. (2022). Ecosystem service delivery by urban agriculture and green infrastructure-a systematic review. Ecosyst. Serv **54**: 101405. DOI: 10.1016/j.ecoser.2022.101405.
479. Walsh, L.E., Mead, B.R., Hardman, C.A., et al. (2022). Potential of urban green spaces for supporting horticultural production: a national scale analysis. ENVIRON RES LETT **17**: 014052. DOI: 10.1088/1748-9326/ac4730.
480. Rawlins, B.G., Harris, J., Price, S., and Bartlett, M. (2013). A review of climate change impacts on urban soil functions with examples and policy insights from England, UK. Soil Use Manag **31**: 46–61.
481. Prokop, G., Jobstmann, H., and Schönbauer, A. (2011). Overview of best practices for limiting soil sealing or mitigating its effects in EU-27. European Communities.
482. Ge, W., Deng, L., Wang, F., and Han, J. (2021). Quantifying the contributions of human activities and climate change to vegetation net primary productivity dynamics in China from 2001 to 2016. Sci. Total Environ. **773**: 145648. DOI: 10.1016/j.scitotenv.2021.145648.
483. UNEP (2021). Patricia Espinosa Outlines the Four Keys to Success at COP26. United Nations Framework Convention on Climate Change. https://unfccc.int/news/patricia-espinosa-outlines-the-four-keys-to-success-at-cop26.
484. Rübbelke, D., and Vögele, S. (2011). Impacts of climate change on European critical infrastructures: The case of the power sector. Environ. Sci. Policy **14**: 53–63. DOI: 10.1016/j.envsci.2010.10.007.
485. Schweikert, A., Chinowsky, P., Espinet, X., and Tarbert, M. (2014). Climate Change and Infrastructure Impacts: Comparing the Impact on Roads in ten Countries through 2100. Procedia Eng. **78**: 306–316. DOI: 10.1016/j.proeng.2014.07.072.
486. Li, Q., Punzo, G., Robson, C., et al. (2022). A Novel Approach to Climate Resilience of Infrastructure Networks. ArXiv *abs/2211.10132*.
487. Kumar, P., Debele, S.E., Sahani, J., et al. (2020). Towards an operationalisation of nature-based solutions for natural hazards. Sci.Total Environ. **731**: 138855. DOI: 10.1016/j.scitotenv.2020.138855.
488. Chen, H., and Sun, J. (2021). Significant Increase of the Global Population Exposure to Increased Precipitation Extremes in the Future. Earth's Future **9**: e2020EF001941.
489. Wang, T., Qu, Z., Yang, Z., et al. (2020). Impact analysis of climate change on rail systems for adaptation planning: A UK case. transport. res. d-tr. e. **83**: 102324. DOI: 10.1016/j.trd.2020.102324.
490. Palin, E.J., Thornton, H.E., Mathison, C.T., et al. (2013). Future projections of temperature-related climate change impacts on the railway network of Great Britain. Clim. Change **120**: 71–93. DOI: 10.1007/s10584-013-0810-8.
491. Jaroszweski, D., Wood, R., and Chapman, L. (2021). Infrastructure. In: The Third UK Climate Change Risk Assessment Technical Report. In R.A. Betts, A.B. Haward, and K.V. Pearson, eds. Prepared for the Climate Change Committee.
492. Kumar, P., Debele, S.E., Sahani, J., et al. (2021). Nature-based solutions efficiency evaluation against natural hazards: Modelling methods, advantages and limitations. Sci.Total Environ. **784**: 147058. DOI: 10.1016/j.scitotenv.2021.147058.
493. Debele, S.E., Kumar, P., Sahani, J., et al. (2019). Nature-based solutions for hydro-meteorological hazards: Revised concepts, classification schemes and databases. ENVIRON RES **179**: 108799. DOI: 10.1016/j.envres.2019.108799.
494. Zeleňáková, M., Purcz, P., Hlavatá, H., and Blišťan, P. (2015). Climate Change in Urban Versus Rural Areas. Procedia Eng. **119**: 1171–1180. DOI: 10.1016/j.proeng.2015.08.968.
495. Chen, B., and Chu, L. (2022). Decoupling the double jeopardy of climate risk and fiscal risk: A perspective of infrastructure investment. Clim. Risk Manag. **37**: 100448. DOI: 10.1016/j.crm.2022.100448.
496. Zeppel, M.J.B., Wilks, J.V., and Lewis, J.D. (2014). Impacts of extreme precipitation and seasonal changes in precipitation on plants. Biogeosciences **11**: 3083–3093. DOI: 10.5194/bg-11-3083-2014.
497. Cai, H., Wang, Y., Zhao, T., and Zhang, H. (2023). A general unit hydrograph distribution and its application on the marginal distribution of global wind speed. Sustainable Horizons **6**: 100056. DOI: 10.1016/j.horiz.2023.100056.
498. Wada, C., Bremer, L., Burnett, K., et al. (2017). Estimating cost-effectiveness of Hawaiian dry forest restoration using spatial changes in water yield and landscape flammability under climate change. Pac. Sci. **71**: 401–424. DOI: 10.2984/71.4.2.
499. Krauss, K.W., Cormier, N., Osland, M.J., et al. (2017). Created mangrove wetlands store belowground carbon and surface elevation change enables them to adjust to sea-level rise. Sci. Rep. **7**: 1030. DOI: 10.1038/s41598-017-01224-2.
500. Langridge, S.M., Hartge, E.H., Clark, R., et al. (2014). Key lessons for incorporating natural infrastructure into regional climate adaptation planning. Ocean Coast Manag. **95**: 189–197. DOI: 10.1016/j.ocecoaman.2014.03.019.
501. Vallejo, L., and Mullan, M. (2017). Climate-resilient infrastructure. http://portal.gms-eoc.org/uploads/resources/3383/attachment/Climate-resilient%20infrastructure%20-%20Getting%20the%20policies%20right.pdf.
502. Gurney, K.R., Romero-Lankao, P., Seto, K.C., et al. (2015). Climate change: Track urban emissions on a human scale. Nature **525**: 179–181. DOI: 10.1038/525179a.
