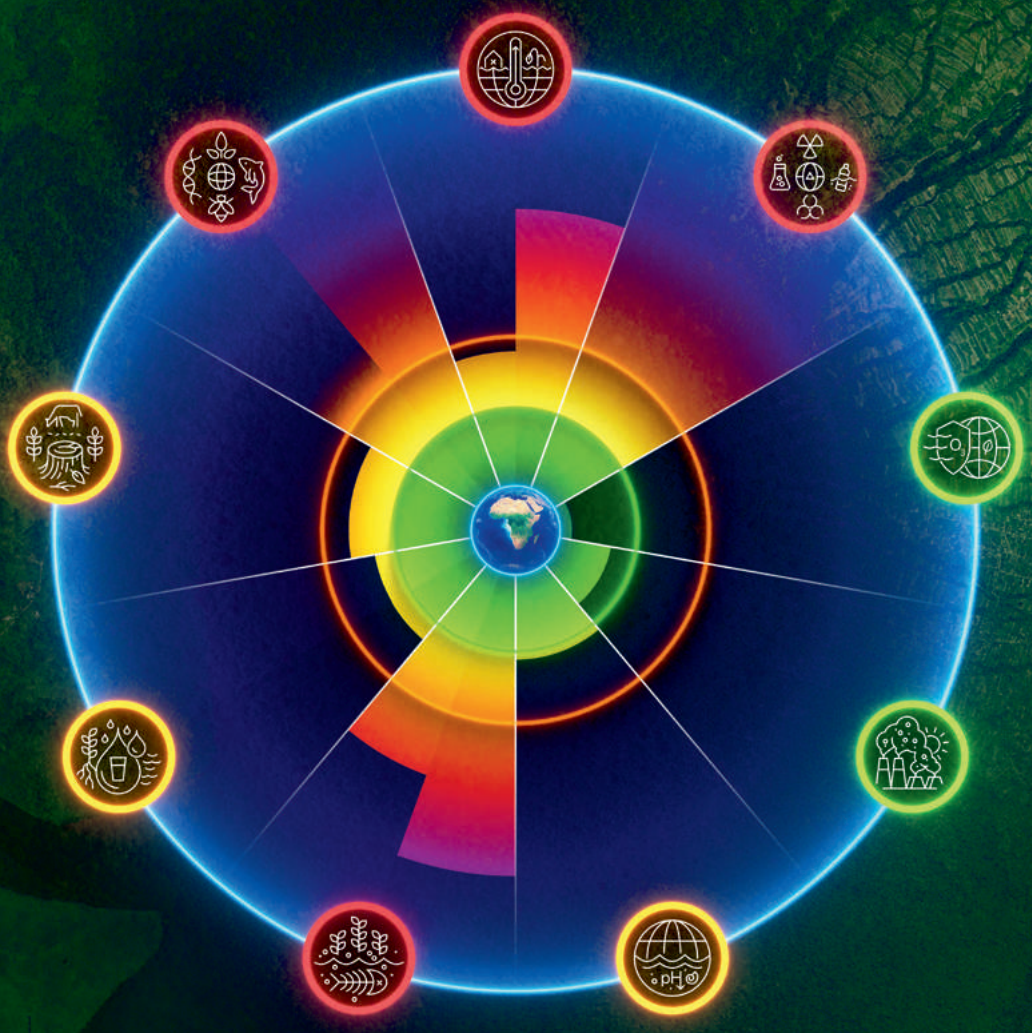
PLANETARY HEALTH CHECK 2026

A Scientific Assessment of the State of Our Planet



Planetary Boundaries
SCIENCE LAB

Photography by Mattias Klum

Foreword

For thousands of years, Indigenous communities of the Amazon have actively shaped and stewarded forest landscapes. Through sophisticated agroforestry systems, they cultivated reliable sources of food and medicine, enriched soils, increased biodiversity, and created highly resilient landscapes, all while preserving the integrity of the forest ecosystems. Indigenous knowledge systems enabling this vitality reflect an understanding that the forest, its waters, its biodiversity, and its people do not function in isolation, but as part of a connected whole. The health of each part directly impacts the other.

The third edition of the Planetary Health Check affirms this deep interconnectedness. Building on the Planetary Boundaries framework, it draws on the latest Earth system science to assess the state of the nine guardrails that define the Safe Operating Space for humanity. The result is the most current and integrated picture yet of how human pressures are affecting the stability, resilience, and future trajectory of the whole Earth system.

This report focuses, in part, on how the capacity of the land biosphere to buffer climate change is weakening and may be significantly overestimated. As biodiversity declines and ecosystems are degraded and eliminated, the biosphere is becoming less able to regulate climate, sustain essential ecological processes, and support the resilience of the Earth system upon which our societies depend.

The Amazon is one such ecosystem, under intense dual pressures from deforestation, degradation, wildfires, and climate change. If it crosses its tipping point, up to 70% of the Amazon forest could transition from lush rainforest to dry tropical savanna, releasing hundreds of billions of tons of carbon dioxide, irretrievably losing myriad species, and diminishing Earth's natural heritage. The resulting impacts would extend far beyond the Amazon itself, with serious implications for climate stability, food and water security, and human health around the world, such as an increased risk of epidemics. Besides an ecological catastrophe, losing the Amazon would be a moral injury: a sign that we had allowed one of Earth's great living worlds to disappear under our care.

To avoid the tipping of the Amazon, it is urgent to implement nature-based solutions: zero deforestation, degradation, and wildfires; large-scale forest restoration with native species; valuing knowledge of Indigenous Peoples and local communities; and implementation of a socio-bioeconomy of healthy standing forests and flying rivers.

This year's Planetary Health Check also draws attention to emerging risks whose full consequences remain uncertain. Human activities are now reaching parts of the Earth system once thought insulated from global environmental change, including the seafloor, where disturbance affects biodiversity, nutrient cycling, and carbon storage in ways we are only beginning to understand. Similarly, we produce novel entities – human-made substances like synthetic chemicals, plastics, and other dangerous pollutants – much faster than we can study their effects on our Planet.

These findings reinforce the importance of ambitious, precautionary, and immediate measures to protect planetary health. They also reveal a broader governance challenge: Earth's climate, oceans, land, and biosphere are deeply interconnected, yet the institutions governing our emissions, pollution, fisheries, ecosystems protection, and development often remain fragmented. The Planetary Boundaries can help us understand our impacts on the whole Earth: They can guide us on our path to a sustainable and equitable world.

The Planetary Health Check reminds us that the future is not predetermined. The same ingenuity, cooperation, and capacity for innovation that have transformed human societies can be directed toward safeguarding the living systems upon which all life depends. In doing so, we may rediscover an understanding long known by Indigenous communities and increasingly supported by Earth system science: Our well-being depends on the health and resilience of the living world.

Thank you for your engagement with this report – may it inspire the understanding, collaboration, and action needed to serve as guardians of our Planet for generations to come.

Carlos A. Nobre,
Planetary Guardian
Earth System Scientist;
Co-Chair, Science Panel for the Amazon
Full Professor for Climate and Sustainability,
Institute for Advanced Study, University of São Paulo

Glossary

Planetary Boundary / Boundaries (PB/PBs)

The science-based guardrails that show how far humanity can push the planet's natural systems while still keeping Earth stable, resilient, and able to support human wellbeing. The PB framework identifies nine major Earth system processes that help keep the Planet in a relatively stable state. For each process, scientists define a boundary: a level of human pressure that should not be exceeded. Breaching these thresholds does not mean immediate disaster, but it does mean that the risk for serious harm increases.

Safe Operating Space

The precautionary zone for human activity in which pressures on the Earth system remain within Planetary Boundaries. Staying within this space ensures Earth remains stable and supportive of life, and reduces the risk of crossing harmful large-scale tipping points.

Zone of Increasing Risk

The space just beyond a Planetary Boundary, where human pressure on an Earth system process is no longer considered within safe limits. In this zone, risks to Earth system stability, resilience, and life-support functions grow as pressure increases.

High Risk Zone

When conditions worsen beyond the Zone of Increasing Risk, they enter the High Risk Zone. Here, the risk of severe, irreversible damage to key planetary functions becomes not just possible, but likely. In this zone, immediate action becomes critical to prevent locking in permanent changes.

Control Variable (CV)

The measures (or proxies) used to check whether an Earth system process is staying within its Safe Operating Space (Planetary Boundary). Usually, scientists track one or two control variables per boundary. For instance, atmospheric CO_2 concentration is a control variable for climate change.

Earth System

The set of interacting processes and components that determine how our Planet functions. It includes the atmosphere, oceans, land, ice, ecosystems, and human activities, all of which influence one another in complex ways. From climate and ocean circulation to biodiversity and the use of natural resources, these connections shape the conditions that support life and determine Earth's future stability.

Tipping Point, Tipping Element

A tipping point is a threshold in the Earth system where small, gradual pressures can trigger large changes, which are often impossible to reverse, and which can come on quite suddenly. Once crossed, self-reinforcing feedbacks push the system further away from its previous state. For example, melting ice exposes less reflective ocean water, which absorbs more sunlight and accelerates melting, creating a self-reinforcing cycle. Parts of the Earth system that feature such a tipping point, such as the Amazon rainforest or Greenland ice sheet, are called "tipping elements".

Resilience

The capacity to absorb pressures, shocks, or disturbances while continuing to function. In the Earth science context, this term is used to describe the ability of ecosystems, other parts of the Earth system, or the Planet as a whole to cope with change and disturbance without losing their essential functions, structure, or ability to recover.

Feedback

A feedback occurs when the effects of a change influence how that change develops. A positive feedback amplifies and reinforces the original change, while a negative feedback counteracts and weakens it. Here, the terms "positive" and "negative" describe the direction of the effect, not whether the outcome is judged to be good or bad. In the Earth system, feedbacks play an important role in either accelerating change or promoting stability.

5 Key Take-Aways

1. **The impacts of transgressing Planetary Boundaries are becoming increasingly clear all around us.** Results published in the last year show that climate change is progressing faster than previously expected, causing unprecedented heatwaves on land and in the ocean and fueling destructive extreme weather events. Tropical coral reefs have experienced their most severe mass bleaching event to date, a shutdown of the main Atlantic overturning circulation is now considered a credible risk even under low- to medium-emission scenarios, and major Antarctic ice masses may have already begun their slide into the ocean. With seven out of nine boundaries transgressed, we have pushed Earth outside of its Safe Operating Space – meaning that we are turning Earth from a safe home into one full of hazards that threaten people across the world.

2. **Protecting and restoring nature is necessary to have a chance of a safe climate landing for humanity.** In the recent past, half of our CO_2 emissions have been absorbed by the ocean and nature on land. When scientists chart a path towards a manageable climate future, their calculations generally assume that forests, wetlands, and other ecosystems will continue to function as "carbon sinks" in this way. But today, the land carbon sink is already showing signs of weakening and stagnation. A new study has confirmed that even a small amount of additional deforestation in the Amazon would likely push the region past a tipping point under current climate projections, resulting in the loss of two-thirds of the remaining forest. The only way to bring Earth below 1.5°C of global warming is to phase out fossil fuels and, simultaneously, to reverse the transgression of the other Planetary Boundaries – especially by safeguarding the integrity of the biosphere.

3. **We have to protect the seafloor.** The seafloor ecosystems play a significant role in the Earth system, yet we are destroying them at an alarming rate. Fishing techniques like bottom trawling produce long-lasting damage: Every year, 1-2% of the seafloor is trawled, with some of the most productive and diverse ocean regions being targeted most frequently. In addition, nascent seafloor mining activities are a looming threat to previously untouched regions of the deep ocean, with currently incalculable impacts on the Earth system. More effective mechanisms to protect these vital but underexplored ecosystems are urgently needed.

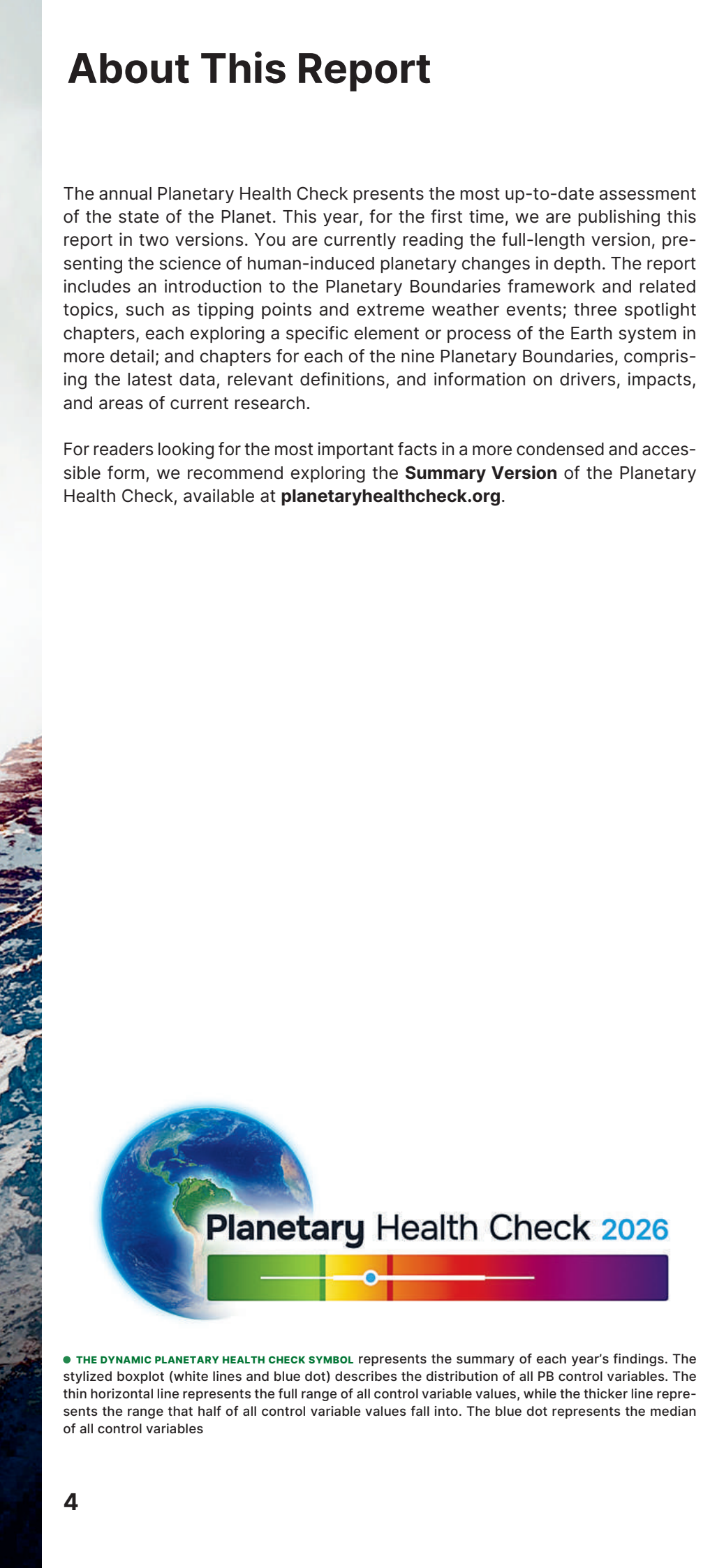
4. **Microplastics, forever chemicals, and other chemical pollutants present both known and yet-unknown dangers.** For example, (micro-)plastics contaminate the whole Planet today, from mountaintops to the deep sea, and forever chemicals like PFASs will not disappear from our environment for millennia. But this is only the tip of the iceberg: Humans are producing tens of thousands of chemicals and mixtures at unprecedented and increasing rates. We are already starting to see the harm these substances cause, from toxic effects on individual organisms to the disruption of Earth system processes. Even more dangerous are those effects that we can currently only guess at. Most of the substances we produce and release are not, or not sufficiently, tested for their impacts on the Earth system. We are flying blind: By the time we have a full picture of the danger, it might be too late to avoid it.

5. **We still have a chance to turn towards a safer, sustainable future.** The impacts of breached Planetary Boundaries are already all around us, and they will continue to become more severe. But today, we still have a narrow window of opportunity. If we manage to bend the curves within this decade, we can put our societies on a course towards a safer, more just future. We have the tools, and we have taken steps in this direction, but our current efforts are far from sufficient. Only by pursuing urgent, ambitious, and decisive action across all sectors of our societies, can we return to living within the Safe Operating Space on a healthy Planet.

About This Report

The annual Planetary Health Check presents the most up-to-date assessment of the state of the Planet. This year, for the first time, we are publishing this report in two versions. You are currently reading the full-length version, presenting the science of human-induced planetary changes in depth. The report includes an introduction to the Planetary Boundaries framework and related topics, such as tipping points and extreme weather events; three spotlight chapters, each exploring a specific element or process of the Earth system in more detail; and chapters for each of the nine Planetary Boundaries, comprising the latest data, relevant definitions, and information on drivers, impacts, and areas of current research.

For readers looking for the most important facts in a more condensed and accessible form, we recommend exploring the **Summary Version** of the Planetary Health Check, available at **planetaryhealthcheck.org**.