503. IPCC (2023). AR6 synthesis report: climate change 2023. Summary for policymakers. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg2/.
504. Sharifi, A. (2021). Co-benefits and synergies between urban climate change mitigation and adaptation measures: a literature review. Sci. Total Environ. **750**: 141642. DOI: 10.1016/j.scitotenv.2020.141642.
505. Daniel, R., Cortesão, J., Steeneveld, G.-J., et al. (2023). Performance of urban climate-responsive design interventions in combining climate adaptation and mitigation. Build. Environ. **236**: 110227. DOI: 10.1016/j.buildenv.2023.110227.
506. Schwaab, J., Meier, R., Mussetti, G., et al. (2021). The role of urban trees in reducing land surface temperatures in European cities. Nat. Commun. **12**: 6763. DOI: 10.1038/s41467-021-26768-w.
507. Selbig, W.R., Loheide, S.P., Shuster, W., et al. (2022). Quantifying the stormwater runoff volume reduction benefits of urban street tree canopy. Sci. Total Environ. **806**: 151296. DOI: 10.1016/j.scitotenv.2021.151296.
508. Shahzad, H., Myers, B., Boland, J., et al. (2022). Stormwater runoff reduction benefits of distributed curbside infiltration devices in an urban catchment. Water Res. **215**: 118273. DOI: 10.1016/j.watres.2022.118273.
509. Willis, K.J., and Petrokofsky, G. (2017). The natural capital of city trees. Science **356**: 374–376.
510. Liu, N., and Morawska, L. (2020). Modeling the urban heat island mitigation effect of cool coatings in realistic urban morphology. J. Clean. Prod. **264**: 121560. DOI: 10.1016/j.jclepro.2020.121560.
511. Santamouris, M., Ding, L., Fiorito, F., et al. (2017). Passive and active cooling for the outdoor built environment – Analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. Sol. Energy **154**: 14–33. DOI: 10.1016/j.solener.2016.12.006.
512. Wardeh, Y., Kinab, E., Escadeillas, G., et al. (2022). Review of the optimization techniques for cool pavements solutions to mitigate Urban Heat Islands. Build. Environ. **223**: 109482. DOI: 10.1016/j.buildenv.2022.109482.
513. Kalkstein, L.S., Eisenman, D.P., de Guzman, E.B., and Sailor, D.J. (2022). Increasing trees and high-albedo surfaces decreases heat impacts and mortality in Los Angeles, CA. Int. J. Biometeorol. **66**: 911–925. DOI: 10.1007/s00484-022-02248-8.
514. Ossola, A., and Lin, B.B. (2021). Making nature-based solutions climate-ready for the 50 °C world. Environ. Sci. Policy **123**: 151–159. DOI: 10.1016/j.envsci.2021.05.026.
515. Axinte, L.F., Mehmood, A., Marsden, T., and Roep, D. (2019). Regenerative city-regions: a new conceptual framework. Reg. Stud. Reg. Sci. **6**: 117–129.
516. Thomson, G., and Newman, P. (2018). Urban fabrics and urban metabolism – from sustainable to regenerative cities. Resour. Conserv. Recycl. **132**: 218–229. DOI: 10.1016/j.resconrec.2017.01.010.
517. Park, S.K. (2021). Legal strategy disrupted: managing climate change and regulatory transformation. Am. Bus. Law. J. **58**: 711–749. DOI: 10.1111/ablj.12194.
518. Ronja, B., Emma, C., Andrea, B., et al. (2022). The value of incorporating nature in urban infrastructure planning. International Institute for Sustainable Development. https://www.iisd.org/publications/report/nature-in-urban-infrastructure-planning.
519. Chausson, A., Turner, B., Seddon, D., et al. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. Global Change Biol. **26**: 6134–6155. DOI: 10.1111/gcb.15310.
520. Kumar, P. (2021). Climate change and cities: challenges ahead. Front. Environ. Sci. **3**: 645613.
521. Gill, S.E., Handley, J., Ennos, A.R., and Pauleit, S. (2007). Adapting cities for climate change: the role of the green infrastructure. Built Environment **33**: 115–133. DOI: 10.2148/benv.33.1.115.
522. Kumar, P., Druckman, A., Gallagher, J., et al. (2019). The nexus between air pollution, green infrastructure and human health. Environ. Int. **133**: 105181. DOI: 10.1016/j.envint.2019.105181.

523. Sahani, J., Kumar, P., Debele, S., et al. (2019). Hydro-meteorological risk assessment methods and management by nature-based solutions. Sci. Total Environ. **696**: 133936. DOI: 10.1016/j.scitotenv.2019.133936.
524. Jing, R., Wang, X., Zhao, Y., et al. (2021). Planning urban energy systems adapting to extreme weather. Adv. Appl. Energy **3**: 100053. DOI: 10.1016/j.adapen.2021.100053.
525. Nik, V.M., Perera, A.T.D., and Chen, D. (2020). Towards climate resilient urban energy systems: a review. Natl. Sci. Rev. **8**: nwaa134.
526. MacArthur, J.L., Hoicka, C.E., Castleden, H., et al. (2020). Canada's green new deal: forging the socio-political foundations of climate resilient infrastructure. Energy Res. Soc. Sci. **65**: 101442. DOI: 10.1016/j.erss.2020.101442.
527. Meyer, P.B., and Schwarze, R. (2019). Financing climate-resilient infrastructure: Determining risk, reward, and return on investment. Front. Eng. Manage. **6**: 117–127. DOI: 10.1007/s42524-019-0009-4.
528. Walkley, A., and Black, I.A. (1934). An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. **37**: 29–38. DOI: 10.1097/00010694-193401000-00003.
529. Davies, B.E. (1974). Loss-on-ignition as an estimate of soil organic matter. Soil Sci. Soc. Am. J. **38**: 150–151. DOI: 10.2136/sssaj1974.03615995003800010046x.
530. Tabatabai, M.A., and Bremner, J.M. (1970). Use of the Leco Automatic 70-Second Carbon Analyzer for total carbon analysis of soils. Soil Sci. Soc. Am. J. **34**: 608–610. DOI: 10.2136/sssaj1970.03615995003400040020x.
531. G. R. BLAKE, and HARTGE, K.H. (1986). Bulk density. In methods of soil analasis Part 1 physical and mineralogical methods, A. Klute, ed. (American Society of Agronomy, Soil Science Society of America.), 363–375.
532. Angelopoulou, T., Balafoutis, A., Zalidis, G., and Bochtis, D. (2020). From Laboratory to proximal sensing spectroscopy for soil organic carbon estimation—a review. Sustainability **12**: 443. DOI: 10.3390/su12020443.
533. Tang, Y., Jones, E., and Minasny, B. (2020). Evaluating low-cost portable near infrared sensors for rapid analysis of soils from South Eastern Australia. Geoderma Reg. **20**: e00240. DOI: 10.1016/j.geodrs.2019.e00240.
534. Li, S., Viscarra Rossel, R.A., and Webster, R. (2021). The cost-effectiveness of reflectance spectroscopy for estimating soil organic carbon. Eur. J. Soil Sci. **73**: e13202.
535. Clingensmith, C.M., and Grunwald, S. (2022). Predicting soil properties and interpreting Vis-NIR Models from acrosscontinental United States. Sensors **22**: 3187. DOI: 10.3390/s22093187.
536. Demattê, J.A.M., Dotto, A.C., Paiva, A.F.S., et al. (2019). The Brazilian soil spectral library (BSSL): a general view, application and challenges. Geoderma **354**: 113793. DOI: 10.1016/j.geoderma.2019.05.043.
537. Jia, X., Chen, S., Yang, Y., et al. (2017). Organic carbon prediction in soil cores using VNIR and MIR techniques in an alpine landscape. Sci. Rep. **7**: 2144. DOI: 10.1038/s41598-017-02061-z.
538. Knox, N.M., Grunwald, S., McDowell, M.L., et al. (2015). Modelling soil carbon fractions with visible near-infrared (VNIR) and mid-infrared (MIR) spectroscopy. Geoderma. **239-240**: 229–239.
539. Shi, Z., Wang, Q., Peng, J., et al. (2014). Development of a national VNIR soil-spectral library for soil classification and prediction of organic matter concentrations. Sci. China: Earth Sci. **57**: 1671–1680. DOI: 10.1007/s11430-013-4808-x.
540. Stevens, A., Nocita, M., Tóth, G., et al. (2013). Prediction of soil organic carbon at the European scale by visible and near infrared reflectance spectroscopy. PLoS One **8**: e66409. DOI: 10.1371/journal.pone.0066409.
541. Viscarra Rossel, R.A., Behrens, T., Ben-Dor, E., et al. (2016). A global spectral library to characterize the world's soil. Earth-Sci. Rev. **155**: 198–230. DOI: 10.1016/j.earscirev.2016.01.012.
542. Wijewardane, N.K., Ge, Y., Wills, S., and Loecke, T. (2016). Prediction of soil carbon in the conterminous United States: visible and near infrared reflectance spectroscopy Analysis of the rapid carbon assessment Project. Soil Sci. Soc. Am. J. **80**: 973–982. DOI: 10.2136/sssaj2016.02.0052.
543. Parducci, A., De Souza, D., Camargo, T., et al. (2019). Analyzing soil fertility by chemical and physical parameters using visible and near-infrared reflectance (VIS-NIR) spectroscopy, involves combining use of VIS-NIR spectrophotometer, SpecSoil-Scan with respective digital platform. SPECLAB HOLDING SA (SPEC-Non-standard) EMPRESA BRASIL PESQUISA AGROPECUARIA (EMPR-Non-standard).
544. Safanelli, J.L., Hengl, T., Sanderman, J., and Parente, L. (2021). Open soil spectral library (training data and calibration models) (Zenodo)L. https://zenodo.org/record/5805138#.ZJAOg8j-elw.
545. Laboratories, H. (2022). Anlysis of soils using near infrared spectroscopy. Hill Laboratories.https://www.hill-laboratories.com/assets/Documents/Technical-Notes/Agriculture/35398v4View.pdf.
546. Reijneveld, J.A., van Oostrum, M.J., Brolsma, K.M., et al. (2022). Empower Innovations in Routine Soil Testing. Agronomy **12**: 191. DOI: 10.3390/agronomy12010191.
547. Semella, S., Hutengs, C., Seidel, M., et al. (2022). Accuracy and reproducibility of laboratory diffuse reflectance measurements with portable VNIR and MIR spectrometers for predictive soil organic carbon modeling. Sensors **22**: 2749. DOI: 10.3390/s22072749.
548. Cambou, A., Allory, V., Cardinael, R., et al. (2021). Comparison of soil organic carbon stocks predicted using visible and near infrared reflectance (VNIR) spectra acquired in situ vs. on sieved dried samples: Synthesis of different studies. Soil Sec. **5**: 100024.
549. Avand, M., Moradi, H., and lasboyee, M.R. (2021). Using machine learning models, remote sensing, and GIS to investigate the effects of changing climates and land uses on flood probability. J. Hydrol. **595**: 125663. DOI: 10.1016/j.jhydrol.2020.125663.
550. West, H., Quinn, N., and Horswell, M. (2019). Remote sensing for drought monitoring & impact assessment: progress, past challenges and future opportunities. Remote Sens. Environ. **232**: 111291. DOI: 10.1016/j.rse.2019.111291.
551. Feng, Y., Negrón-Juárez, R.I., and Chambers, J.Q. (2020). Remote sensing and statistical analysis of the effects of hurricane María on the forests of Puerto Rico. Remote Sens. Environ. **247**: 111940. DOI: 10.1016/j.rse.2020.111940.
552. Igun, E., Xu, X., Hu, Y., and Jia, G. (2022). Strong heatwaves with widespread urban-related hotspots over Africa in 2019. Atmos. Oceanic Sci. Lett. **15**: 100195. DOI: 10.1016/j.aosl.2022.100195.
553. Wei, M., Zhang, Z., Long, T., et al. (2021). Monitoring landsat based burned area as an indicator of sustainable development goals. Earth's Future **9**: e2020EF001960.