Nishant Rajput, www.pexels.com

Planetary Health Check 2026

● **THE DYNAMIC PLANETARY HEALTH CHECK SYMBOL** represents the summary of each year's findings. The stylized boxplot (white lines and blue dot) describes the distribution of all PB control variables. The thin horizontal line represents the full range of all control variable values, while the thicker line represents the range that half of all control variable values fall into. The blue dot represents the median of all control variables

Table of Contents

Foreword 1
Glossary 2
5 Key Take-Aways 3
About This Report 4
Executive Summary 6

1 The Health of the Planet 10
1.1 From Holocene to Anthropocene 11
1.2 The Planetary Boundaries Framework 14
1.3 The Nine Planetary Boundaries 16
1.4 Planetary Health Check 2026 at a Glance 17
1.5 What's New in the 2026 Planetary Health Check 20

2 Challenges of Diagnosing the Earth System 24
2.1 Assessing Planetary Boundaries 25
2.2 One Earth System: Why Planetary Boundaries are Connected 28
2.3 From Safe to Safe and Just Operating Space 31

3 Today's Impacts and Tomorrow's Risks 32
3.1 Extreme Weather Events of 2025 and 2026 33
3.2 Tipping Points 36

4 Spotlights 40
4.1 Earth Resilience: When Land Stops Buffering Climate Change 41
4.2 Seafloor Integrity: Why the Bottom of the Ocean Matters 45
4.3 Novel Entities: Known Impacts and Unknown Planetary Threats 50

5 Planetary Boundary Information Sheets 54
5.1 Climate Change 55
5.2 Change in Biosphere Integrity 61
5.3 Land System Change 68
5.4 Freshwater Change 74
5.5 Modification of Biogeochemical Flows 79
5.6 Ocean Acidification 84
5.7 Increase in Atmospheric Aerosol Loading 90
5.8 Stratospheric Ozone Depletion 95
5.9 Introduction of Novel Entities 99

6 Solutions & Outlook 102

7 Tables & References 106

Executive Summary

Photography by Mattias Klum

The Planetary Health Check (PHC) provides an annual assessment of the state of the Planet. It is structured around the Planetary Boundaries: the nine critical processes that regulate stability, resilience, and the conditions that support life on Earth. For each boundary, one or two indicators, known as control variables, are used to assess its status. These show whether conditions remain within the Safe Operating Space – the range in which the risk of destabilizing the Planet remains low. Beyond a boundary lies the Zone of Increasing Risk, followed by the High-Risk Zone, where the risk of large-scale and potentially irreversible changes becomes high. The *2026 Planetary Health Check* finds that seven of the nine Planetary Boundaries are transgressed, and trends for all seven continue to point in the wrong direction, indicating further deterioration in the conditions that support long-term planetary stability.

Seven Out of Nine Planetary Boundaries are Transgressed

- **Climate Change – strongly transgressed.** Climate Change refers to the disruption of Earth's energy balance, driven mainly by greenhouse-gas emissions from fossil fuels and land-use change, alongside other human influences on Earth's energy balance, including aerosols. Atmospheric carbon dioxide and human-caused radiative forcing, the variables used to measure Climate Change in the Planetary Boundaries framework, have both exceeded their safe levels. The consequences are clearly visible as rising temperatures, extreme weather, ecosystem damage, sea-level rise, and growing risks to health, food, water, infrastructure, and economic stability. Continued warming also increases the likelihood of self-reinforcing changes and potentially irreversible tipping points.

- **Change in Biosphere Integrity – strongly transgressed.** This describes the diversity and functioning of life across land, freshwater, and ocean ecosystems, which are being degraded by habitat conversion, resource extraction, pollution, climate change, and numerous other stressors. In the Planetary Boundaries framework, **Change in Biosphere Integrity** is measured through species extinction rates, as well as the share of potential natural plant productivity appropriated by humans; both measures are in the High Risk Zone, far beyond safe levels. Further decline could weaken nature's capacity to regulate carbon, water, nutrients, soils, and climate, undermining food security, clean water, livelihoods, and ecosystem resilience while increasing the risk of cascading Earth system change.

- **Land System Change – transgressed.** Land System Change is driven primarily by the loss and degradation of natural landscapes, especially forests, through agricultural expansion, logging, infrastructure development, and, increasingly, climate-related heat, drought, fire, and pest outbreaks. Remaining forest cover across the assessed forest biomes has fallen below the safe level, reducing carbon storage, moisture recycling, soil protection, biodiversity, and regional cooling. Continued forest loss could intensify water stress, wildfire and flood risks, and raises the possibility of large-scale ecosystem shifts, including in the Amazon.

- **Freshwater Change – transgressed.** This boundary covers changes to both freshwater flows in rivers, lakes, reservoirs, and groundwater, and water stored in soils and available to plants. Human-induced disturbances to both measures are beyond safe levels, increasing droughts, floods, ecosystem stress, groundwater depletion, crop losses, and pressure on drinking water and energy systems. Further disruption could weaken carbon storage, increase fire and flood risks, and contribute to large-scale ecosystem decline, as well as threatening drinking water availability and food production.

- **Modification of Biogeochemical Flows – strongly transgressed.** Human activity has greatly increased nitrogen and phosphorus flows, mainly through fertilizer use. Both nutrient cycles are in the High-Risk Zone, far beyond safe levels, causing polluted water, algal blooms, oxygen-depleted dead zones, biodiversity loss, and nitrogen-related air pollution. These disruptions damage freshwater and marine ecosystems and create risks for fisheries, drinking water, food systems, and health. Because excess nutrients can remain in soils and groundwater for decades, impacts may persist long after inputs are reduced.

- **Ocean Acidification – transgressed.** Ocean acidification occurs as the ocean absorbs human-produced carbon dioxide, changing seawater chemistry and making it harder for many organisms to build and maintain shells and skeletons. The global boundary has now been transgressed, with particularly strong changes in the Arctic and Southern Oceans. Shell damage and dissolution are already being observed in *pteropods*, small planktonic snails that form an important part of marine food webs, while

deep-water corals are increasingly exposed to corrosive conditions. Continued acidification could disrupt marine food webs, fisheries, coastal livelihoods, and biodiversity, while also weakening the ocean's carbon uptake and its role in climate regulation.

- **Atmospheric Aerosol Loading – within the Safe Operating Space globally, but with significant regional transgression.** Aerosols are airborne particles from fossil fuel combustion, industry, transport, biomass burning, dust, and smoke that influence sunlight, clouds, rainfall, and atmospheric circulation. The global measure remains within safe limits and has generally improved in recent decades. However, aerosol loading over South Asia exceeds the proposed regional boundary and may disrupt monsoon rainfall. Aerosols also cause severe health impacts, reduce crop productivity, and complicate climate policy because some particles temporarily mask greenhouse-gas warming.

- **Stratospheric Ozone Depletion – within the Safe Operating Space.** The stratospheric ozone layer protects life from harmful ultraviolet radiation and has been severely damaged by long-lived human-made chemicals, such as chlorofluorocarbons. International controls have enabled substantial recovery, bringing the global boundary back within safe limits, although ozone levels remain below mid-20th-century conditions and recent recovery may have slowed. Incomplete recovery or emerging pressures could increase risks to human health, crops, ecosystems, and atmospheric circulation.

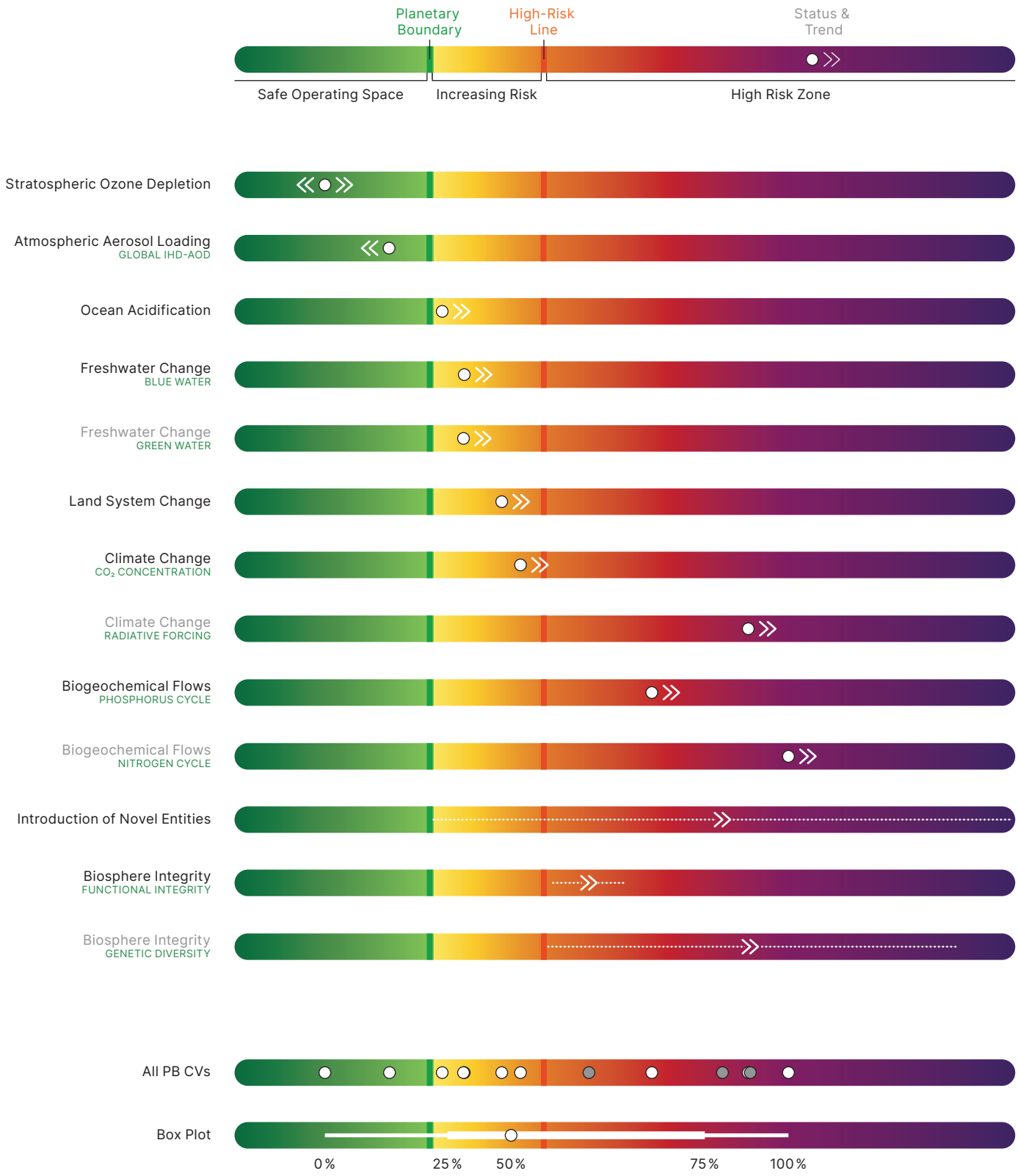
- **Introduction of Novel Entities – strongly transgressed.** Novel Entities comprise a broad and diverse range of chemicals, materials and other substances associated with human activity, including synthetic chemicals, plastics, pesticides and PFASs, which are released into the Earth system faster than they can be adequately tested, monitored, or regulated. The boundary is transgressed because substances continue to enter the environment without adequate safety assessment while their production, diversity, and release grow rapidly. Many can persist, spread globally, accumulate in organisms, and cause long-lasting or irreversible harm to ecosystems, food and water systems, human health, and other Planetary Boundary processes.

For most of the past 11,700 years, humanity developed under the relatively stable conditions of the Holocene. This period supported the emergence of agriculture, cities, and complex societies. Since the mid-20th century, however, rapid growth in population, resource and energy use, land conversion, and pollution has transformed humanity into a force capable of altering the Planet at a global scale – a shift often described as the Great Acceleration and the onset of the Anthropocene **(CH. 1.1)**.

The consequences are becoming increasingly visible. Global warming has accelerated in recent years, while many extreme events such as heatwaves, floods, droughts, and storms are becoming more frequent and more intense, causing growing harm to ecosystems and human populations alike. At the same time, biodiversity continues to decline, freshwater systems are increasingly disrupted, pollution is accumulating across land and ocean, and nutrient overload is degrading ecosystems and water quality. Signs of weakening land carbon sinks further raise concerns that forests and other ecosystems may lose part of their capacity to absorb human-caused emissions and could increasingly become sources of carbon. Together, these developments show that the Planet's capacity to buffer human pressures cannot be taken for granted.

These pressures span the nine Planetary Boundaries and do not act in isolation. Climate, ecosystems, freshwater, land, oceans, and nutrient cycles interact through complex feedbacks, so damage in one area can weaken resilience elsewhere and increase the risk of self-reinforcing or irreversible change **(CHS. 2.2 AND 3.2)**. The 2026 report places particular focus on three examples of these wider risks: the fragility of the land carbon sink **(CH. 4.1)**; the health and protection of the seafloor in the face of destructive fishing practices and prospective deep-sea mining **(CH. 4.2)**; and the potentially incalculable risks posed by pollution with human-made chemicals and materials (*Novel Entities*), including effects that may remain unknown until damage is widespread **(CH. 4.3)**.

Taken together, the 2026 assessment shows broad and increasing pressure across the Earth system. Seven of the nine Planetary Boundaries are transgressed, several control variables lie in the High-Risk Zone, and all seven transgressed boundaries show worsening trends. The farther and longer human pressures move beyond the boundaries, the greater the risk of large-scale and potentially irreversible Earth-system change. Earth's biological, physical, and chemical resilience still provides an opportunity to reduce these risks and move back towards the Safe Operating Space, but accelerating warming and signs of weakening natural buffers show that this window is closing rapidly.



● **PLANETARY HEALTH AT A GLANCE.** Just as a blood test provides insights into a human body's health and identifies areas of concern, this Planetary Health Check evaluates the 13 assessed control variables across the 9 Planetary Boundary (PB) processes to report on Earth's stability, resilience, and life-support functions – the overall health of our Planet. The 2026 assessment shows that seven of the nine PBs have been breached: Climate Change, Change in Biosphere Integrity, Land System Change, Freshwater Change, Modification of Biogeochemical Flows, Introduction of Novel Entities, and Ocean Acidification. All of these show worsening trends, suggesting further deterioration in the near future. Two PB processes remain within the Safe Operating Space: Increase in Atmospheric Aerosol Loading (improving global trend) and Stratospheric Ozone Depletion (currently stable). The Planetary Health Check Symbol (● **FIG. 5**) summarizes all of these findings, showing the Planet's overall health at a glance.

1 The Health of the Planet

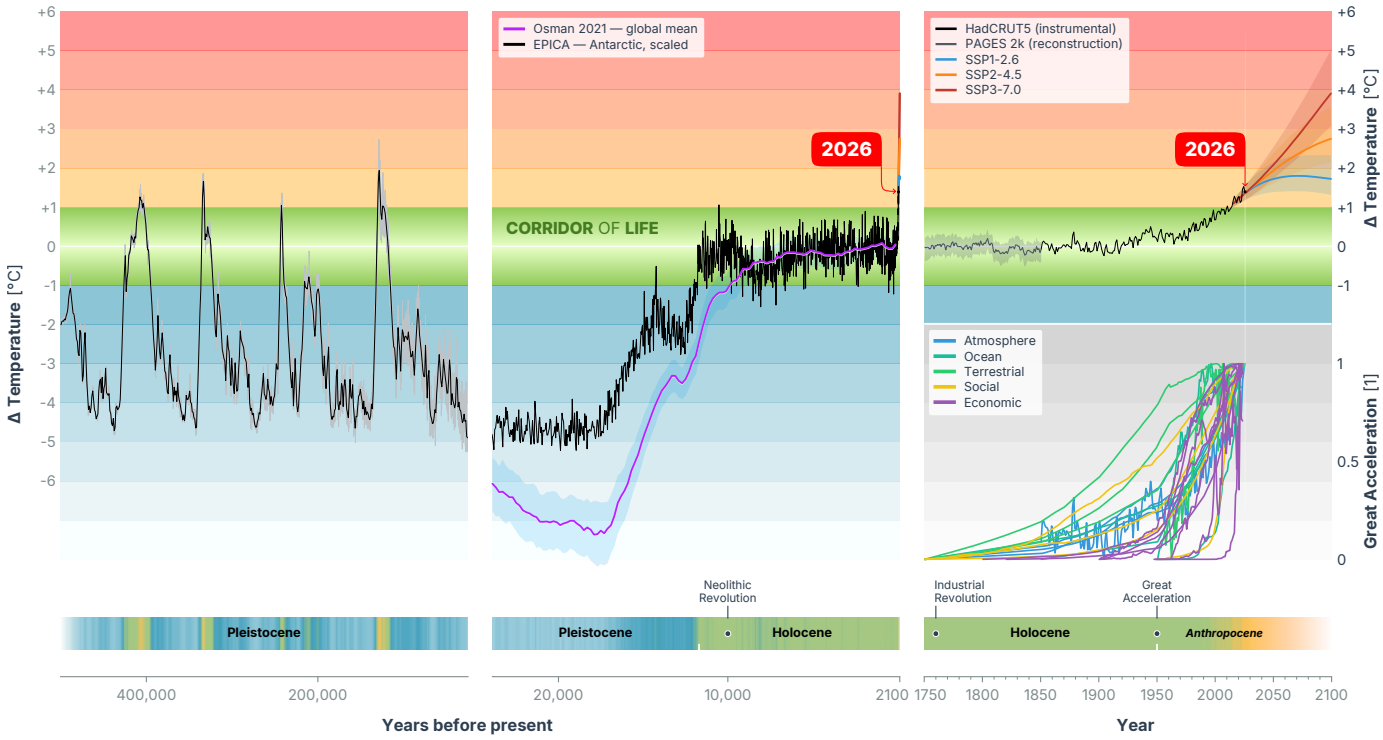
Photography by Mattias Klum

Human pressures on our Planet take many forms: Fossil fuel combustion changes the climate. Deforestation and land conversion reduce ecosystem functions. Freshwater extraction and river regulation alter water cycles. Fertilizer use disrupts nitrogen and phosphorus flows. Synthetic chemicals, plastics, and other pollutants accumulate across the environment. Biodiversity loss weakens the living systems that help regulate the Planet.