554. WMO (2022). State of the global climate 2021. World Meteorological Organization. https://library.wmo.int/doc_num.php?explnum_id=11178.
555. Huang, N., Wang, L., Zhang, Y., et al. (2021). Estimating the net ecosystem exchange at global FLUXNET sites using a random forest model. IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens. **14**: 9826–9836. DOI: 10.1109/JSTARS.2021.3114190.
556. Yao, T., Bolch, T., Chen, D., et al. (2022). The imbalance of the Asian water tower. Nat. Rev. Earth Environ. **3**: 618–632. DOI: 10.1038/s43017-022-00299-4.
557. Hugonnet, R., McNabb, R., Berthier, E., et al. (2021). Accelerated global glacier mass loss in the early twenty-first century. Nature **592**: 726–731. DOI: 10.1038/s41586-021-03436-z.
558. Su, H., Jiang, J., Wang, A., et al. (2022). Subsurface temperature reconstruction for the global ocean from 1993 to 2020 using satellite observations and deep learning. Remote Sens. **14**: 3198. DOI: 10.3390/rs14133198.
559. Su, H., Zhang, T., Lin, M., et al. (2021). Predicting subsurface thermohaline structure from remote sensing data based on long short-term memory neural networks. Remote Sens. Environ. **260**: 112465. DOI: 10.1016/j.rse.2021.112465.
560. Ehret, T., De Truchis, A., Mazzolini, M., et al. (2022). Global tracking and quantification of oil and gas methane emissions from recurrent sentinel-2 imagery. Environ. Sci. Technol. **56**: 10517–10529. DOI: 10.1021/acs.est.1c08575.
561. Stark, H., Moeller, H., Courreges-Lacoste, G., et al. (2013). The Sentinel-4 mission and its implementation. https://www-cdn.eumetsat.int/files/2020-04/pdf_conf_p_s1_10_stark_v.pdf.
562. Quesada-Ruiz, S., Attié, J.L., Lahoz, W.A., et al. (2020). Benefit of ozone observations from Sentinel-5P and future Sentinel-4 missions on tropospheric composition. Atmos. Meas. Tech. **13**: 131–152. DOI: 10.5194/amt-13-131-2020.
563. Peng, Z., Lin, C., Di, X., and Zhe, X. (2018). Recent progress of Fengyun meteorology satellites. Chinese J. Space Sci. **38**: 788–796. DOI: 10.11728/cjss2018.05.788.
564. Zhu, L., Wang, M., Shao, J., et al. (2015). Remote sensing of global volcanic eruptions using Fengyun series satellites. IEEE Int. Geosci. Remote Sens. Symp. 4797-4800.
565. Li, C., Cai, R., Tian, W., et al. (2023). Land cover classification by Gaofen satellite images based on CART algorithm in Yuli County, Xinjiang, China. Sustainability **15**: 2535. DOI: 10.3390/su15032535.
566. Zhang, W., and Dong, Y. (2022). Research on flood remote sensing monitoring based on multi-source remote sensing data. 2022 3rd International Conference on Geology, Mapping and Remote Sensing (ICGMRS). https://ieeexplore.ieee.org/document/9849315.
567. Chen, J.M., Ju, W., Ciais, P., et al. (2019). Vegetation structural change since 1981 significantly enhanced the terrestrial carbon sink. Nat. Commun. **10**: 4259. DOI: 10.1038/s41467-019-12257-8.
568. Huang, L., Li, Z., Zhou, J.M., and Zhang, P. (2021). An automatic method for clean glacier and nonseasonal snow area change estimation in High Mountain Asia from 1990 to 2018. Remote Sens. Environ. **258**: 112376. DOI: 10.1016/j.rse.2021.112376.
569. Myneni, R.B., Keeling, C.D., Tucker, C.J., et al. (1997). Increased plant growth in the northern high latitudes from 1981 to 1991. Nature **386**: 698–702. DOI: 10.1038/386698a0.
570. Piao, S., Wang, X., Park, T., et al. (2020). Characteristics, drivers and feedbacks of global greening. Nat. Rev. Earth Environ. **1**: 14–27.
571. Fan, L., Wigneron, J.-P., Ciais, P., et al. (2023). Siberian carbon sink reduced by forest disturbances. Nat. Geosci. **16**: 56–62. DOI: 10.1038/s41561-022-01087-x.
572. WIGNERON, J.P., and CIAIS, P. (2022). Rôle des forêts dans le bilan de carbone de la planète. https://planet-vie.ens.fr/thematiques/ecologie/cycles-biogeochimiques/role-des-forets-dans-le-bilan-de-carbone-de-la-planete#:~:text=%C3%80%20l%27%C3%A9chelle%20de%20la%20plan%C3%A8te%2C%20les%20for%C3%AAts%20constituent,en%20effet%20de%20diff%C3%A9rents%20facteurs%20naturels%20et%20anthropiques.
573. Bouvet, A., Mermoz, S., Le Toan, T., et al. (2018). An above-ground biomass map of African savannahs and woodlands at 25m resolution derived from ALOS PALSAR. Remote Sens. Environ. **206**: 156–173. DOI: 10.1016/j.rse.2017.12.030.
574. Wigneron, J.P., Fan, L., Ciais, P., et al. (2020). Tropical forests did not recover from the strong 2015–2016 El Niño event. Sci. Adv. **6**: eaay4603. DOI: 10.1126/sciadv.aay4603.
575. Qin, Y., Xiao, X., Wigneron, J.-P., et al. (2022). Large loss and rapid recovery of vegetation cover and aboveground biomass over forest areas in Australia during 2019–2020. Remote Sens. Environ. **278**: 113087. DOI: 10.1016/j.rse.2022.113087.
576. Dubayah, R., Armston, J., Healey, S.P., et al. (2022). GEDI launches a new era of

biomass inference from space. Environ. Res. Lett. **17**: 095001. DOI: 10.1088/1748-9326/ac8694.

577. Tucker, C., Brandt, M., Hiernaux, P., et al. (2023). Sub-continental-scale carbon stocks of individual trees in African drylands. Nature **615**: 80–86. DOI: 10.1038/s41586-022-05653-6.
578. Mugabowindekwe, M., Brandt, M., Chave, J., et al. (2023). Nation-wide mapping of tree-level aboveground carbon stocks in Rwanda. Nat. Clim. Change **13**: 91–97. DOI: 10.1038/s41558-022-01544-w.
579. Potapov, P., Li, X., Hernandez-Serna, A., et al. (2021). Mapping global forest canopy height through integration of GEDI and Landsat data. Remote Sens. Environ. **253**: 112165. DOI: 10.1016/j.rse.2020.112165.
580. Liu, S., Brandt, M., Nord-Larsen, T., et al. (2023). The overlooked contribution of trees outside forests to tree cover and woody biomass across Europe.
581. Schwartz, M., Ciais, P., Ottl'e, C., et al. (2022). High-resolution canopy height map in the Landes forest (France) based on GEDI, Sentinel-1, and Sentinel-2 data with a deep learning approach. ArXiv abs/2212.10265.
582. Grunwald, S. (2021). Grand challenges in pedometrics-AI research. Front. in Soil Sci. **1**: 714323. DOI: 10.3389/fsoil.2021.714323.
583. S. Russell, and Norvig, P. (2020). Artificial intelligence: a modern approach (Pearson)L. https://www.pearson.com/en-us/subject-catalog/p/Russell-Artificial-Intelligence-A-Modern-Approach-4th-Edition/P200000003500/9780137505135.
584. LeCun, Y., Bengio, Y., and Hinton, G. (2015). Deep learning. Nature **521**: 436–444. DOI: 10.1038/nature14539.
585. Mizuta, K., Grunwald, S., Phillips, M.A., et al. (2021). Sensitivity assessment of metafrontier data envelopment analysis for soil carbon sequestration efficiency. Ecol. Indic. **125**: 107602. DOI: 10.1016/j.ecolind.2021.107602.
586. Khaledian, Y., and Miller, B.A. (2020). Selecting appropriate machine learning methods for digital soil mapping. Appl. Math. Model. **81**: 401–418. DOI: 10.1016/j.apm.2019.12.016.
587. Grunwald, S. (2022). Artificial intelligence and soil carbon modeling demystified: power, potentials, and perils. Carbon Footprints **1**: 6. DOI: 10.20517/cf.2022.03.
588. Lu, H., Li, S., Ma, M., et al. (2021). Comparing machine learning-derived global estimates of soil respiration and its components with those from terrestrial ecosystem models. Environ. Res. Lett. **16**: 054048. DOI: 10.1088/1748-9326/abf526.
589. Grunwald, S., Thompson, J.A., and Boettinger, J.L. (2011). Digital soil mapping and modeling at continental scales: finding solutions for global issues. Soil Sci. Soc. Am. J. **75**: 1201–1213. DOI: 10.2136/sssaj2011.0025.
590. McBratney, A.B., Mendonça Santos, M.L., and Minasny, B. (2003). On digital soil mapping. Geoderma **117**: 3–52. DOI: 10.1016/S0016-7061(03)00223-4.
591. Ainsworth, E.A., and Long, S.P. (2021). 30 years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation. Global Change Biol. **27**: 27–49. DOI: 10.1111/gcb.15375.
592. Okada, M., Lieffering, M., Nakamura, H., et al. (2001). Free-air CO2 enrichment (FACE) using pure CO2 injection: System description. New Phytol. **150**: 251–260. DOI: 10.1046/j.1469-8137.2001.00097.x.
593. Kimball, B.A. (2016). Crop responses to elevated CO2 and interactions with H2O, N, and temperature. Curr. Opin. Plant Biol. **31**: 36–43. DOI: 10.1016/j.pbi.2016.03.006.
594. Long, S.P., Ainsworth, E.A., Leakey, A.D.B., et al. (2006). Food for thought: Lower-than-expected crop yield simulation with rising CO2 concentrations. Science **312**: 1918–1921. DOI: 10.1126/science.1114722.
595. Ainsworth, E.A., and Long, S.P. (2005). What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. New Phytol. **165**: 351–372.
596. Allen, L.H., Kimball, B.A., Bunce, J.A., et al. (2020). Fluctuations of CO2 in free-air CO2 enrichment (FACE) depress plant photosynthesis, growth, and yield. Agric. For. Meteorol. **284**: 107899. DOI: 10.1016/j.agrformet.2020.107899.
597. Drag, D.W., Slattery, R., Siebers, M., et al. (2020). Soybean photosynthetic and biomass responses to carbon dioxide concentrations ranging from pre-industrial to the distant future. J. Exp. Bot. **71**: 3690–3700. DOI: 10.1093/jxb/eraa133.
598. Rich, R.L., Stefanski, A., Montgomery, R.A., et al. (2015). Design and performance of combined infrared canopy and belowground warming in the B4WarmED (Boreal Forest Warming at an Ecotone in Danger) experiment. Global Change Biol. **21**: 2334–2348. DOI: 10.1111/gcb.12855.
599. Noyce, G.L., Kirwan, M.L., Rich, R.L., and Megonigal, J.P. (2019). Asynchronous nitrogen supply and demand produce nonlinear plant allocation responses to warming and elevated CO2. Proc. Natl. Acad. Sci. USA **116**: 21623–21628. DOI: 10.1073/pnas.1904990116.
600. Cai, C., Yin, X., He, S., et al. (2016). Responses of wheat and rice to factorial combinations of ambient and elevated CO2 and temperature in FACE experiments. Global Change Biol. **22**: 856–874. DOI: 10.1111/gcb.13065.
601. Kimball, B.A., Conley, M.M., Wang, S., et al. (2008). Infrared heater arrays for warming ecosystem field plots. Global Change Biol. **14**: 309–320. DOI: 10.1111/j.1365-2486.2007.01486.x.
602. Peng, B., Guan, K., Tang, J., et al. (2020). Towards a multiscale crop modelling framework for climate change adaptation assessment. Nat. Plants **6**: 338–348. DOI: 10.1038/s41477-020-0625-3.
603. Yahdjian, L., and Sala, O.E. (2002). A rainout shelter design for intercepting different amounts of rainfall. Oecologia **133**: 95–101. DOI: 10.1007/s00442-002-1024-3.