Today, the consequences of these pressures are becoming clearly visible. They are causing damage to ecosystems, reduced harvest security, strained water supplies, declining natural buffers, growing health risks, and increasing pressure on communities and infrastructure. Taken together, human actions are threatening to push Earth out of the relatively stable state that has allowed human civilizations to thrive.

1.1 From Holocene to Anthropocene

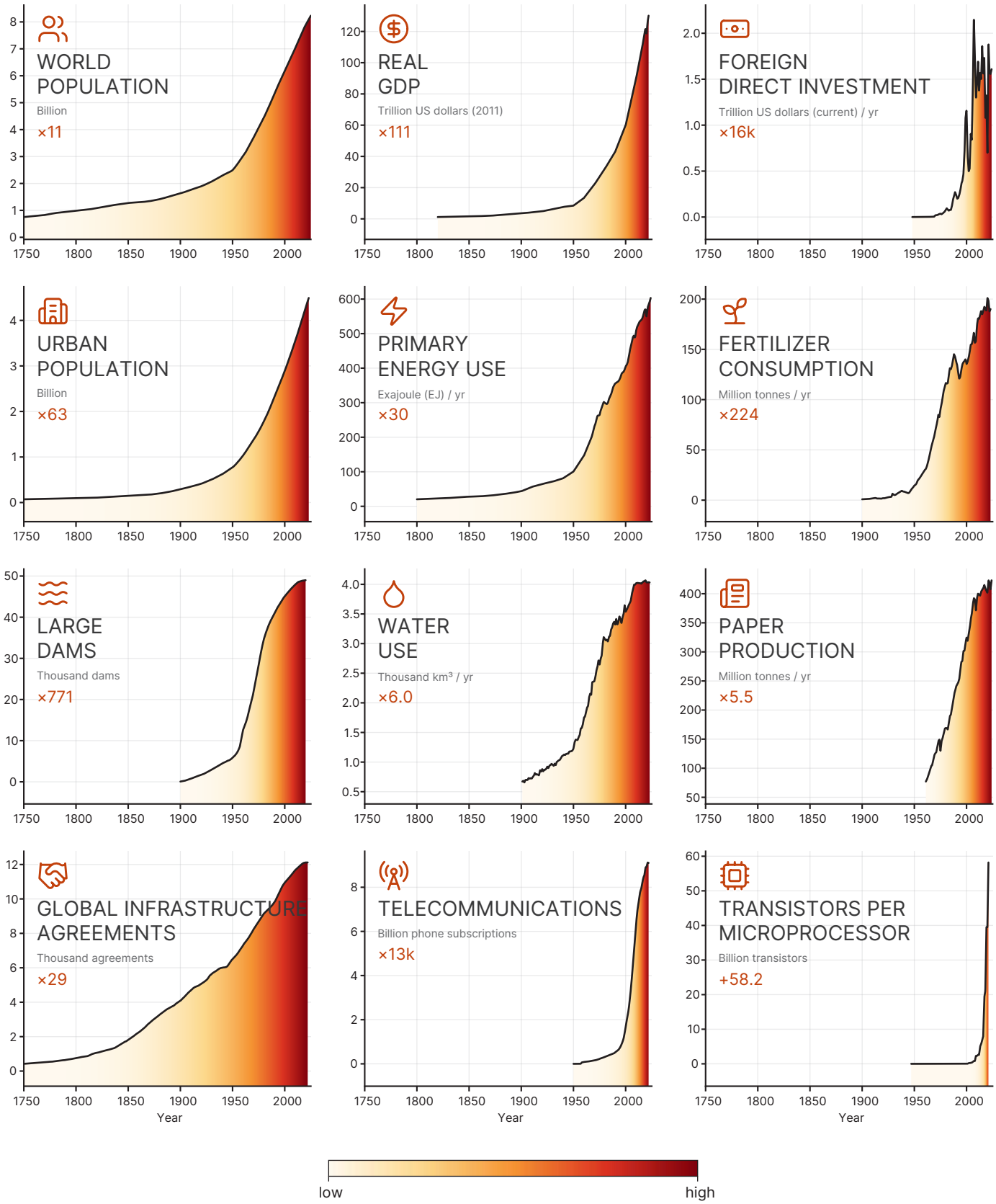
The **Safe Operating Space** is an Earth system state that allows humanity to advance and thrive.[9–11] It includes conditions similar to those of the Holocene epoch, beginning around 11,700 years ago. The Holocene epoch, during which agriculture and modern civilizations developed, was characterized by relatively stable and moderate planetary conditions, compared to the colder and more variable ice age conditions in the preceding Pleistocene (● FIG. 1).[12–14] Freshwater was consistently available across many regions, although with pronounced regional patterns and intermittent shifts in large-scale circulation patterns.[15,16] Biogeochemical cycles (such as carbon, nitrogen, and phosphorus) operated within balanced ranges, sustaining plant nutrients and ecosystem health. Biodiversity during the Holocene was subject to various fluctuations,[17] but overall the Holocene is



● **FIGURE 1:** Humanity's journey on Earth – Global temperature and the Great Acceleration from 500,000 years before present (BP) until 2100. The figure is a composite of different data sets including paleo data estimates, recent measurements, and future projections. For a full detailed description of this figure, please see Supplementary Materials. Data from: Jouzel et al. 2007,[1] Masson-Delmotte et al. 2010,[2] Osman et al. 2021,[3] PAGES 2k Consortium 2019,[4] Morice et al. 2021,[5] CRU 2026,[6] IPCC Summary for Policymakers 2021,[7] Steffen et al. 2015.[8] Key takeaway: For over 10,000 years, humanity lived in a very stable climatic period (the green corridor) in which human societies developed and adapted their technologies and cultures. By transgressing several Planetary Boundaries, including the one for Climate Change, we are moving beyond Holocene-like conditions and entering a new and dangerous terrain in which a rapidly changing global society must safeguard human well-being.

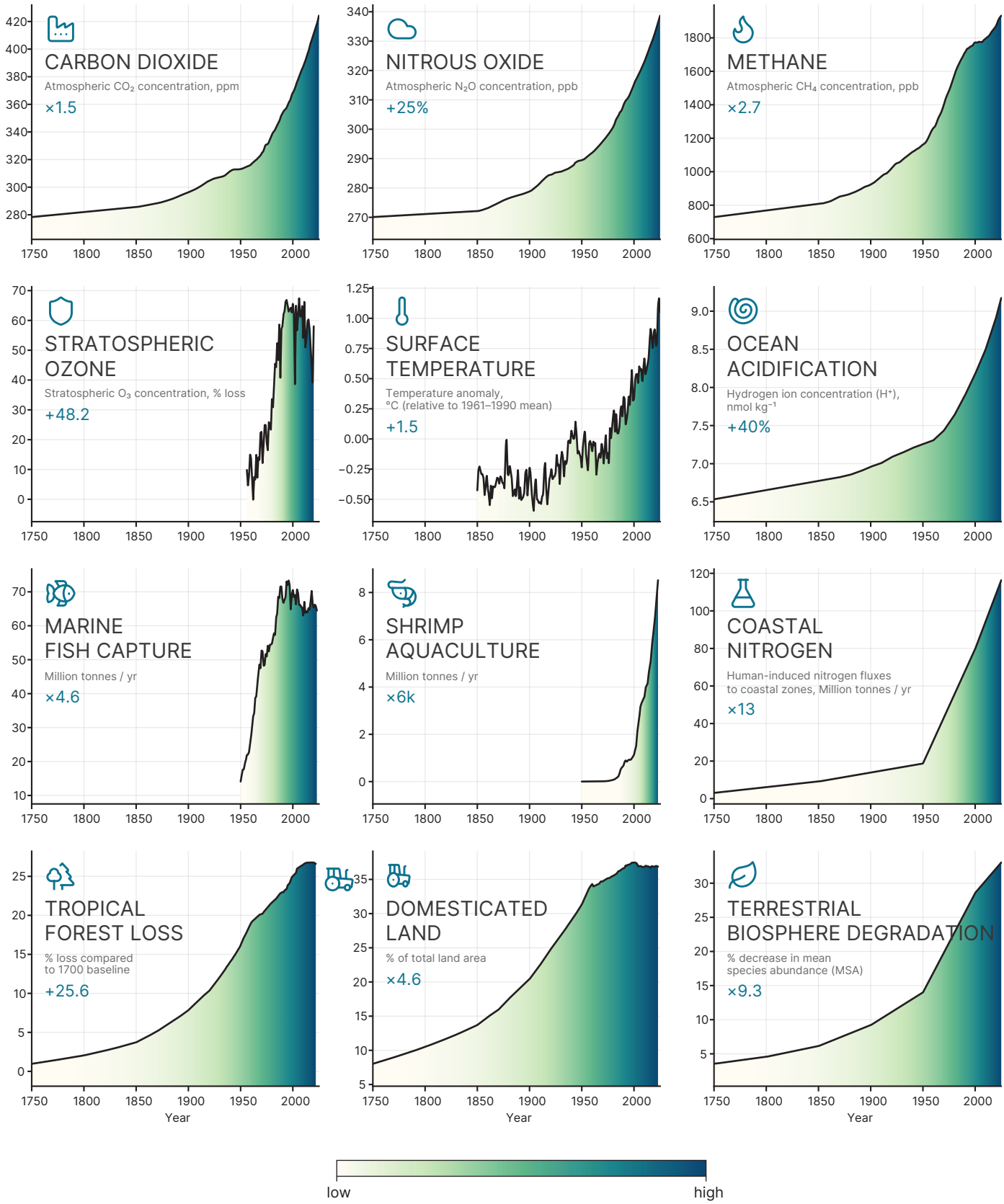
The Great Acceleration

Socio-economic trends since 1750



● **FIGURE 2:** The Great Acceleration – Recent trends in the Earth system. This updated figure extends the original "Great Acceleration" analysis by Steffen et al. (2015)[8] with the most recent data available for the 2026 assessment, incorporating new datasets and, in some cases, revised or additional indicators. For a list of data sources, see Supplementary Materials. The left-hand side shows the rapid growth in socio-economic drivers such as population, GDP, and energy use. The right-hand side illustrates corresponding Earth system responses, including atmospheric CO_2 levels, global temperature,

Biophysical trends since 1750



ocean acidification, and biodiversity decline. These coupled trends, which accelerated markedly after 1950, characterize the Great Acceleration and are a defining feature of the Anthropocene, highlighting the intensifying pressure humans place on the Earth system. Although a few indicators, such as marine fish capture, domesticated land, and stratospheric ozone depletion, show signs of flattening or recovery, most trends continue to rise steeply. Together, these trajectories reinforce the urgency of respecting the Planetary Boundaries to safeguard Earth's resilience.

considered an epoch of high biological resilience,[18] with ecosystems capable of adapting to external pressures and providing crucial services such as pollination and pest control. Natural regulatory systems, such as ocean currents and atmospheric patterns, played vital roles in stabilizing the environment over long periods.

This period of relatively stable living conditions, combined with the agricultural revolution, enabled the global human population to grow from less than 10 million at the beginning of the Holocene to over a billion by the beginning of the 19th century, and to more than 8 billion today.[19] In recent decades, human activities have intensified,[8] potentially surpassing Earth's capacity to sustain its stability. The result is a new relationship between humanity and Earth. Human societies have become a planetary force, powerful enough to alter the conditions that made their own development possible. The term *Anthropocene* captures this shift: an era in which human actions are reshaping the atmosphere, oceans, land, freshwater systems, and biosphere at a global scale. This has led to rapidly increasing pressures on the planet, a phenomenon known as the "Great Acceleration" (● FIG. 2).

Today, we can see the impacts of these pressures picking up pace as well. Recent research finds that global warming has accelerated significantly since around 2015.[20] During 2016–2025, global temperature increased at an observed rate of about 0.30°C per decade – nearly 60% faster than the average rate of 0.19°C per decade over 1980-2020.[21] Earth's energy imbalance has more than doubled since 1976–1995, and the number of marine-heatwave days has more than tripled since 1991. In 2025, the largest coral bleaching event on record exposed 84.4% of the world's reef area to bleaching-level heat stress.[22] Other extreme events are becoming more frequent and more intense, as the severe floods, tropical storms and droughts of the last year demonstrate (SEE CH. 3.1). Accelerated warming moves the planet more quickly away from Holocene-like conditions: It increases the urgency for reversing course towards a safe landing after overshooting temperature targets, narrows the time available for humans and nature to adapt, and exacerbates the likelihood of record-breaking extremes and cascading impacts.

Recent research finds that global warming has accelerated significantly since around 2015.

These impacts are not isolated events, but expressions of how human actions are pushing Earth out of the stable, Holocene-like state.[8] To safely navigate the Anthropocene, and ensure sustainable development for future generations in a stable and resilient Earth system, respecting the Planetary Boundaries is of critical importance.

1.2 The Planetary Boundaries Framework

In the current era of rapid environmental change, the Planetary Boundaries (PBs) framework helps define how to maintain the planet's stability and resilience. It defines a Safe Operating Space, in which the conditions on Earth will remain reliable and civilization-friendly for generations to come. The framework complements, rather than replaces, local and sector-specific tools like ecological footprints, chemical safety standards, and species protection measures. By providing global "health metrics" for the whole Planet, the Planetary Boundaries framework enables integration of local and global efforts to address mounting evidence of human-driven Earth system destabilization.

The biophysical Earth system consists of all of the interconnected components of our planet: air, water, ice, land, and all living species. These components constantly interact, forming a large network, where changes in one area can affect the others. Considering the Earth system this way helps us take better care of our Planet. In general, there are three major aspects of today's Earth system that are crucial for humanity to thrive:

The "Health of the Planet" refers to how well the Earth maintains these three key aspects, which are essential for keeping humanity within a "Safe Operating Space". Scientists have defined this space by setting boundaries for critical processes that regulate stability, resilience, and life-support functions.

Stability

The Earth system's ability to maintain relatively constant conditions over long periods, as seen during the Holocene.

Resilience

The Earth's capacity to withstand disturbances and recover from them, such as the ability of a forest to recover from a wildfire disturbance and return to a comparable pre-fire state.

Life-support functions

The essential processes provided by the Earth system that sustain life on our Planet, for example by maintaining temperature ranges suitable for abundant life in many regions or sustaining the water cycles.

Rooted in Earth system science, Planetary Boundaries have been defined for the nine critical Earth system processes identified as crucial for maintaining the Earth system's stability, resilience and life-support systems. The Planetary Boundaries framework also identifies zones of increasing and high risk (Info Box 1). Gradual changes, interactions, or tipping points **(CH. 3.2)** may occur within these zones, becoming more likely the further we move away from the Safe Operating Space. Societies are unprepared for the impacts of a destabilizing Earth system, underscoring the need for monitoring and maintaining PB statuses, in order to prevent further transgressions and ensure global stability. By establishing the objective of adhering to the Planetary Boundaries, Earth's societies can safeguard our planet's resilience and ensure a sustainable future for all life forms.[9] However, the PB processes are significantly influenced by human activities, which have proliferated since the mid-20th century, resulting in the transgression of seven of the nine Planetary Boundaries. This "Great Acceleration"[8] **(● FIG. 2)** raises uncertainties about our global environmental future and emphasizes the urgency of preventing further transgressions.

Recognizing the critical need to monitor and manage these transgressions, the Planetary Boundaries framework was introduced in 2009,[9] and refined in 2015[11] and 2023[10] following significant scientific advancements across all disciplines involved. Since 2024, Planetary Boundaries Science (PBScience) has published an annual report on the health status of our Planet. This report encapsulates the most recent scientific advancements, provides updates based on new insights, and quantifies the status of each of the nine Planetary Boundaries annually. Its primary purpose is to maintain ongoing dialogue and awareness about our planet's health.

Criteria for setting the position of Planetary Boundaries

The position of Planetary Boundaries is determined through a comprehensive assessment of various scientific factors. These assessments consider:

- **Global scientific evaluations, such as those from the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).**
- **Deviations from the Holocene range of variability (SEE CH. 1.1).**
- **Analyses of ecological resilience.**
- **Earth System Model (ESM) simulations.**
- **Expert identification of positive feedback mechanisms (e.g., interactions between forest decline and the carbon cycle).**
- **Potential tipping points.**

By integrating these diverse sources of information, PBs are set to ensure stability and prevent significant disruptions to planetary processes. This precautionary approach aims to maintain the resilience of the Earth system and avoid irreversible environmental damage.

1.3 The Nine Planetary Boundaries

Nine processes have been scientifically identified as key in regulating the stability, resilience, and life-support functions of the Earth system; these are known as the Planetary Boundaries (PBs) processes. To describe the state of these 9 processes, PBs assessments use representative variables, called "control variables". The colors (green for "within the Safe Operating Space", yellow for "Zone of Increasing Risk", and red for "High Risk Zone") refer to the state of boundary transgression; SEE ● FIG. 4. To date, the PBs framework uses 1–2 control variables per PB (SEE ● TABLES IN CH. 7).