604. Martinez-Meza, E., and Whitford, W.G. (1996). Stemflow, throughfall and channelization of stemflow by roots in three Chihuahuan desert shrubs. J. Arid Environ. **32**: 271–287. DOI: 10.1006/jare.1996.0023.
605. Gomez-Gomez, J.-d.-D., Pulido-Velazquez, D., Collados-Lara, A.-J., and Fernandez-Chacon, F. (2022). The impact of climate change scenarios on droughts and their propagation in an arid Mediterranean basin. A useful approach for planning adaptation strategies. Sci. Total Environ. **820**: 153128.
606. Calel, R. (2013). Carbon markets: a historical overview. WIREs Clim. Change **4**: 107–119. DOI: 10.1002/wcc.208.
607. UN (1998). Kyoto protocol to the United Nations Framework Convention on climate change. United Nations. https://unfccc.int/resource/docs/convkp/kpeng.pdf.
608. Lovell, H.C. (2010). Governing the carbon offset market. WIREs Clim. Change **1**: 353–362. DOI: 10.1002/wcc.43.
609. Michaelowa, A., Shishlov, I., and Brescia, D. (2019). Evolution of international carbon markets: lessons for the Paris Agreement. WIREs Clim. Change **10**: e613.
610. Fuss, S., Lamb, W.F., Callaghan, M.W., et al. (2018). Negative emissions—part 2: costs, potentials and side effects. Environ. Res. Lett. **13**: 063002. DOI: 10.1088/1748-9326/aabf9f.
611. Ruseva, T., Hedrick, J., Marland, G., et al. (2020). Rethinking standards of permanence for terrestrial and coastal carbon: implications for governance and sustainability. Curr. Opin. Environ. Sustain. **45**: 69–77. DOI: 10.1016/j.cosust.2020.09.009.
612. Linsenmeier, M., Mohommad, A., and Schwerhoff, G. (2022). Policy sequencing towards carbon pricing among the world's largest emitters. Nat. Clim. Change **12**: 1107–1110. DOI: 10.1038/s41558-022-01538-8.
613. UNCC (2022). About carbon pricing. United Nations Climate Change. https://unfccc.int/about-us/regional-collaboration-centres/the-ciaca/about-carbon-pricing.
614. Bechtel, M.M., Scheve, K.F., and van Lieshout, E. (2020). Constant carbon pricing increases support for climate action compared to ramping up costs over time. Nat. Clim. Change **10**: 1004–1009. DOI: 10.1038/s41558-020-00914-6.
615. Bank, W. (2022). State and Trends of Carbon Pricing 2022. In state and trends of carbon pricing, (World Bank). https://openknowledge.worldbank.org/handle/10986/37455.
616. Wei, Y.M., Mi, Z.F., and Huang, Z. (2015). Climate policy modeling: an online SCI-E and SSCI based literature review. Omega **57**: 70–84. DOI: 10.1016/j.omega.2014.10.011.
617. Mildenberger, M., Lachapelle, E., Harrison, K., and Stadelmann-Steffen, I. (2022). Limited impacts of carbon tax rebate programmes on public support for carbon pricing. Nat. Clim. Change **12**: 141–147. DOI: 10.1038/s41558-021-01268-3.
618. Cong, R.G., and Wei, Y.M. (2010). Potential impact of (CET) carbon emissions trading on China's power sector: A perspective from different allowance allocation options. Energy **35**: 3921–3931. DOI: 10.1016/j.energy.2010.06.013.
619. Cong, R.G., and Wei, Y.M. (2012). Experimental comparison of impact of auction format on carbon allowance market. Renew. Sust. Energ. Rev. **16**: 4148–4156. DOI: 10.1016/j.rser.2012.03.049.
620. Hepburn, C. (2017). Make carbon pricing a priority. Nat. Clim. Change **7**: 389–390. DOI: 10.1038/nclimate3302.
621. Weitzman, M.L. (1974). Prices vs. quantities. Rev. Econ. Stud. **41**: 477–491. DOI: 10.2307/2296698.
622. Bertram, C., Luderer, G., Pietzcker, R.C., et al. (2015). Complementing carbon prices with technology policies to keep climate targets within reach. Nat. Clim. Change **5**: 235–239. DOI: 10.1038/nclimate2514.
623. Nordhaus, W.D. (2006). After Kyoto: alternative mechanisms to control global warming. Am. Econ. Rev. **96**: 31–34. DOI: 10.1257/000282806777211964.
624. EPA. EU emissions trading system. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.
625. IEA (2020). China's emissions trading scheme. https://www.iea.org/reports/chinas-emissions-trading-scheme.
626. Zhang, Z. (2022). China's carbon market: development, evaluation, coordination of local and national carbon markets, and common prosperity. J. Clim. Fin. **1**: 100001.
627. Pizer, W.A. (2002). Combining price and quantity controls to mitigate global climate change. J. Public. Econ. **85**: 409–434. DOI: 10.1016/S0047-2727(01)00118-9.
628. Liu, Y., Li, H., Wang, H., et al. (2023). Integrated life cycle analysis of cost and CO2 emissions from vehicles and construction work activities in highway pavement service life. Atmosphere **14**: 194. DOI: 10.3390/atmos14020194.
629. Paustian, K., Collier, S., Baldock, J., et al. (2019). Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. Carbon Manag. **10**: 567–587. DOI: 10.1080/17583004.2019.1633231.
630. UN (1992). United Nations Framework Convention on climate change. United Nations. https://unfccc.int/resource/docs/convkp/conveng.pdf.
631. UNESCO (2009). Report by the director-general on the UNESCO World Conference on education for sustainable development and the bonn declaration. Education for sustainable development – moving into the second half of the United Nations decade. https://unesdoc.unesco.org/ark:/48223/pf0000181881.
632. UNESCO (2010). UNESCO strategy for the second half of the United Nations decade of education for sustainable development. United Nations decade of education for sustainable development. https://unesdoc.unesco.org/ark:/48223/pf0000215466.