1 Climate Change
The alteration of Earth's radiative balance, for example by accumulating greenhouse gases in the atmosphere, affects global temperatures and climate patterns.

2 Change in Biosphere Integrity
The decline in the diversity, extent, and health of living organisms and ecosystems affects the biosphere's ability to co-regulate the state of the Planet by impacting the energy balance and chemical cycles on Earth.

3 Land System Change
The transformation of natural landscapes, such as through deforestation and urbanization, diminishes ecological functions like carbon sequestration, moisture recycling, and habitats for wildlife, all crucial for Earth system health.

4 Freshwater Change
The alteration of freshwater cycles, including rivers and soil moisture, leads to impacts on natural functions such as carbon sequestration and biodiversity, and potential shifts in future precipitation levels.

5 Modification of Biogeochemical Flows
The disruption of natural nutrient cycles, such as nitrogen and phosphorus, affects land biodiversity and water quality, potentially triggering dead zones in freshwater and marine systems.

6 Ocean Acidification
Changes in ocean acidification, impacting marine biodiversity and the ocean's capacity to regulate climate.

7 Increase in Atmospheric Aerosol Loading
The rise in airborne particles from human activities or natural sources influences the climate by altering temperature and precipitation patterns.

8 Stratospheric Ozone Depletion
The thinning of the ozone layer in the upper atmosphere, primarily due to human-made chemicals, increases harmful UV radiation that can reach Earth's surface.

9 Introduction of Novel Entities
The introduction and accumulation of human-made substances, such as plastics and synthetic chemicals, along with the mobilization of naturally occurring elements, can disrupt important Earth system processes and pose risks of permanent damage to life in the biosphere.

For more detailed information on each PB, please refer to their respective Information Sheets included later in this report (CH. 5).

1.4 Planetary Health Check 2026 at a Glance

Seven out of the nine Planetary Boundaries (PBs) have been breached, indicating significant environmental stress and potential for irreversible changes (● FIGS. 3 & 4). These boundaries include:

- **Climate Change:**
  Both the atmospheric concentration of CO_2 as well as the total anthropogenic radiative forcing at the top of the atmosphere have exceeded their safe levels.

- **Change in Biosphere Integrity:**
  Both the loss in genetic diversity as well as in the functional integrity of the biosphere have exceeded their safe levels.

- **Land System Change:**
  The globally remaining forest areas for all three biomes (tropical, boreal and temperate) have fallen below the safe levels.

- **Freshwater Change:**
  Human-induced disturbances of both blue (referring to water in lakes, rivers and reservoirs) and green water (water in soil available to plants) flows have exceeded the safe level.

- **Modification of Biogeochemical Flows:**
  Both the global phosphorus flow into the ocean as well as the industrial fixation of nitrogen (the extraction of nitrogen from the atmosphere) are disrupting the corresponding nutrient cycles beyond the safe level.

Info Box 1

Planetary Boundaries Diagrams

The current state of each control variable is visualized by the length of the wedge in the diagram, showing whether it is within the Safe Operating Space or beyond its PB (indicating PB transgression). Key visual markers are the PB (dark green circle) and the High-Risk Line (thin orange line).

The ● GREEN area represents the Safe Operating Space that provides a high chance of keeping the respective boundary process in a healthy state that can support good, livable conditions on Earth – as long as the control variable's status stays within the PB (dark green circle).

To account for the degree of transgression (the risk level) along with uncertainties arising from limitations in data availability, model capabilities and current understanding of Earth system processes, the range beyond the PB is split into two zones:

The ● YELLOW to ● ORANGE zone indicates a zone of increasing risk, where the respective boundary in question has been surpassed, but the current status of the control variable has not yet reached the High-Risk Zone. Specifically, the likelihood for damage increases as the boundary transgression continues, but it is not yet possible to give a precise description of this increasing risk.

The ● RED to ● PURPLE zone illustrates a high-risk situation, for example a high probability of destabilizing the Earth system due to a very strong boundary transgression.

The potential damage resulting from such a transgression involves losing a Holocene-like Earth system state or substantially eroding Earth system resilience, potentially causing regional to global regime shifts or crossing tipping points (SEE CH. 3.2). Even if the crossing of tipping points can be prevented, PB transgressions may destabilize Earth's life-support systems, undermining their functions across regional to global scales.

For some PB processes, the Zone of Increasing Risk has either not been quantitatively defined (**Introduction of Novel Entities**), or current values remain uncertain (**Change in Biosphere Integrity**). To emphasize this uncertainty, the outer edges of the corresponding wedges are blurred. Nevertheless, existing knowledge is sufficient to place the current values of these control variables for **Introduction of Novel Entities** and **Change in Biosphere Integrity** in the High-Risk Zone.[10]

- **Introduction of Novel Entities:**
  The amount of human-made substances that are released into the environment without adequate testing is above the safe level.

- **Ocean Acidification:**
  The world's oceans are acidifying to an unsafe degree. After recent data and methodological updates, we assess for the first time that the Ocean Acidification boundary has been transgressed.

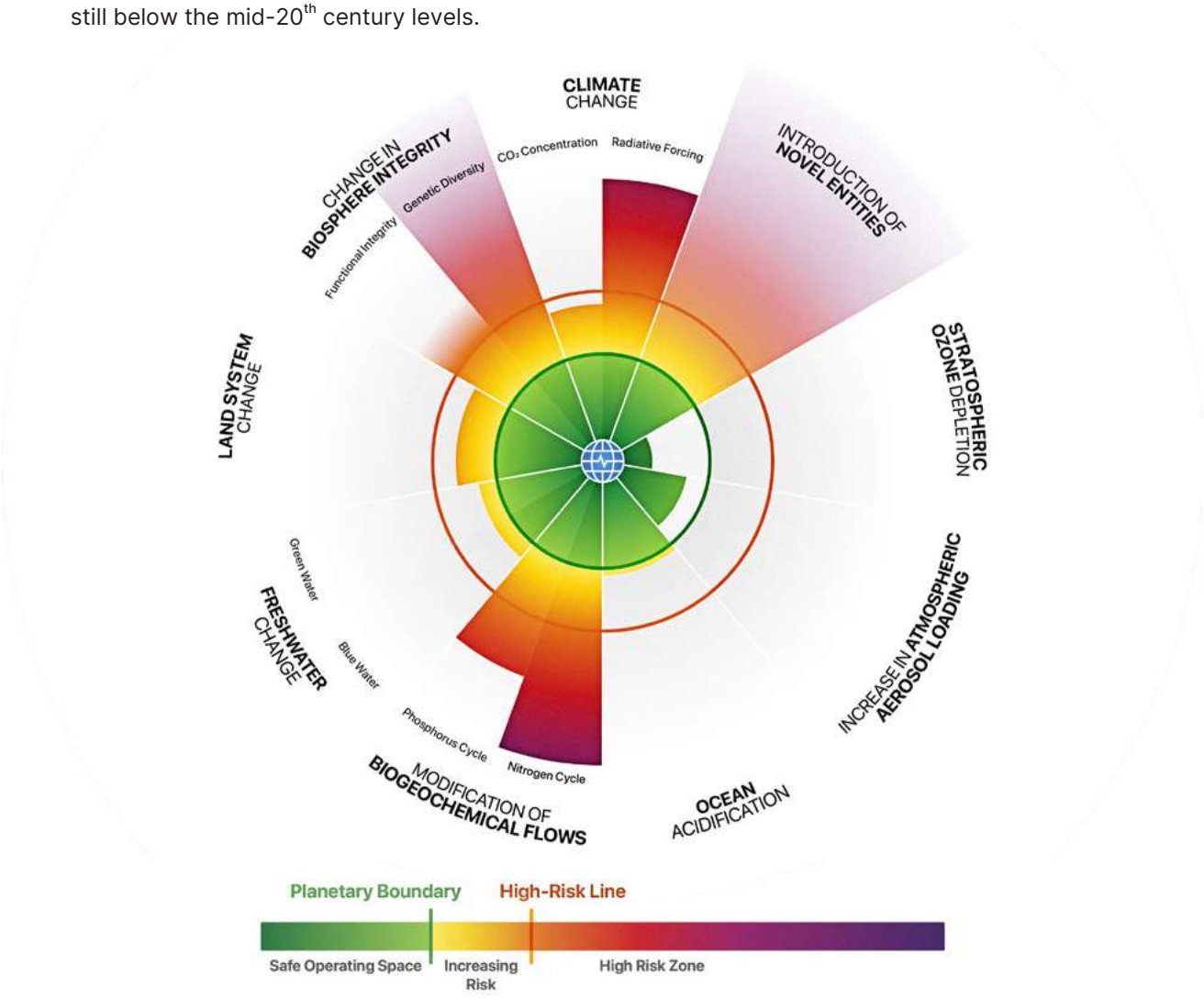
The two remaining PBs that are not transgressed are:

- **Increase in Atmospheric Aerosol Loading:**
  The difference in atmospheric aerosol loading between the two hemispheres of the Earth is within the Safe Operating Space.

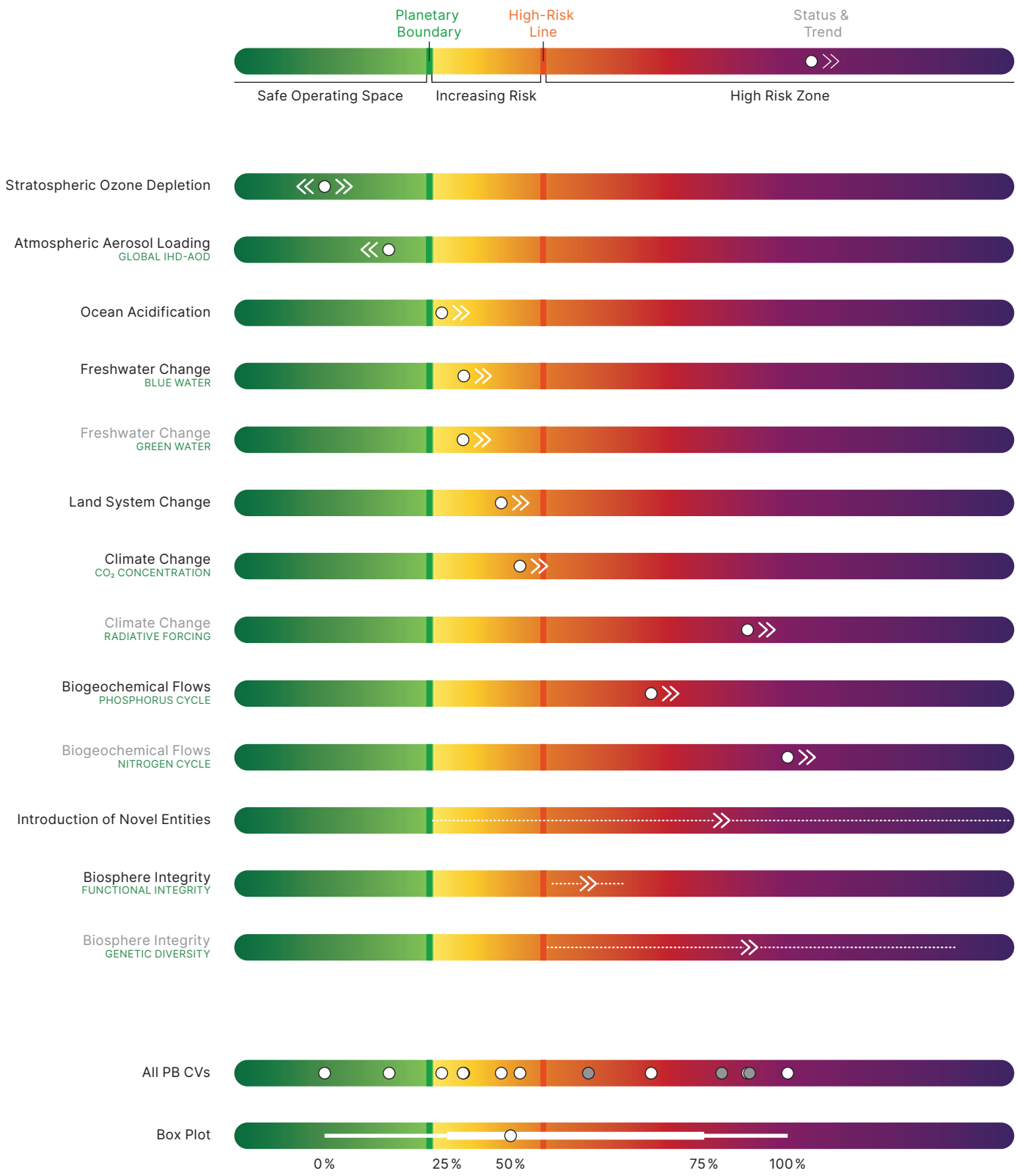
- **Stratospheric Ozone Depletion:**
  The current total amount of stratospheric ozone is within the Safe Operating Space, but values are still below the mid-20th century levels.

The 2026 Planetary Boundaries and Planetary Health Check diagrams

Since the framework was first introduced, the iconic Planetary Boundaries graphic (often called 'radar plot' or 'spider diagram') has been used to show the status of Planet Earth (● FIG. 3). By rearranging the Planetary Boundaries diagram into a collection of bar charts resembling a blood test result, the official Planetary Health Check Diagram (● FIG. 4) opens the possibility to include more details, and further indicators of concern. Extending its list of variables is in the scope of future Planetary Health Checks. The dynamic PHC symbol (● FIG. 5) is a summary of this diagram, in the form of a box plot. How to read the diagrams is explained in Info Box 1.



● FIGURE 3: The iconic Planetary Boundaries (PBs) diagram visually represents the current status of the nine PB processes that regulate our planet's health. Each process is quantified by one or more control variables based on observational data, model simulations and expert opinions.



● **FIGURE 4:** Planetary health at a glance. Just as a blood test provides insights into a human body's health and identifies areas of concern, this Planetary Health Check evaluates the 13 control variables across the 9 Planetary Boundary (PB) processes to report on Earth's stability, resilience, and life-support functions: the overall health of our planet. On the lower colorbar, a classic boxplot summarizes the distribution of all 13 control variable values at once. The boxplot is the dynamic core of the Planetary Health Check symbol (● **FIG. 5**) and denotes the distribution of all current values of PB control variables with the thin line representing the full range, the thicker line the inner 25–75% of control variable values and the dot representing the median of all control variable values.

The dynamic Planetary Health Check symbol

Our overall assessment of all nine Planetary Boundaries shows that the Planet's health in 2026 lies near the upper end of the Zone of Increasing Risk, close to the High-Risk Zone (● FIG. 5). At this level, the likelihood of large-scale and potentially irreversible changes across the Earth system is already substantial. Earth's remarkable biological, physical, and chemical resilience still leaves a window for returning to the Safe Operating Space, but evidence of accelerating warming and signs of weakening carbon sinks show that this window is closing rapidly.

● FIGURE 5: The dynamic Planetary Health Check symbol represents the summary of each year's findings. The stylized boxplot (white lines and blue dot) describes the distribution of all PB control variables (which are individually shown in ● FIG. 3 and 4). The thin line represents the full range of all control variable values, the thicker line represents the 25–75% range of all control variable values and the dot represents the median of all control variable values.

1.5 What's New in the 2026 Planetary Health Check

Each Planetary Health Check updates the formal Planetary Boundaries assessments where suitable new data or methodological advances are available. It also presents new supporting evidence and explores scientific developments that may inform future revisions of the framework.

The advances in the 2026 edition fall into three categories. First, **report-wide advances** concern the format, analytical transparency and overall framing of the assessment. Second, three **Spotlights** provide deeper syntheses of emerging Earth-system risks that extend beyond the annual boundary assessments. Third, the **boundary-by-boundary overview** summarizes the specific changes made to each information sheet, distinguishing updates to control-variable data and methods from additional evidence, visualizations and future research directions.

Report-wide advances

The following developments affect the presentation, evidence base or analytical approach of the report as a whole:

- **Two complementary report formats:** For the first time, the Planetary Health Check is published as both a comprehensive scientific report and a shorter *Summary Version* designed for a broader audience. The two versions present the same assessment but provide different levels of methodological detail and scientific context.

- **A broader and more transparent evidence base:** Several information sheets now present multiple independent datasets or indicators alongside one another. Examples include additional estimates of Human Appropriation of Net Primary Production for Biosphere Integrity and four annually updated ocean-carbonate datasets for Ocean Acidification. A growing share of the underlying data-processing workflows is also being incorporated into a digital assessment platform that combines the data, methods analysis steps used in the Planetary Boundaries assessment (PB Analyzer[23]). This makes the annual updates more transparent, traceable and reproducible.

- **Clearer distinction between the current assessment and future development:** The 2026 report more clearly separates changes to the formal Planetary Boundary assessments from emerging scientific directions that could inform future revisions. These include marine biosphere indicators, atmospheric moisture-recycling analyses, broader measures of ocean integrity and more actionable approaches to assessing Novel Entities.

- **Greater attention to regional Earth-system risks:** Alongside the global assessment, the report introduces a regional aerosol assessment for South

Asia, where high aerosol loading can disrupt monsoon rainfall even though the global boundary remains within the Safe Operating Space.

- **A stronger Earth-system perspective:** The report places greater emphasis on how the Planetary Boundaries interact and jointly shape Earth-system resilience. This includes the dependence of climate stability on functioning land, freshwater, ocean and biosphere systems, as well as links among nutrient pollution, deoxygenation, atmospheric circulation and ecosystem functioning.