633. Carrico, A.R., Vandenbergh, M.P., Stern, P.C., and Dietz, T. (2015). US climate policy needs behavioural science. Nat. Clim. Change **5**: 177–179. DOI: 10.1038/nclimate2518.

634. Mochizuki, Y., and Bryan, A. (2015). Climate change education in the context of education for sustainable development: rationale and principles. J. Educ. Sustain. Dev. **9**: 4–26. DOI: 10.1177/0973408215569109.
635. Anderson, A.H. (2012). Climate change education for mitigation and adaptation. J. Edu. Sustain. Dev. **6**: 191–206. DOI: 10.1177/0973408212475199.
636. Wouterse, F., Andrijevic, M., and Schaeffer, M. (2022). The microeconomics of adaptation: Evidence from smallholders in Ethiopia and Niger. World Dev. **154**: 105884. DOI: 10.1016/j.worlddev.2022.105884.
637. Hudson, S.J. (2001). Challenges for environmental education: issues and ideas for the 21st century: environmental education, a vital component of efforts to solve environmental problems, must stay relevant to the needs and interests of the community and yet constantly adapt to the rapidly changing social and technological landscape. Bioscience **51**: 283–288. DOI: 10.1641/0006-3568(2001)051[0283:CFEEIA]2.0.CO;2.
638. Allcott, H., and Mullainathan, S. (2010). Behavior and energy policy. Science **327**: 1204–1205. DOI: 10.1126/science.1180775.
639. Kollmuss, A., and Agyeman, J. (2002). Mind the gap: why do people act environmentally and what are the barriers to pro-environmental behavior. Environ. Educ. Res. **8**: 239–260. DOI: 10.1080/13504620220145401.
640. Brownlee, M.T.J., Powell, R.B., and Hallo, J.C. (2013). A review of the foundational processes that influence beliefs in climate change: opportunities for environmental education research. Environ. Educ. Res. **19**: 1–20. DOI: 10.1080/13504622.2012.683389.
641. Trott, C.D. (2022). Climate change education for transformation: exploring the affective and attitudinal dimensions of children's learning and action. Environ. Educ. Res. **28**: 1023–1042. DOI: 10.1080/13504622.2021.2007223.
642. Thaler, R.H. (2018). From cashews to nudges: the evolution of behavioral economics. Am. Econ. Rev. **108**: 1265–1287. DOI: 10.1257/aer.108.6.1265.
643. Ivanova, D., Stadler, K., Steen-Olsen, K., et al. (2015). Environmental impact assessment of household consumption. J. Ind. Ecol. **20**: 12371.
644. UNEP (2020). Emissions gap report 2020. United Nations Environment Programme Copenhagen Climate Centre (UNEP-CCC). https://www.unep.org/emissions-gap-report-2020.
645. IPCC (2022). Climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg3/.
646. UNEP (2021). Emissions gap report 2021. United Nations Environment Programme Copenhagen Climate Centre (UNEP-CCC). https://unepccc.org/.
647. Brizga, J., Feng, K.S., and Hubacek, K. (2017). Household carbon footprints in the Baltic States: A global multi-regional input-output analysis from 1995 to 2011. Appl. Energy **189**: 780–788. DOI: 10.1016/j.apenergy.2016.01.102.
648. Creutzig, F., Roy, J., Lamb, W.F., et al. (2018). Towards demand-side solutions for mitigating climate change. Nat. Clim. Change **8**: 268–271.
649. van den Berg, N.J., Hof, A.F., Akenji, L., et al. (2019). Improved modelling of lifestyle changes in integrated assessment models: cross-disciplinary insights from methodologies and theories. Energy Strateg. Rev. **26**: 100420. DOI: 10.1016/j.esr.2019.100420.
650. Saujot, M., Le Gallic, T., and Waisman, H. (2021). Lifestyle changes in mitigation pathways: policy and scientific insights. Environ. Res. Lett. **16**: 015005.
651. Vita, G., Lundstrom, J.R., Hertwich, E.G., et al. (2019). The environmental impact of green consumption and sufficiency lifestyles scenarios in Europe: connecting local sustainability visions to global consequences. Ecol. Econ. **164**: 106322. DOI: 10.1016/j.ecolecon.2019.05.002.
652. Ivanova, D., Barrett, J., Wiedenhofer, D., et al. (2020). Quantifying the potential for climate change mitigation of consumption options. Environ. Res. Lett. **15**: 093001. DOI: 10.1088/1748-9326/ab8589.
653. Akenji, L., Bengtsson, M., Toivio, V., et al. (2022). 1.5–degree lifestyles: towards a fair consumption space for all (Hot or Cool Institute)L. https://hotorcool.org/1-5-degree-lifestyles-report/.
654. van Vuuren, D.P., Stehfest, E., Gernaat, D., et al. (2018). Alternative pathways to the 1.5 degrees C target reduce the need for negative emission technologies. Nat. Clim. Change 8, 391-397.
655. van Sluisveld, M.A.E., Martinez, S.H., Daioglou, V., and van Vuuren, D.P. (2016). Exploring the implications of lifestyle change in 2 degrees C mitigation scenarios using the IMAGE integrated assessment model. Technol. Forecast. Soc. Change. **102**: 309–319. DOI: 10.1016/j.techfore.2015.08.013.
656. Dalkmann, H., and Brannigan, C. (2007). Transport and climate change. Module 5e: sustainable transport: a sourcebook for policy-makers in developing cities (Deutsche Gesellschaft Fuer Technische Zusammenarbeit)L.
657. Enriquez, A., PhD, B., Dalkmann, H., and Brannigan, C. (2014). GIZ sourcebook 5e transport and climate change.
658. Kanyama, A.C., Nassen, J., and Benders, R. (2021). Shifting expenditure on food, holidays, and furnishings could lower greenhouse gas emissions by almost 40%. J. Ind. Ecol. **25**: 1602–1616. DOI: 10.1111/jiec.13176.
659. Chaudhary, A., and Krishna, V. (2021). Region-specific nutritious, environmentally friendly, and affordable diets in India. One Earth **4**: 531–544. DOI: 10.1016/j.oneear.2021.03.006.