Planetary Boundary	What is new in 2026?	Assessment implication
Climate Change	· **Updated control-variable data:** CO_2 concentration is 426 ppm and radiative forcing is +3.10 W/m^2. · **New supporting data:** A CERES time series shows Earth's energy imbalance from March 2000 to January 2026; the CO_2 emissions map now has a resolution of 0.1° instead of 1.0°.	Both control variables remain beyond their respective Planetary Boundaries.
Change in Biosphere Integrity	· **Additional data sources:** Several HANPP estimates are now shown, giving a range of 21–30%; all place functional integrity in the High-Risk Zone. · **Future development:** Selected IPBES indicators and approaches for including marine biosphere integrity are presented.	The broader evidence base does not change the risk classification. The IPBES and marine indicators are not yet part of the formal assessment.
Land System Change	· **No new control-variable data:** The satellite forest-cover data still extend to 2022. · **Improved classification and data use:** Mixed potential forest is now divided more accurately into boreal and temperate forest using temperature data. Two previously omitted ESA forest-cover classes are also included, increasing the estimated current forest cover from approximately 59% to 64%. · **Corrected global boundary:** Double counting in the aggregation of biome thresholds has been removed, changing the global boundary from 75% to 78%.	The methodology, current value and global threshold have been revised, but the boundary remains transgressed. The improved numerical status reflects the corrected calculation and more complete use of existing data, not actual forest recovery.
Freshwater Change	· **Updated publication basis:** The same 1901–2019 analysis and values of 22.6% for blue water and 22.0% for green water are now based on the published Virkki et al. (2026) study and data release. · **New discussion:** Operationalization, impact assessment, regional validation and moisture recycling are addressed.	Both control variables remain beyond their respective Planetary Boundaries. The evidence base is more traceable, but the data period and formal assessment are unchanged.
Modification of Biogeochemical Flows	· **No new control-variable data:** Current values remain 165 Tg N/yr and 18.2 Tg P/yr. · **Refined analysis:** The nitrogen Zone of Increasing Risk map has been recalculated using nitrogen surplus; new research topics include ammonia fuel, phosphorus assessment and freshwater deoxygenation.	Both nutrient boundaries remain strongly transgressed. The spatial analysis has improved, but the formal global assessment is unchanged.
Ocean Acidification	· **Additional data sources:** CMEMS-LSCE-FFNN, ETHZ OceanSODA and JMA-MLR are now shown alongside UExP-FNN-U. · **Updated synthesis:** All four products extend through 2024; new maps compare 1750 and 2024, and the discussion considers broader Ocean Integrity indicators.	The additional products strengthen the evidence base. The boundary remains transgressed, with a current value of approximately 2.85.
Increase in Atmospheric Aerosol Loading	· **New regional assessment:** South Asian AOD is approximately 0.32, exceeding the proposed regional boundary of 0.25; a new figure shows global AOD.	The global boundary remains within the Safe Operating Space, while the proposed regional boundary for South Asia is transgressed.
Stratospheric Ozone Depletion	· **No new control-variable data:** The series still ends in 2022, with a current value of 285.7 DU. · **Expanded discussion:** New material addresses Southern Hemisphere trends, vertical ozone structure and emerging risks such as space-debris re-entry.	The boundary remains within the Safe Operating Space. The control variable and formal assessment are unchanged.
Introduction of Novel Entities	· **Updated supporting data:** Antibiotic-production data have been replaced by antimicrobial resistance data and a new graph. · **Methodological development:** The chapter discusses a more actionable future control variable.	The boundary remains transgressed. The new dataset provides supporting evidence but does not constitute a numerical update of the formal control variable.

● **TABLE 1.1:** Boundary-by-boundary: What's new in the 2026 information sheets. The table distinguishes updates to control-variable data from additional datasets, methodological changes and expanded scientific discussion. The middle column identifies what has changed in each information sheet, including whether new data, additional data sources, methodological revisions or expanded scientific discussions have been introduced. The final column clarifies whether these changes affect the formal boundary definition, current control-variable value or risk classification.

Spotlights: Emerging risks and Earth-system responses

Alongside the annual assessment of the nine Planetary Boundaries, the 2026 report includes three spotlight chapters. These chapters do not introduce new formal boundaries or control variables – instead, they synthesize emerging evidence on important Earth system processes and pressures that cut across several boundaries or indicate priorities for governance and future research.

- **Earth Resilience: When Land Stops Buffering Climate Change** examines evidence that the land carbon sink may be weakening and explains why current Earth system models could overestimate the capacity of ecosystems to continue absorbing carbon under intensifying climate and ecological pressures.
- **Seafloor Integrity: Why the Bottom of the Ocean Matters** synthesizes emerging evidence on the seafloor's role in biodiversity, nutrient cycling and carbon storage. It assesses growing pressures from bottom trawling, mining and infrastructure, and reviews the governance challenges involved in protecting the seafloor.
- **Novel Entities: Known Impacts and Unknown Planetary Threats** traces the pathway from the production and release of chemicals and materials to environmental exposure and ecosystem impacts. It highlights both established damage and the potentially larger risks posed by chemical pollution that remain poorly understood.

Boundary-by-boundary updates

The extent and nature of the updates differ among the nine Planetary Boundaries because the underlying datasets are released at different frequencies. For some boundaries, new annual observations or updated control-variable values are available. For others, the 2026 assessment adds independent datasets, improves the use or classification of existing data, corrects a calculation, or expands the scientific interpretation without extending the underlying observation period.

Photography by Maxar Technologies

2 | Challenges of Diagnosing the Earth System

Photography by Maxar Technologies

2.1 Assessing Planetary Boundaries

Assessing Planetary Boundaries requires combining many different kinds of scientific evidence. No single observing system can capture all nine boundary processes. Some control variables can be measured relatively directly, while others must be estimated by combining observations with models. Scientists therefore use instruments ranging from satellites orbiting high above the Earth's surface to sensors deployed in soils, rivers, oceans, and the atmosphere, together with simulations performed on high-performance computers.[24] The choice of methods depends on several factors, such as the component of the Earth system under assessment and the availability of observational data. Since observational records are often short, with historical data frequently lacking, model simulations become necessary to extend temporal coverage and generate consistent estimates of PBs over longer periods.[25]

Essential data sources for assessing and monitoring our planet, particularly within the PBs framework, are:

- **Earth system modeling**
  Earth-system models simulate the physical behavior and interactions among the atmosphere, oceans, land, ice, and biosphere. They help scientists estimate variables that cannot be measured directly, fill gaps between observations, and examine changes over periods extending beyond the observational record. Models are essential for assessing several PBs, but the accuracy of their results depends on the processes represented, the input data used, and the assumptions made.[26]

- **In-situ observations**
  These measurements are collected directly at the location of interest. For example, at weather stations, from soil-moisture sensors, through river-gauging networks, or from instruments measuring ocean chemistry. Because of this direct, on-site collection, they can provide highly detailed and accurate information at specific locations. However, in-situ observation networks are unevenly distributed, can be expensive and labor-intensive to maintain, and often provide limited coverage of remote regions and the open ocean.[27]

- **Satellite-based remote sensing**
  Remote sensing (RS) refers to collecting data using satellites, aerial, or ground-based platforms. For example, RS techniques can be used to monitor variables such as forest cover and ecosystem health. Among the range of observation scales, satellite-based RS is particularly relevant for PB assessments, since these are conducted at the global scale. RS provides extensive and continuous coverage in both space and time, with some records spanning several decades. Nevertheless, some variables cannot be observed directly and are therefore considered hybrid, requiring integration with other methods to obtain a comprehensive assessment.[28]

- **Reanalysis data**
  Reanalysis integrates observations from many sources (e.g., including satellite-based RS and in-situ measurements) with a numerical model to produce a spatially and temporally complete reconstruction of past environmental conditions. Reanalysis products are particularly valuable where direct observations contain gaps. However, they are not observations alone, since their results reflect both the available measurements and the model used to integrate them.[29]

Using geospatial artificial intelligence to monitor the planet

Geospatial artificial intelligence (GeoAI) presents a promising avenue for integrating geospatial data and supporting more timely and detailed Earth system assessments.[30–32] These novel techniques can process high-frequency, high-volume data streams from satellites and ground sensors, as well as socio-economic data, to identify anomalies, forecast changes, and uncover patterns across vast areas. GeoAI-supported systems are already transforming how we monitor key environmental changes. Applications include near-real-time daily CO_2 emissions estimates,[33] above ground biomass mapping,[34] ecosystem stress detection, and more. Using GeoAI techniques to combine satellite data, historical climate records, and information on human activities could improve how quickly and precisely we can monitor changes across the land, ocean, atmosphere, and biosphere.

Realizing this potential, however, requires scientific rigor, transparency in the choice of methods and data, high interpretability, and high reproducibility. It also requires closing observational gaps, especially in low- and middle-income regions. This

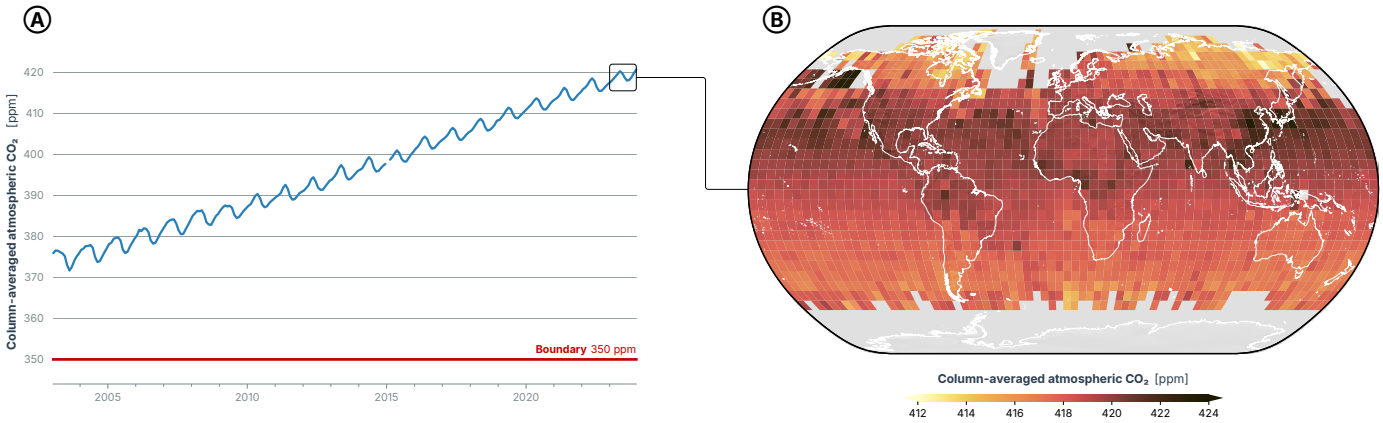
can be achieved through a more equitable data infrastructure as well as by including local stakeholders in the infrastructure design process. These aspects become even more relevant in high-stakes situations, such as climate-related hazards, where decisions can directly affect people's lives.[35] Therefore, validated, open access, and harmonized data streams whose uncertainties are known and quantified will be imperative to build trustworthy AI-supported insights as we move toward more timely monitoring of Planetary Boundaries.

In this context, one of the primary objectives of the Planetary Boundaries Science (PBScience) Lab is the evolution of the PBAnalyzer into a full Planetary Boundary intelligence system.[36] This system aims to harness advanced AI approaches (e.g., large language models and GeoAI models) to analyze and integrate different types of data – delivering annual, and ideally near-real time, assessments of PBs. Thus, such a functional and integrated system can provide the best available evidence to researchers, policymakers, and stakeholders across all Planetary Boundaries. In doing so, it can serve as a decision-support aid to better protect humanity and the Planet.

From atmosphere to biodiversity: illustrative remote sensing applications

Remote sensing provides a powerful set of tools for monitoring environmental changes relevant to the Planetary Boundaries. The following examples focus on satellite-based remote sensing, while recognizing that some of the resulting datasets also incorporate in-situ observations, modeling, or reanalysis.

Atmospheric CO_2 concentration: This dataset provides atmospheric CO_2 observations derived from satellite measurements. With a spatial resolution of 5° × 5°, corresponding to approximately 555 km × 555 km at the equator, with the longitudinal dimension decreasing with increasing latitude. The data captures how atmospheric CO_2 is distributed and evolving across the globe over time as shown in ● **FIGURE 6**. It offers a single representative CO_2 value averaged across the entire atmospheric column referred to as XCO_2 (i.e., observed CO_2 from the Earth's surface to the top of the atmosphere). These satellite-based observations, which have been validated through comparison with in-situ measuring stations, extend coverage to large parts of the world that are otherwise unobserved.

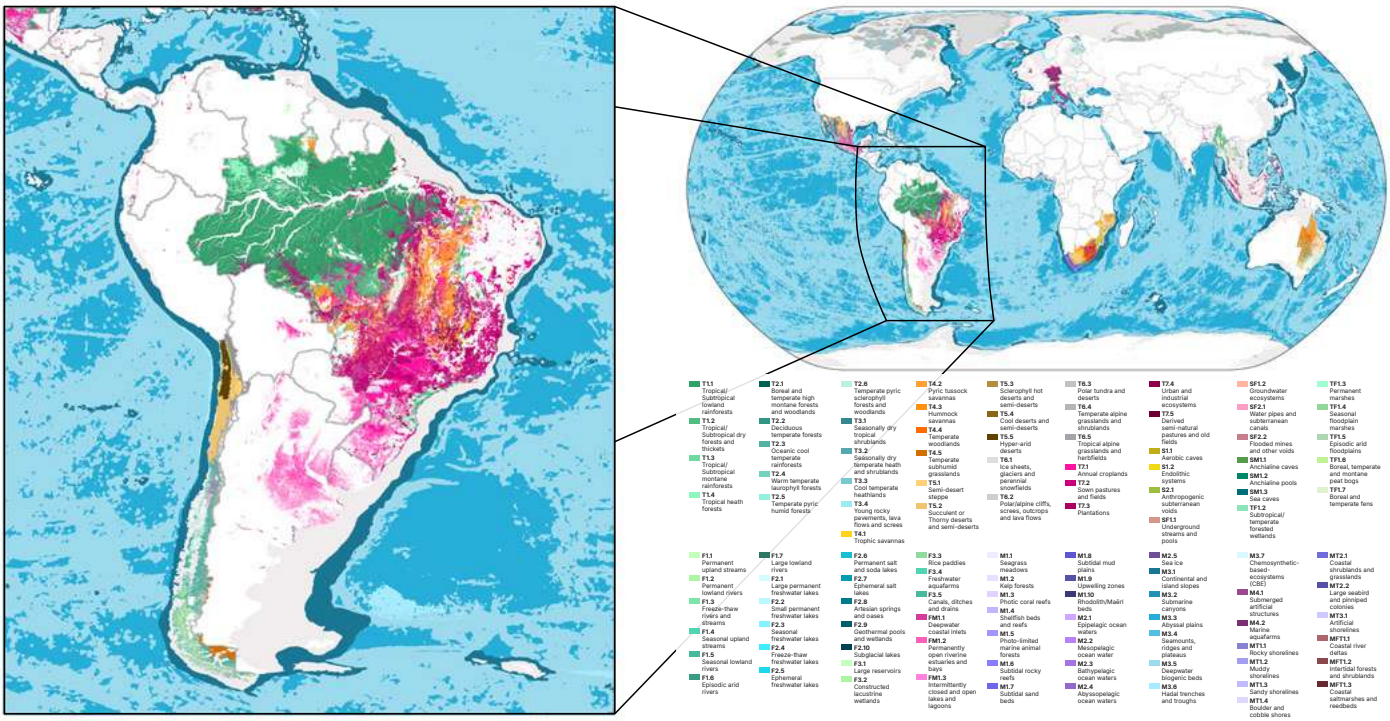


● **FIGURE 6:** Panel (A) presents the global mean column-averaged atmospheric CO_2 concentration (XCO_2) over land from 2003 to 2023, based on satellite observations with a spatial resolution of 5° × 5°. Panel (B) shows the spatial distribution of XCO_2 across both land and ocean for the year 2023. Overall, the data shows a sustained increase in atmospheric CO_2 concentrations between 2003 and 2023. The use of land-only XCO_2 in panel (a) is motivated by data availability, as earlier satellite-based observations are primarily restricted to land surfaces, while combined land and ocean coverage becomes consistently available from 2009 onward. Additionally, the dataset is currently updated through 2023; more recent years will be incorporated once the corresponding processing and validation steps are completed. See reference [37] for the data and additional information.

Global Ecosystems Atlas: This dataset represents the distribution of the world's ecosystems, developed through a synthesis of existing geospatial datasets, in-situ observations, and satellite remote-sensing data. GeoAI techniques are used to help classify ecosystems and fill spatial gaps in the available information **(SEE ● FIG. 7)**. The Atlas aims to provide a map with a spatial resolution of 100 m × 100 m, covering 110 ecosystem classes across all realms of the biosphere (terrestrial, marine, subterranean, and freshwater). The deployed GeoAI techniques are exploiting a globally distributed set of ecosystem functional group occurrence records using the forthcoming "EcoTrain" open access training and validation dataset. The Atlas currently represents the distribution of ecosystems at a particular point in time rather than changes through time. Once completed, it could provide an important spatial basis for assessing ecosystem extent and supporting future monitoring.

The way forward

Due to the size and complexity of observing the whole planet, PBScience collaborates with partners across the different Earth-observation communities to access data, methods, and expertise. One of our main goals is to ensure that the PHC is based on frequent, high-quality data streams for each of the PB control variables. Annual updates are the immediate priority, while more frequent status updates may become possible for some variables as observation systems and analytical methods continue to improve. In this report, we present some of the most up-to-date data sources currently available **(SEE ALSO ● TABLE 7.2 IN CH. 7)**. We are committed to improving and increasingly automating the assessment and monitoring workflow, and are actively seeking new partners for Earth system analysis. Therefore, PBScience welcomes collaboration with partners who can help close observational gaps, validate emerging indicators, and strengthen the long-term monitoring of the Planetary Boundaries.



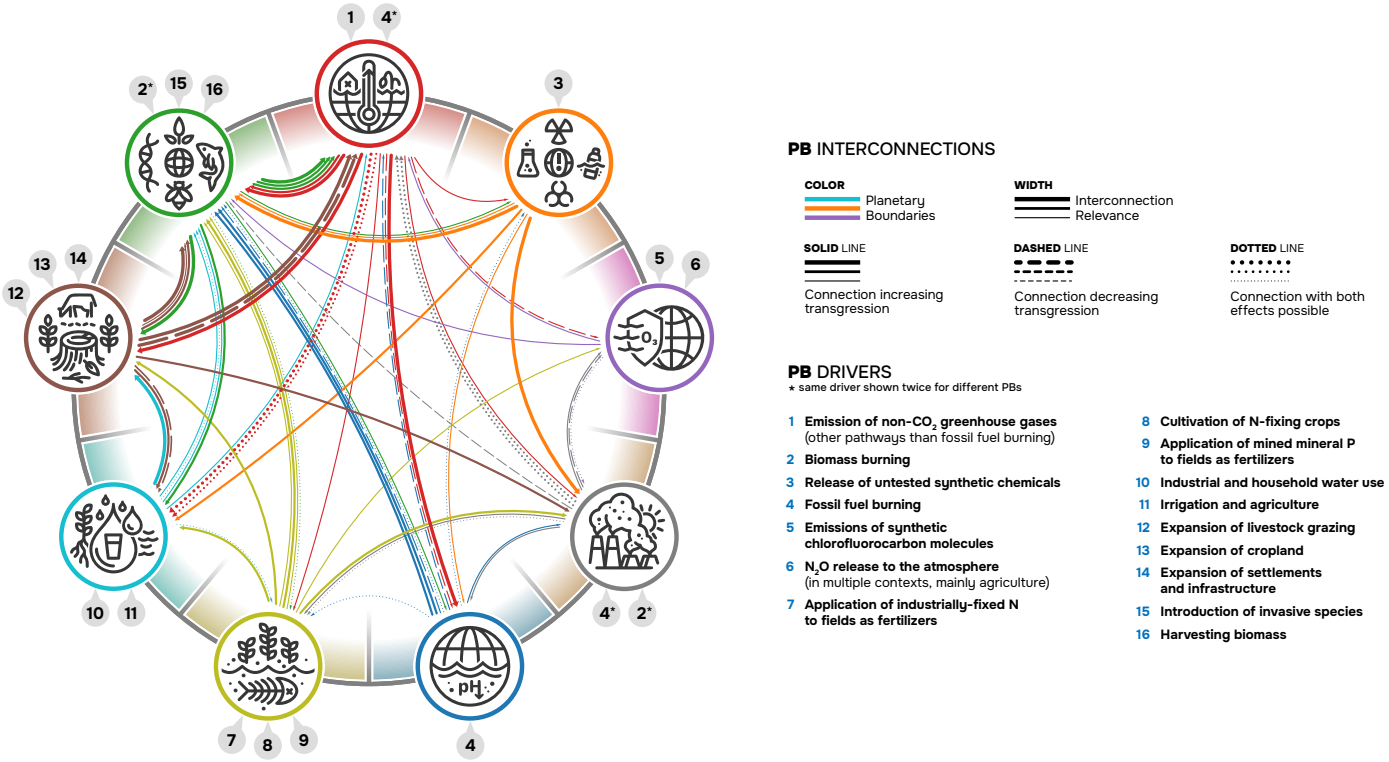
● **FIGURE 7:** The figure shows the ongoing Global Ecosystem Atlas (GEA) effort to map 110 ecosystems across all realms of the biosphere (terrestrial, marine, subterranean, and freshwater) with the spatial resolution of 100 m × 100 m. This product is synthesized based on collected ground surveys as well as satellite-based RS data supported by AI methods. At the time of writing, approximately 58% of the intended global coverage has been completed, and work towards full global coverage is continuing.[38]

2.2 One Earth System: Why Planetary Boundaries are Connected

The nine Planetary Boundaries are often presented as separate segments of a circle. This separation is useful: it allows scientists to identify critical Earth system processes, select measurable control variables and assess where risks are increasing. In the Earth system itself, however, there are no walls between the boundaries. Climate, water, land, the ocean, the atmosphere and the biosphere are continuously connected through flows of energy, moisture, carbon, nutrients and living organisms.[9–11] The Planetary Boundaries framework has recognized this interdependence from the beginning. Boundary levels are precautionary guardrails for individual processes, but their positions have largely been assessed under the simplifying assumption that other boundaries are not substantially transgressed.[9,10] In reality, transgressing one boundary may increase pressure on another or change the level of risk associated with it. A network analysis of the nine boundaries found that their interactions and feedbacks predominantly amplify human impacts, potentially narrowing the Safe Operating Space compared with an assessment that treats every boundary independently.[39]

Shared drivers, different consequences

Planetary Boundaries are connected in two important ways. First, several boundaries share the same underlying human drivers. Burning fossil fuels, for example, contributes directly to **Climate Change** and **Ocean Acidification**, and is a major source of **Atmospheric Aerosol Loading**. Agriculture and land conversion affect **Land System Change**, Biosphere



● **FIGURE 8:** Planetary Boundaries form an interconnected causal network. The diagram shows the most significant and best-understood interactions among Planetary Boundary (PB) processes, together with major human drivers of boundary transgression. Arrows indicate the direction of an interaction, with their color identifying the source PB process. Arrow width represents the estimated relative strength of the interaction, while line style distinguishes reinforcing, dampening, and mixed or context-dependent effects. Numbered drivers can affect several PB processes simultaneously. The network is selective rather than exhaustive and reflects current scientific understanding.

KEY TAKEAWAY: Planetary Boundaries can be assessed separately, but they do not function independently. Interactions can amplify risks across the Earth system, while shared drivers can push several boundaries at once. Understanding these connections is therefore essential for identifying actions that create benefits across multiple boundaries without shifting pressure from one part of the Earth system to another.

Integrity, Freshwater Change and **Modification of Biogeochemical Flows** while also contributing to **Climate Change**.[10,11] Material production and waste introduce **Novel Entities** that can affect organisms, ecosystems and biogeochemical processes.

Second, the Earth system processes represented by the boundaries interact with each other after these pressures have been introduced. **Climate Change** alters rainfall and temperature and changes the frequency and intensity of disturbances such as droughts, wildfires, floods, storms and pest outbreaks, affecting forests, freshwater systems and biodiversity. In turn, forest loss changes carbon storage, evapotranspiration, surface reflectivity and regional moisture recycling, feeding back on climate and water availability.[40–42] Nutrient loading can degrade rivers, lakes and coastal seas, trigger oxygen loss and alter biological processes that regulate carbon and nutrient cycling.

Distinguishing these two forms of connection is important. Two boundaries may deteriorate together because they share a human driver, because one physically affects the other, or through a combination of both. Understanding the mechanism helps identify whether an intervention is addressing the root cause, interrupting a damaging feedback or merely treating one visible symptom.

Interactions can amplify risk

Recent modeling studies provide increasingly quantitative evidence of these relationships. Simulations of the **Climate Change** and **Land System Change** boundaries show that maintaining atmospheric carbon dioxide within its safe boundary can help stabilize the extent of major forest biomes. Increasing transgression of the **Climate Change** boundary, in contrast, causes progressively larger shifts in forest distributions and pushes the **Land System Change** boundary farther into the risk zone. These changes also affect habitat structure and soil moisture, and in turn influence the climate through carbon, water and energy exchanges.[43]

Complementary Earth system simulations show the other side of this relationship: extensive land-system transgression can produce warmer and drier conditions, reduce vegetation carbon stores and alter the exchange of water and energy between the land and atmosphere. Scenarios in which pressures on both climate and land were reduced produced benefits for carbon storage and global temperature.[44]

These results do not yet allow scientists to recalculate every Planetary Boundary as a precise function of the other eight. Many interaction strengths remain uncertain, and some effects vary among regions and over time. They do, however, support a crucial conclusion: **The risk associated with the state of one boundary can depend on the state of others.**

Multiple pressures weaken resilience

Interactions also matter because several pressures can converge on the same component of the Earth system. A forest may simultaneously experience warming, changing rainfall, clearance, fragmentation, fire and biodiversity loss. Marine ecosystems may face warming, acidification, deoxygenation, nutrient loading, overexploitation and chemical pollution at the same time. Together, these pressures can reduce the system's capacity to absorb the others and recover from disturbance.[45–47]

This connects Planetary Boundaries directly to Earth system resilience and tipping risk. Boundaries identify conditions intended to keep risk low; resilience describes the capacity of Earth system components to withstand pressure; and tipping points describe potentially self-reinforcing changes once that capacity is overwhelmed.[48,49] A major review of climate tipping interactions concluded that the documented links among ice sheets, ocean circulation, forests, monsoons and permafrost are predominantly destabilizing. Tipping cascades cannot be ruled out, although their likelihood, sequence and timing remain highly uncertain.[49]

The significance of these interactions is therefore not that every boundary transgression will immediately trigger an abrupt change. Rather, multiple transgressions can progressively erode the buffers that have helped maintain a relatively stable Earth system.

Solutions can create synergies – or shift pressure elsewhere

Interconnections are not only a source of risk. They also mean that well-designed interventions can generate benefits across several boundaries. Protecting ecosystems can conserve biodiversity while supporting carbon storage, moisture recycling and water regulation.[40,50] Transforming food systems can reduce land conversion, fertilizer losses, water demand and greenhouse-gas emissions.[51,52] Phasing

out fossil fuels simultaneously reduces pressure on climate, ocean chemistry and air pollution.

However, an intervention that benefits one boundary is not automatically safe for the Earth system as a whole. A 2025 modeling study found that land-based climate-mitigation measures – including increased bioenergy supply, the protection and restoration of forests and peatlands, and improved agricultural management – reduced transgression of the **Climate Change, Land System Change, Biosphere Integrity** and nitrogen boundaries but, through greater irrigation demand, increased freshwater boundary transgression by 94%. Adding dietary change and reduced food waste improved outcomes across all five assessed boundaries.[53]

A broader scenario analysis similarly found that coordinated action on climate, diets, land, water and nutrient efficiency could substantially reduce pressure across eight assessed boundaries. Nevertheless, **Climate Change, Biosphere Integrity** and **Modification of Biogeochemical Flows** remained outside their Safe Operating Space in 2050, partly because environmental systems respond slowly and some losses cannot be rapidly reversed.[52] The Montreal Protocol offers an encouraging example of positive cross-boundary action. Controlling ozone-depleting substances enabled recovery of the stratospheric ozone layer while also avoiding substantial additional warming, since many of these substances are powerful greenhouse gases.[54]

Maintaining the Safe Operating Space as a whole

The Planetary Boundaries should continue to be measured individually: combining them into a single score would conceal important differences in mechanisms, spatial patterns, uncertainty and reversibility. But they cannot be managed as nine independent policy targets.

Understanding their connections helps us to:

1. recognize when a transgression increases risk elsewhere;
2. address shared drivers rather than isolated symptoms;
3. identify interventions that create benefits across several boundaries;
4. detect trade-offs before pressure is transferred from one Earth system process to another.

The Safe Operating Space is ultimately a property of the Earth system as a whole. Safeguarding it therefore requires keeping all Planetary Boundaries in view – using their individual assessments as complementary indicators of the health, resilience and stability of one interconnected planet.

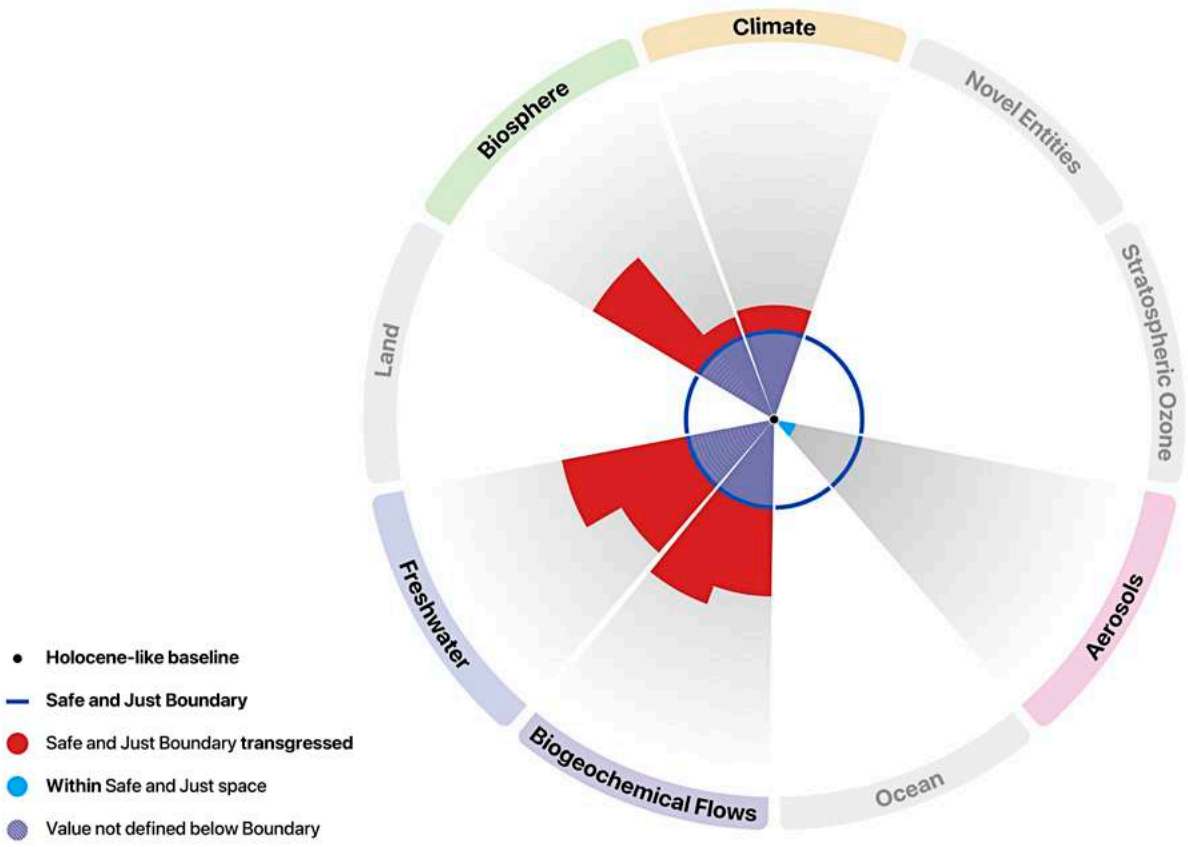
Photography by NASA

2.3 From Safe to Safe and Just Operating Space

Building on the Planetary Boundaries framework, the Earth Commission published its concept of "Safe and Just Earth System Boundaries" in 2023.[55] This framework adds the dimension of justice – establishing additional thresholds designed to avoid significant harm to people and ecosystems, while safeguarding Earth's resilience. Furthermore, it defines minimum levels of access to essentials for a dignified life. Together, these three elements (safe and just boundaries, as well as access levels) define the safe and just space where humanity can equitably thrive, reflecting the deep connection between planetary health and human well-being.

The addition of justice considerations effectively results, for a few of the boundaries, in more stringent quantifications compared to the "safe" thresholds that are designed to ensure only the stability of the Earth system. For example, while a global temperature rise of 1.5°C is defined as the safe boundary to avoid irreversible changes on Earth due to **Climate Change**, vulnerable communities already face severe climate-related impacts below this threshold. Accordingly, the just boundary is set at 1.0°C of warming, which is already significantly higher than the warmest temperature on Earth since human civilization began evolving.

Though the Safe and Just Boundaries are based on the Planetary Boundary domains, the corresponding control variables, boundary thresholds and measurements were developed independently. Despite this difference in implementation, a comparison of the respective results (SEE ● FIG. 9) shows that the frameworks broadly agree on boundary transgressions – demonstrating the robustness of the two approaches.



● FIGURE 9: Safe and Just Earth System Boundaries. This framework was developed by the Earth Commission based on the Planetary Boundaries and so far has only assessed 5 of the 9 PBs.[55] This figure uses a different normalization strategy than the Planetary Boundaries diagram shown in this report. However, it is clear that both frameworks agree which boundaries are transgressed.

3 Today's Impacts and Tomorrow's Risks

Photography by Maxar Technologies

3.1 Extreme Weather Events of 2025 and 2026

Extreme weather events are one of the starkest signs that we are bringing Earth out of balance. Floods, droughts, heatwaves, and storms are becoming more frequent or more intense in many parts of the world, demonstrating the concrete and destructive consequences of changes in the Earth system. They show that the effects of transgressing Planetary Boundaries are not confined to distant projections: They are already shaping conditions today and, in many cases, increasing the risks faced by societies and ecosystems.