660. Hong, C.P., Burney, J.A., Pongratz, J., et al. (2021). Global and regional drivers of land-use emissions in 1961-2017. Nature **589**: 554–561. DOI: 10.1038/s41586-020-03138-y.
661. Edelenbosch, O.Y., McCollum, D.L., Pettifor, H., et al. (2018). Interactions between social learning and technological learning in electric vehicle futures. Environ. Res. Lett. **13**: 124004. DOI: 10.1088/1748-9326/aae948.
662. Falchetta, G., and Noussan, M. (2021). Electric vehicle charging network in Europe: an accessibility and deployment trends analysis. Transp. Res. D Transp. Environ. **94**: 102813. DOI: 10.1016/j.trd.2021.102813.
663. Girod, B., van Vuuren, D.P., and de Vries, B. (2013). Influence of travel behavior on global CO2 emissions. Transp. Res. A Policy. Pract. **50**: 183–197. DOI: 10.1016/j.tra.2013.01.046.
664. Kaufmann, V., and Ravalet, E. (2016). From weak signals to mobility scenarios: a prospective study of France in 2050. International Scientific Conference on Mobility and Transport Transforming Urban Mobility (TUM).
665. Ding, Q., Cai, W.J., Wang, C., and Sanwal, M. (2017). The relationships between household consumption activities and energy consumption in china- an input-output analysis from the lifestyle perspective. Appl. Energy **207**: 520–532. DOI: 10.1016/j.apenergy.2017.06.003.
666. Guneralp, B., Zhou, Y.Y., Urge-Vorsatz, D., et al. (2017). Global scenarios of urban density and its impacts on building energy use through 2050. Proc. Natl. Acad. Sci. USA **114**: 8945–8950. DOI: 10.1073/pnas.1606035114.
667. Meng, W., Zhong, Q., Chen, Y., et al. (2019). Energy and air pollution benefits of household fuel policies in northern China. Proc. Natl. Acad. Sci. USA **116**: 16773–16780. DOI: 10.1073/pnas.1904182116.
668. Pachauri, S., Poblete-Cazenave, M., Aktas, A., and Gidden, M.J. (2021). Access to clean cooking services in energy and emission scenarios after COVID-19. Nat. Energy **6**: 1067–1076. DOI: 10.1038/s41560-021-00911-9.
669. Beylot, A., Vaxelaire, S., and Villeneuve, J. (2016). Reducing gaseous emissions and resource consumption embodied in french final demand: how much can waste policies contribute. J. Ind. Ecol. **20**: 905–916. DOI: 10.1111/jiec.12318.
670. Grubler, A., Wilson, C., Bento, N., et al. (2018). A low energy demand scenario for meeting the 1.5 degrees C target and sustainable development goals without negative emission technologies. Nat. Energy 3, 515-527.
671. Koide, R., Kojima, S., Nansai, K., et al. (2021). Exploring carbon footprint reduction pathways through urban lifestyle changes: a practical approach applied to Japanese cities. Environ. Res. Lett. **16**: 084001. DOI: 10.1088/1748-9326/ac0e64.
672. Moran, D., Wood, R., Hertwich, E., et al. (2020). Quantifying the potential for consumer-oriented policy to reduce European and foreign carbon emissions. Clim. Policy **20**: S28–S38. DOI: 10.1080/14693062.2018.1551186.
673. Bishop, G., Styles, D., and Lens, P.N.L. (2021). Environmental performance comparison of bioplastics and petrochemical plastics: a review of life cycle assessment (LCA) methodological decisions. Resour. Conserv. Recycl. **168**: 105451. DOI: 10.1016/j.resconrec.2021.105451.
674. Wood, R., Moran, D., Stadler, K., et al. (2018). Prioritizing consumption-based carbon policy based on the evaluation of mitigation potential using input-output methods. J. Ind. Ecol. **22**: 540–552. DOI: 10.1111/jiec.12702.
675. BUDIMAN, A. (2022). Locomotion: Modelling for just and net-zero Europe. European Environmental Bureau. https://meta.eeb.org/2022/05/30/modelling-for-just-and-net-zero-europe/.
676. Van de Ven, D.J., Gonzalez-Eguino, M., and Arto, I. (2018). The potential of behavioural change for climate change mitigation: a case study for the European Union. Mitig. Adapt. Strateg. Glob. Chang. **23**: 853–886. DOI: 10.1007/s11027-017-9763-y.
677. Keppo, I., Butnar, I., Bauer, N., et al. (2021). Exploring the possibility space: taking stock of the diverse capabilities and gaps in integrated assessment models. Environ. Res. Lett. **16**: 053006. DOI: 10.1088/1748-9326/abe5d8.

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AUTHOR CONTRIBUTIONS

Fang W., J. D. H., M. K., J. P. W., X. Y., D. B., A. S., F. F., X. J., Y. S. O., P. P., X. L., M. C. R., M. J. C., B. H., E. J., Y. Z., C. S., J. Z., N. J., H. C., J. M. C., and J. M. T. conceived, organized, and revised the manuscript, and wrote Abstract, Introduction, and Global implications and future perspectives, and. K. W., Z. L., and Y. S. wrote section about emissions and drivers of climate change. Z. F., X. F., H. W., H. Y., F. O. K., F. B., E. A., J. R., S. M. S., H. W., S. X. C., S. K., X. Z., Y. G., and M. E. wrote section about evidence of climate change in Earth's spheres and its impact on environmental and public health. Faming W., W. A., R. B., X. W., J. S., R. L., W. Z., Xianfeng L., M. D., S. L., X. H., R. W., and Z. B. wrote section about strategies for climate change mitigation. S. G., G. M. V., C. O., D. L. E., P. K., S. P., C. Z., L. H., Z. M., H. D., and Y. S. wrote sections about strategies for climate change adaptation and education as well as carbon quantification, modeling, and pricing. Y. F., M. W., and L. X. organized and revised references.

DECLARATION OF INTERESTS

Fang Wang, Yuli Shan, Wei Zhao, Chaojun Ouyang, Haijun Wang, and Jean-Pierre Wigneron are Editorial Board members of The Innovation Geoscience and were blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of these members and their research group. The other authors declare no conflicts of interest.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

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