Whether, and by how much, human-induced climate change has altered the likelihood or intensity of a particular extreme is answered by the science of extreme event attribution. Many methods have been developed, differing in detail.[56,57] However, they all compare the likelihood and/or intensity of an extreme weather event today, in a world with climate change, and the same event in a world without human-induced climate change. These estimates are based on climate models and weather observations.[56,58] The science has developed rapidly over the last decade, highlighted by the AR6 Synthesis Report of the IPCC, which states "evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts and tropical cyclones, and, in particular, their attribution to human influence, has further strengthened".[59]

The effects of Climate Change are relatively easier to quantify, largely because greenhouse gases are well mixed in the atmosphere, irrespective of where they are emitted. Their climatic influence is therefore global and can be modeled with a reasonable degree of consistency and confidence. In contrast, the effects of other Planetary Boundary transgressions – such as **Land System Change**, **Change in Biosphere Integrity**, or **Freshwater Change** – tend to have more local effects on extreme events. Although no less dangerous, their impacts can be more challenging to disentangle in attribution studies.

To give an overview of recent extreme weather events, we identify the ten highest-impact events from April 2025 to April 2026, based on three categories: (i) total number of deaths, (ii) total number of people affected, and (iii) total economic damage. The result is a set of 21 unique events, which are listed in ● **TABLE 3.1** and mapped in ● **FIG. 10**. For each event, we assess whether human-induced Climate Change has increased its likelihood or intensity. This assessment is based on event-specific attribution studies where available, and otherwise on evidence from similar events (referred to as "causal field" attribution).

The lists show some overlap: Several events appear in multiple impact categories, and some entries describe the same event spanning multiple countries. Most notable among these are the floods in Pakistan and Tropical Cyclone *Senyar*, which struck Indonesia and surrounding countries and had huge impacts across all three categories. Interestingly, no heatwave appears in the top ten of any category this

Data source

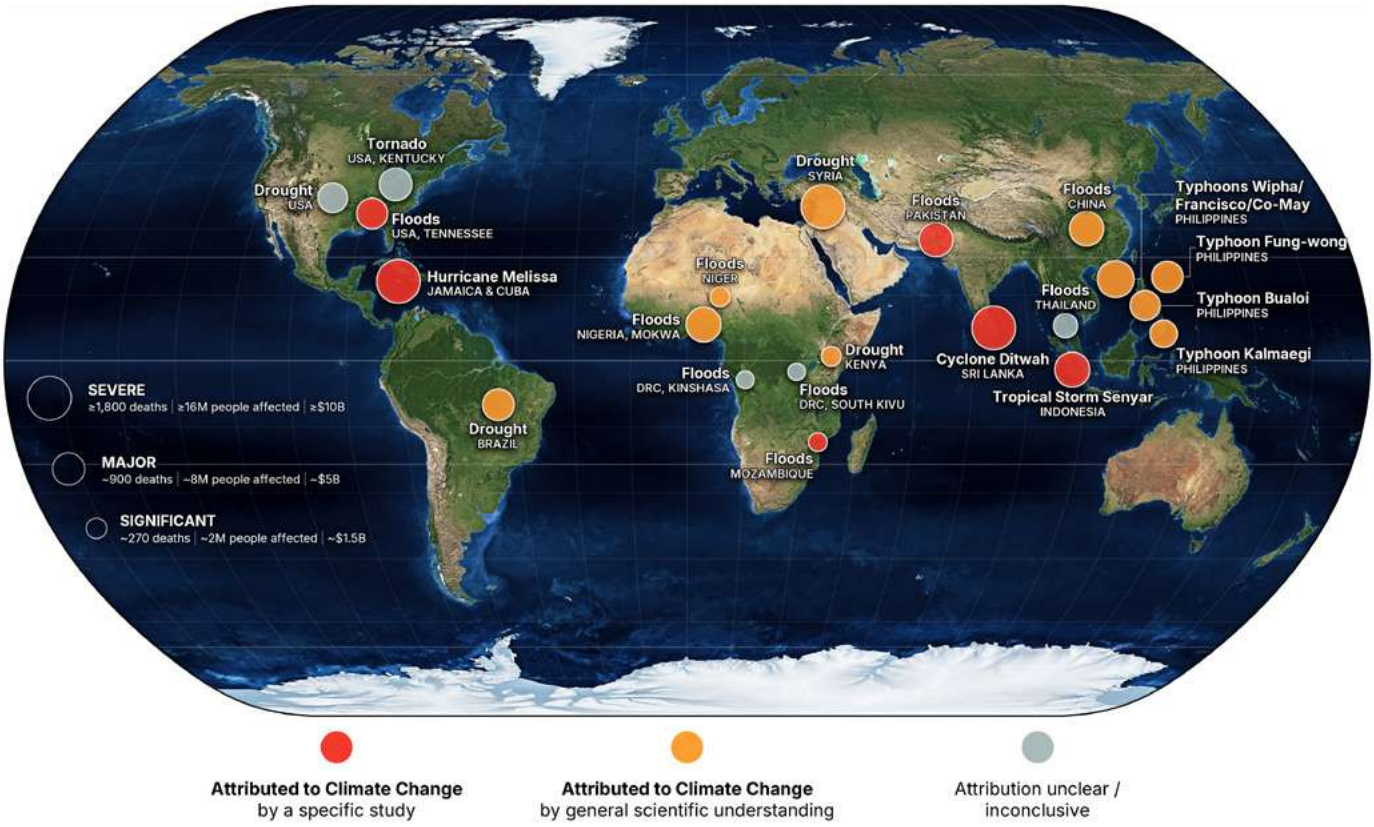
The analysis presented here is based on the Emergency Events Database (EM-DAT), maintained by the Centre for Research on the Epidemiology of Disasters. EM-DAT is the longest-running and most widely used global disaster database.[61,62] Established in 1988, it systematically records disasters worldwide, providing standardized data on fatalities, affected populations, and economic losses across meteorological, hydrological, geophysical, climatological, and biological hazards. EM-DAT applies clear inclusion criteria to ensure consistency over time. Despite its global coverage, EM-DAT has important limitations.[63,64] It relies on official statistics, which often lag behind by years and vary substantially across countries and event types. For example, EM-DAT records 60,000 and 50,000 European heat deaths in 2022 and 2023, respectively, but hardly any heat deaths in the rest of the world for those years. Consequently, heat-related death tolls and economic damages are severely underestimated in the database, probably by orders of magnitude. Nevertheless, EM-DAT remains a key resource for global disaster risk research and international assessments.

year. This could simply be due to chance, but it may also point once again to reporting bias, as heat waves are still dramatically under-reported in most of the global South.[63,65] More broadly, it is striking how few events have *not* been made more severe by climate change. This is especially true since "causal field" attributions are more likely to *under*estimate the influence of climate change than to overestimate it.[60] For example, the influence of climate change on tornado formation remains somewhat uncertain, and gaps in data collection (e.g., due to political instability such as in the Democratic Republic of the Congo) sometimes make firm conclusions difficult.

Some patterns echo last year's assessment.[23] In particular, the Philippines continues to be repeatedly hit by typhoons, underscoring how climate change is increasingly shaping risk in the region. Another standout event is Hurricane *Melissa*, which caused very high economic losses and affected large numbers of people with a comparatively moderate death toll. This highlights both the effectiveness of early warning systems and early action in saving lives, and the hard limits of adaptation. Entire islands, along with their buildings and infrastructure, cannot simply be moved out of harm's way.

While *Melissa* highlights what action can achieve, most disasters continue to highlight human inaction.[66] Repeated exposure to disasters and consequences of climate change is testing limits of adaptation of communities and infrastructures. The 2025 floods in Pakistan highlight how recovery and adaptation efforts are challenged and push vulnerable communities even further as the country is still recovering from the 2022 floods.[67,68] In other parts of the world, such as East Africa, the combination of ongoing droughts and conflicts is driving large-scale food insecurity for millions of people.[69] Further, while heatwaves may not be in the worst disasters reported for 2025/26 according to EM-DAT, they continue to threaten lives and livelihoods globally. Many forms of loss and damage – such as loss of land and cultural heritage and impacts on mental health – are not recorded or cannot readily be quantified.

Climate Change is making extreme weather events more frequent and intense, significantly heightening global risks. However, the severity of these events' impacts also depends substantially on other Planetary Boundary transgressions, including **Land System Change, Freshwater Change, Change**



● **FIGURE 10:** Approximate locations of the most impactful weather events between April 2025 and April 2026. Events which can be clearly attributed to human-induced Climate Change are shown in red, events categorized based on evidence from similar events ("causal field") are shown in orange. Events indicated in gray have either no causal field, or the literature in the causal field is ambiguous. Adapted from Otto and Raju (2023).[60]

in Biosphere Integrity and Atmospheric Aerosol Loading. These factors also amplify the vulnerability and exposure of communities, especially among marginalized and socio-economically disadvantaged groups. Intersectional vulnerabilities, which are based on disadvantages stemming from multiple different sources (e.g., gender, occupation, migration, and socioeconomic status) must be addressed in particular. Without prioritizing these considerations in adaptation strategies, extreme weather events will continue to disproportionately devastate the most marginalized populations, undermining global resilience and equity goals. Extreme event attribution helps us to understand hazards and their drivers, highlighting that human activities have pushed us beyond safe Planetary Boundaries. To mitigate disaster impacts effectively, **Climate Change** and other Planetary Boundary transgressions must be understood and addressed collectively, not in isolation. This holistic approach is essential to building resilience, safeguarding vulnerable populations, and ultimately securing planetary health.

No.	Event	Country	Time	Impact metric [Deaths/People Affected/Cost]	Made more likely or more intense by human environmental changes?
1	Tropical storm "Senyar"	Indonesia	11/2025	1,109 confirmed deaths 3.2 million people affected USD 4.0 billion	Yes (AS)
2	Flooding in Mokwa	Nigeria	05/2025	1,100 confirmed deaths	Yes (CF)[1]
3	Floods	Pakistan	06/2025–09/2025	1,037 confirmed deaths 7.0 million people affected USD 3.0 billion	Yes (AS)
4	Tropical cyclone "Ditwah"	Sri Lanka	11/2025	1,823 confirmed deaths USD 4.1 billion	Yes (AS)
5	Typhoon "Kalmaegi" (Tino)	Philippines	11/2025	372 confirmed deaths 5.5 million people affected	Yes (CF)
6	Flood	Thailand	11/2025	276 confirmed deaths 4.0 million people affected	Unclear
7	Flood	Niger	06/2025–10/2025	238 confirmed deaths	Yes (CF)
8	Flood	Mozambique	01/2026–03/2026	201 confirmed deaths	Yes (AS)
9	Flood	DRC, Kinshasa	04/2025	165 confirmed deaths	Inconclusive (AS)
10	Flood	DRC, South Kivu	05/2025	154 confirmed deaths	Inconclusive (CF)
11	Hurricane Melissa	Jamaica, Cuba	10/2025	7.5 million people affected USD 10.0 billion	Yes (AS)
12	Flood	China	07/2025	USD 5.8 billion	Yes (CF)
13	Tornado	US, Kentucky	05/2025	USD 5.2 billion	Unclear
14	Drought	Brazil	01/2025–06/2025	USD 4.8 billion	Yes (CF)
15	Floods	US, Tennessee	04/2025	USD 4.6 billion	Yes (AS)
16	Drought	US	2025	USD 4.1 billion	Unclear
17	Drought	Syria	06/2025	16.2 million people affected	Yes (CF)
18	Typhoons "Wipha" (Crising), "Francisco" (Dante), and "Co-May" (Emong)	Philippines	07/2025	11.1 million people affected	Yes (CF)
19	Typhoon "Fung-wong" (Uwan)	Philippines	11/2025	7.7 million people affected	Yes (CF)
20	Typhoon "Bualoi" (Opong)	Philippines	09/2025	6.9 million people affected	Yes (CF)
21	Drought	Kenya	2025–ongoing	2.2 million people affected	Yes (CF)

[1] Note: the high death toll was caused by a broken dam.

● **TABLE 3.1:** The most impactful extreme weather events (04/2025–04/2026), and their attribution to Climate Change. Attributions are based either on an event-specific attribution study ("AS") or on a "causal field," meaning evidence from comparable events and general scientific understanding of that event type ("CF"). Note that only the impact metrics that lead to inclusion in this list are reported here: E.g., a missing death toll means that the event does not rank among the ten deadliest of the period, and does not imply that no deaths occurred.

3.2 Tipping Points

The behaviors of the interconnected components of the Earth system – the major ocean and atmospheric circulations, for example, or the polar ice sheets, or large terrestrial biomes, among others – all influence and respond to changes in Earth's climate. Our understanding of the fundamental functioning of these systems has significantly improved over the last decades, and from it, the current picture of an interwoven and ever-adapting Earth system has emerged. The resilience of Earth system components determines their capacity to absorb and buffer recurring small or low-magnitude changes and disturbances. Earth's climate system components have often responded to these perturbations – think of a prolonged drought, for example, or an extreme precipitation event – by balancing and buffering out the disturbance, thus helping to maintain the remarkably stable Earth system conditions of the Holocene over the past 11,700 years.

This stability is not a given, however, and when a system is placed under consistent strain, its continued functioning can no longer be guaranteed. When a system is so critically perturbed that it transitions from one resilient state into another, reorganizing itself such that instead of absorbing or buffering perturbations, the system actually self-amplifies them, we say the system has crossed a tipping point. Tipping points are thus thresholds in individual, large-scale Earth system components, the crossing of which leads to a fundamental shift in the system's dynamics, often taking it from a set of feedbacks that keep the system stable to another set that force it into an entirely new state.[22,70,71] These can be triggered both by relatively small-scale (in either space or time) perturbations in a strained system – like extreme weather events – as well as by larger-scale disruptions. And indeed, at other points in Earth's history, specific systems – the Atlantic Meridional Overturning Circulation (AMOC), for example – are believed to have fundamentally reorganized or ceased functioning altogether due to external pressure. In the case of the AMOC and Subpolar Gyre, a major release of freshwater about 8200 years ago from the Canadian Shield during the retreat of the Laurentide Ice Sheet led to a reduction in its strength and a consequent cooling of the North Atlantic.[72]

Planetary Boundaries are not tipping points. To set a Planetary Boundary at a tipping point would bring us far too close to the brink, ignoring the precautionary principle used to set each of the nine boundaries. You can instead think of a tipping point as an upcoming hazard on a highway, and the Planetary Boundary as a warning sign placed before it, alerting you to the danger if you keep driving down the road. In that sense, transgressing a Planetary Boundary – as we have, already, in seven of the nine boundaries – does not mean imminent disaster. It does, however, mean we are in a risk zone beyond the safe operating space, and that we may be increasing the risk of approaching or crossing tipping points.

While Planetary Boundaries are not tipping points, some Planetary Boundaries are strongly informed by the tipping points of known or suspected tipping elements because transgressing these boundaries can increase the risk of large-scale, non-linear transitions. The **Climate Change** and **Change in Biosphere Integrity** boundaries provide some of the clearest examples of how tipping points science informs Planetary Boundaries, as they are designed to reduce the risk of triggering tipping transitions in these systems or large-scale ecosystem collapse. The risk of crossing several tipping thresholds increases substantially between approximately 1–2°C of global warming above pre-industrial temperatures.[71] At the same time, atmospheric CO_2 concentrations of around 426 ppm are already far beyond the proposed safe level of 350 ppm, illustrating how strongly the **Climate Change** boundary is transgressed.

Planetary Boundaries are not tipping points, but some are strongly informed by known or suspected tipping elements.

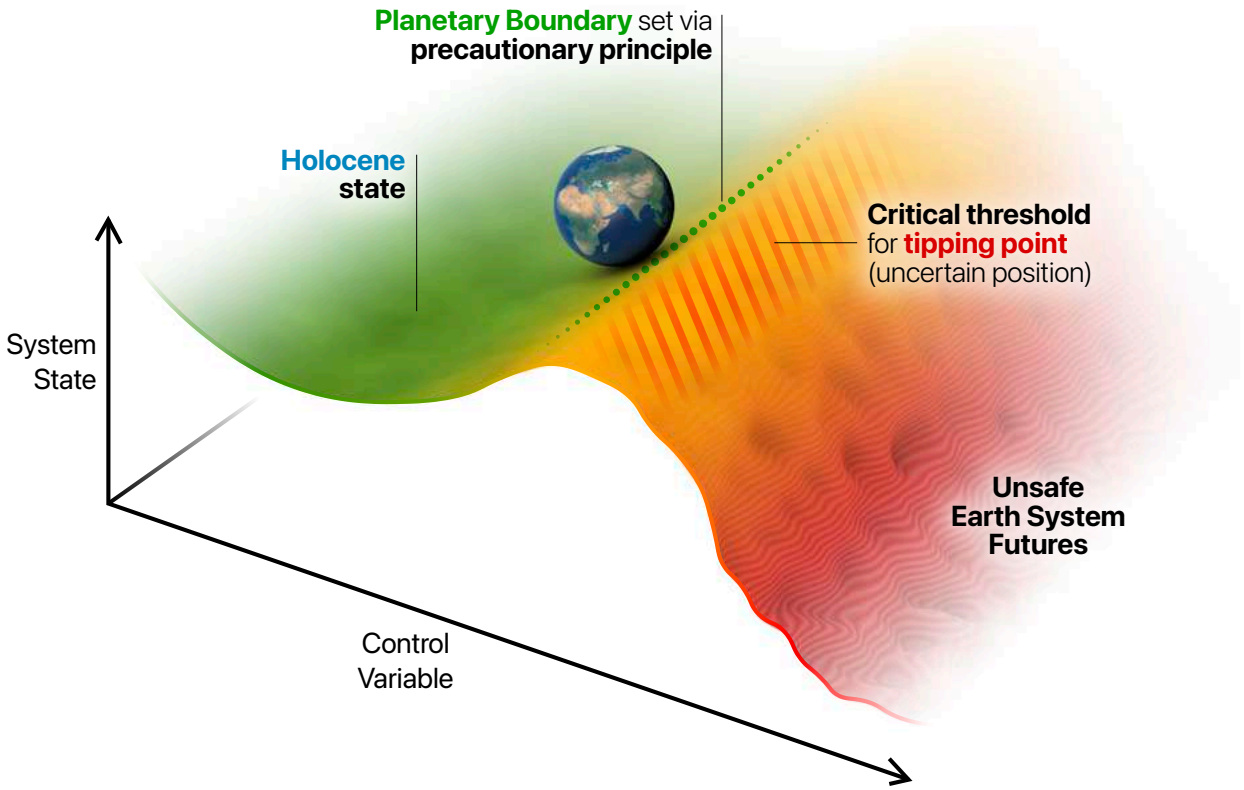
Further, crossing one Planetary Boundary can increase pressures on other systems and raise the likelihood of additional tipping events through cascading interactions. In this sense, tipping points and Planetary Boundaries are linked in both directions: exceeding a Planetary Boundary can increase the probability of triggering tipping behavior, while tipping in one sub-system can amplify changes elsewhere and contribute to the transgression of additional boundaries. These interactions mean that Earth system risks cannot be understood by examining individual boundaries or tipping elements in isolation. Tipping point science therefore informs Planetary Boundaries not

only by helping identify dangerous thresholds, but also by emphasizing the importance of resilience, feedbacks, and cascading change within the coupled Earth system.

What is a tipping system? What systems can tip?

Tipping systems, as presented here, are components of the Earth system wherein changes in external forcing or internal dynamics can induce irreversible shifts when a critical threshold (tipping point) is crossed. Simply put, just like camels' backs loaded with weight, these are systems that, under pressure, can be pushed "over the edge" into a fundamental reorganization by a comparatively small trigger – a piece of straw, if you will. Strictly speaking, many systems, from individual glaciers to whole ice sheets, can exhibit these tipping behaviors. But in the context of global change, Planetary Boundaries, and the functioning of the Earth system, we are primarily concerned with the large-scale features of the climate system susceptible to tipping. These are those systems which, if they tipped, would have far-reaching consequences for the functioning of the whole Earth, as well as those who live on it.

Many of these systems tip because they respond non-linearly to external stimuli. This means that a gradual change to the external conditions may not lead to a gradual change in the system state. Think about adjusting the volume of your car's speaker system – a reasonable expectation is that the volume increases an amount proportional to the knob's rotation. Non-linear system responses are complicated and difficult to anticipate because they do not respond with such equal proportionality. Imagine if turning the volume knob from six to seven increased the volume ten times the amount that turning it from five to six did. Tipping systems respond similarly. These behaviors make anticipating the consequences of changes to the system difficult, underscoring the urgent need to reduce the pressures on the Earth system by returning to within the Planetary Boundaries.



● **FIGURE 11:** Stylized stability landscape of the Earth system. Tipping points and Planetary Boundaries are interconnected – both address Earth system stability, but they serve distinct roles. Beyond a tipping point, a system fundamentally changes due to a shift in feedback dynamics: When stabilizing feedbacks are dominated by destabilizing ones, they drive the system to a qualitatively different state, often abruptly and/or irreversibly. Where quantifiable, the Planetary Boundaries are set in a safe distance away from risks of crossing tipping points.

With that in mind, there are several large-scale "tippable" Earth system components (we call these major tipping systems "tipping elements") of critical concern. The AMOC, as mentioned, as well as parts of the Subpolar Gyre in the North Atlantic and the overturning of the Southern Ocean.[22,70,71] From the cryosphere, the polar ice sheets, high-latitude permafrost, as well as sub-ice sheet scale glacial systems all exhibit feedbacks that make them susceptible to tipping dynamics. Certain terrestrial and marine biomes are likewise believed to exhibit tipping behavior. Included among those are the Amazon rainforest, boreal forests, and warm-water coral reefs. Warm-water reefs, it's worth noting, are likely already in the process of tipping.[22]

The Global Tipping Points Report 2025 provides a comprehensive overview of the current state of Earth system tipping points science.[22]

How do tipping elements interact within the Earth system?

As interconnected components of the climate system, the different tipping elements interact with each other – changes to one, and in some cases the tipping of one, could lead to tipping or widespread change in the behavior of another.[49] Take the AMOC, for example, a key element when considering tipping cascades. This critical circulation delivers warm water from the South Atlantic and tropics to the North Atlantic which contributes to the relatively mild climates in northern Europe. Intensifying climate extremes are increasing precipitation in the North Atlantic, while warming Arctic temperatures are are reducing sea ice extent and accelerating melting of the Greenland Ice Sheet. All of these increase the total freshwater delivered to the North Atlantic, diluting the salty ocean water, making it less dense, thus weakening the density-driven circulation that powers the AMOC. As a density-driven circulation, the AMOC is highly sensitive to both temperature increase and fluctuations in freshwater delivery. Changes in the AMOC can in turn trigger tipping in other systems, or amplify its impacts. For example, a weaker AMOC could alter rainfall and atmospheric circulation patterns in highly vulnerable regions like the Amazon. There, the impacts of a weakened AMOC vary by region. By provoking a southward shift of the precipitation band known as the Intertropical Convergence Zone (ITCZ) a weakened AMOC may lead to increased precipitation in the southern and eastern Amazon[73,74] while decreasing total precipitation in the North.[75] Such a spatial reorganization of precipitation patterns may in turn weaken the moisture recycling process that today accounts for up to 50% of local precipitation, especially in the western Amazon.[76] The potential dieback of parts of the Amazon rainforest would reduce its

Photography by NASA

carbon storage capacity, turning it into a source of carbon dioxide, rather than a sink, and thus reinforcing global warming.

More globally, recent investigations have shown that a collapse or slowdown of the AMOC could have considerable consequences for the Earth's monsoon systems.[77,78] "Monsoon" refers to seasonal precipitation patterns where oceanic conditions drive precipitation patterns alternating from wet summer seasons with high precipitation to very dry winter seasons. They are found within the tropics of all continents, as well as in the tropical oceans of the western North Pacific, eastern North Pacific, and the southern Indian Ocean, where they are the primary factor affecting climate variability. Studies investigating the effect of AMOC slowdown on monsoon systems are limited. That said, the current understanding suggests that AMOC slowdown reorganizes interhemispheric sea surface temperature gradients and provokes a southward shift of the ITCZ. As a consequence, monsoons north of the equator (the Indian, southeast Asian, and West African monsoons) weaken, while the South American monsoon wet season strengthens and relocates.[77] Together, these findings further emphasize the need to investigate how this relationship extends to other monsoon regions.

Reducing tipping risk requires not only staying within Planetary Boundaries, but understanding the feedbacks and cascades that connect them.

A weakened AMOC furthermore can impact heat distribution in the Southern Hemisphere, potentially accelerating ice loss in parts of Antarctica, creating further feedbacks through sea-level rise and additional freshwater input into the oceans. Global warming and a weakening of the AMOC may initiate a decrease in northward oceanic heat transport, resulting in increased sea-surface temperatures in the Southern Ocean and a reduction in the area covered by sea ice[422]. Enhanced ice shelf melting can destabilize marine ice sheets by initiating rapid grounding line retreat and thinning which results in ice sheet mass loss and sea-level rise. Ice shelf melt rates are predominantly controlled by the temperature of Circumpolar Deep Water which circulates ice shelf cavities,[79] but they are also sensitive to changes in surface air temperatures.[80] Increases in the Southern Ocean heat reservoir, therefore, have the potential to contribute to the destabilization of the West Antarctic Ice Sheet. Additionally, AMOC resilience in turn may be impacted by additional freshwater input to the Southern Ocean caused by increased melting of the Antarctic Ice Sheet, further complicating the feedbacks between ocean circulation and Antarctic ice sheet dynamics.[81]

Changes to the AMOC, and its consequent impacts on ice sheets, large biomes, monsoons and related systems may have long-term and dramatic consequences for the people and societies that rely on them. The world's monsoon regions are home to half of the world's population, who rely vitally on the monsoon's wet season to sustain agriculture and fisheries. Disturbances to monsoon regimes pose a severe threat not only to regional stability, but potentially to global food security. In parts of the Amazon, for example, these hydrological systems are already undergoing significant changes.[82] Model simulations further show that disruptions associated with an AMOC collapse could severely affect water availability and food security across multiple countries.[83]

These impacts and interactions illustrate how a tipping element – here exemplified by the AMOC – can act as both a trigger and amplifier within a network of tipping elements and associated components of the climate system. Feedback loops raise the risk of cascading changes across the Earth system. Freshwater and heat weaken the AMOC, which reshapes the climate in ways that promote further carbon release – driving more warming, which weakens the AMOC further. Because many of these links are destabilizing, even gradual changes in one could significantly increase the likelihood of crossing multiple tipping points, underscoring the urgent need to better understand tipping points and dynamics in order to anticipate long-term climate risk.

Summary

The science of tipping points builds on our understanding of a deeply interconnected Earth system, demonstrating how changes in one component can reverberate across others in ways that are difficult to predict and potentially impossible to reverse. Breaching a Planetary Boundary does not guarantee that a tipping point will be triggered – but it increases the risk, and each additional boundary breached narrows the margin further. What emerges from this picture is not a set of isolated thresholds to be managed independently, but a coupled system in which gradual pressure can give way to rapid, self-reinforcing change. Reducing that risk requires not only staying within Planetary Boundaries, but understanding the feedbacks and cascades that connect them – because the interactions between tipping elements mean that Earth system risks cannot be assessed in isolation.

4 | Spotlights

Photography by Mattias Klum

4.1 Earth Resilience: When Land Stops Buffering Climate Change

Authors: Boris Sakschewski and Jonathan F. Donges, Potsdam-Institute for Climate Impact Research

Earth resilience describes the capacity of the Earth system to absorb disturbances while maintaining stable, habitable conditions for human societies and the wider living world.[10,84] A great example is that the Earth system has shown a remarkable capacity to redistribute CO_2 from the atmosphere into the land and oceans. So far, **about half of the emissions humans have added to the atmosphere since the industrial revolution have been absorbed by land and ocean carbon sinks, vastly reducing the warming that would otherwise have occurred**.[85,86] In other words, the climate change we see today would be significantly stronger without those carbon sinks. The CO_2 buffering of the Earth system is described in the global carbon budget as a balance between anthropogenic CO_2 sources, atmospheric growth, and uptake by land and ocean sinks **(● FIG. 12)**. But this buffering capacity is not guaranteed. It depends on the balance between processes that add carbon to these sinks, and processes that remove carbon from them. Today, the global land sink appears to be weakening, and it is important to better understand why.[87,88]

The continued existence of the global net land carbon sink should not be mistaken for a healthy and resilient biosphere.

What makes land a carbon sink?

A useful way to understand the land sink is as a balance between gains and losses. In carbon budget terms, land carbon uptake, excluding direct land-use change, has generally exceeded land-use change emissions, so the combined land balance has remained a net carbon sink globally.[85] However, recent carbon-budget assessments indicate that land carbon uptake, excluding direct land-use change, has been relatively stagnant since around 2000.[85,89] This suggests that, while the land biosphere is still buffering climate change, it does so less reliably than before.

On the gain side, several processes strengthen the land carbon sink by increasing carbon uptake and storage. This includes the fertilizing effect of higher CO_2 levels on plants, forest regrowth in some regions, longer growing seasons in some climates, changes in land management, and carbon accumulation in vegetation and soils.[89–91] But none of these gains are unlimited. They depend on water availability, nutrient supply, suitable temperatures, healthy soils, ecological recovery and connectivity, and time (see also Info Sheets on **Climate Change, Biosphere Integrity, Land System Change,** and **Freshwater Change**).[92–96] Forests and soils also face basic biomass limits: They cannot accumulate carbon indefinitely because growth slows as forests mature, turnover continues, and additional carbon must be retained in long-lived pools.[90,97,98]

On the loss side, many factors weaken the land carbon sink by directly or indirectly increasing the amount of carbon released into the atmosphere. Climate change is one of the leading reasons: Warming can reduce plant productivity, increase ecosystem respiration, intensify drought stress, and amplify disturbances such as fire, disease outbreaks and mortality.[87,88,94–96,99–103] In other words, the same land biosphere that has buffered climate change is increasingly being stressed by it.

Declining ecological integrity and functioning also play a considerable part in reducing the land carbon sink. The current land sink is carried disproportionately by the few remaining relatively intact and recovering ecosystems **(SEE ● FIG. 13)**.[85,90] Meanwhile, human societies appropriate a large share of global plant productivity for their own purposes, leaving less energy available for natural ecosystems. Today, roughly one quarter of potential terrestrial plant productivity is appropriated for human use.[104,105] Alongside and beyond this redistribution of energy, ecosystems are losing area, quality, and biodiversity, as well as connectivity. Habitats are being converted, fragmented, degraded, polluted, simplified, and disrupted by infrastructure, resource extraction, and other forms of interference.[10,11,106–109]

Hence, the continued existence of the global net land carbon sink should not be mistaken for a healthy and resilient biosphere. So far, carbon gains are still outweighing carbon losses in the global balance, but only by a limited margin. These gains can

mask ecosystem degradation and make the land system appear more stable than it really is. The central concern is not only that the land carbon sink could weaken; it is that the living systems that make the sink possible are being undermined at the same time, gradually losing their ability to store additional carbon or hold the carbon they already store.

The complexity of the system shows that the land sink is not simply the sum of independent gains and losses. Many of the processes involved are interconnected through feedbacks, linking **Climate Change, Change in Biosphere Integrity, Land System Change, Freshwater Change,** and the **Modification of Biogeochemical Flows** **(SEE ALSO CH. 2.2)**.[10,11,107,110] Some feedbacks help stabilize the system, while others amplify ongoing change. Earth resilience therefore depends not only on the current balance, but also on which feedbacks become stronger over time. As losses increase and carbon is released, these feedbacks become particularly important, because they can further reinforce the very processes that weaken the sink.

Historically, several land processes have acted as **stabilizing, or negative, feedbacks**. CO_2 fertilization is the clearest example: Higher atmospheric CO_2 can enhance photosynthesis and water-use efficiency, increasing carbon uptake and partially offsetting emissions.[89,91] This has helped slow the rate of atmospheric CO_2 accumulation and warming. Yet stabilizing feedbacks have limits. In the case of CO_2 fertilization, nutrient constraints, water stress, heat stress, ecosystem degradation, and saturation effects can reduce its effectiveness.[92–96,98,101,102,111] Importantly, a weakening negative feedback already means more warming than expected, even if it never fully disappears: The land system does not need to become a net carbon source for resilience to decline.

There is also a hidden vulnerability in this buffering effect. Additional carbon stored through past CO_2 fertilization has increased biomass and soil carbon stocks in many regions. This can be viewed as a kind of ecological credit: carbon that has been kept out of the atmosphere for now. But larger carbon stocks also create more carbon that can potentially be released later through drought, fire, pests, mortality, or land-use disturbance. In that sense, successful buffering today can increase what is at risk tomorrow.[97,98,101–103]

Other feedbacks work in the opposite direction. Climate extremes provide a clear example of **change-amplifying, or positive, feedback**. Heatwaves and droughts reduce productivity directly, but they also increase mortality risk, fire weather, pest outbreaks, and recovery times **(SEE ALSO CH. 3.1)**.[94–96,99–101,103] These impacts can release carbon to the atmosphere, contributing to further warming and increasing the likelihood of future extremes. Mortality and repeated disturbance reduce biomass and can shift ecosystems toward lower-carbon states with weaker recovery potential.[101,102] Such feedbacks are not necessarily runaway processes. They may eventually be constrained by ecological limits or by the amount of carbon available to lose. Nevertheless, extreme events will become even more intense and frequent under future climate change,[86,112] and they can cumulatively worsen the situation and push Earth towards less habitable states.

Feedbacks are also the precondition for known or suspected tipping elements: critical, large-scale components of the Earth system characterized by threshold behavior **(SEE ALSO CH. 3.2)**. The global land carbon sink as a whole may not show tipping behavior, but it is certainly linked to tipping elements, including tropical forests, boreal forests, and permafrost regions.[49,113,114] Weakening land sinks can therefore increase the risk of crossing tipping points elsewhere, while tipping-like change can in turn further reduce land carbon storage.[49,115]

In summary, the land carbon sink is integral to Earth resilience, but Earth resilience can erode long before the land sink disappears entirely. Gains can weaken, losses can increase, and stabilizing feedbacks can lose strength while change-amplifying feedbacks become more important. The result is not necessarily a runaway collapse, but a gradual reduction in the Earth's capacity to buffer human pressures. In such a world, atmospheric CO_2 rises faster than expected, ecosystems recover more slowly, and the Earth system may settle into less resilient configurations than current expectations assume.

Why our models are probably too optimistic

Current Earth system models have improved substantially and represent exceptional scientific achievements in our understanding of the Earth system. However, they still simplify many of the processes that determine land carbon resilience.[116,117] One important example is the representation of natural vegetation, because vegetation currently plays a major role in the global net land carbon sink.

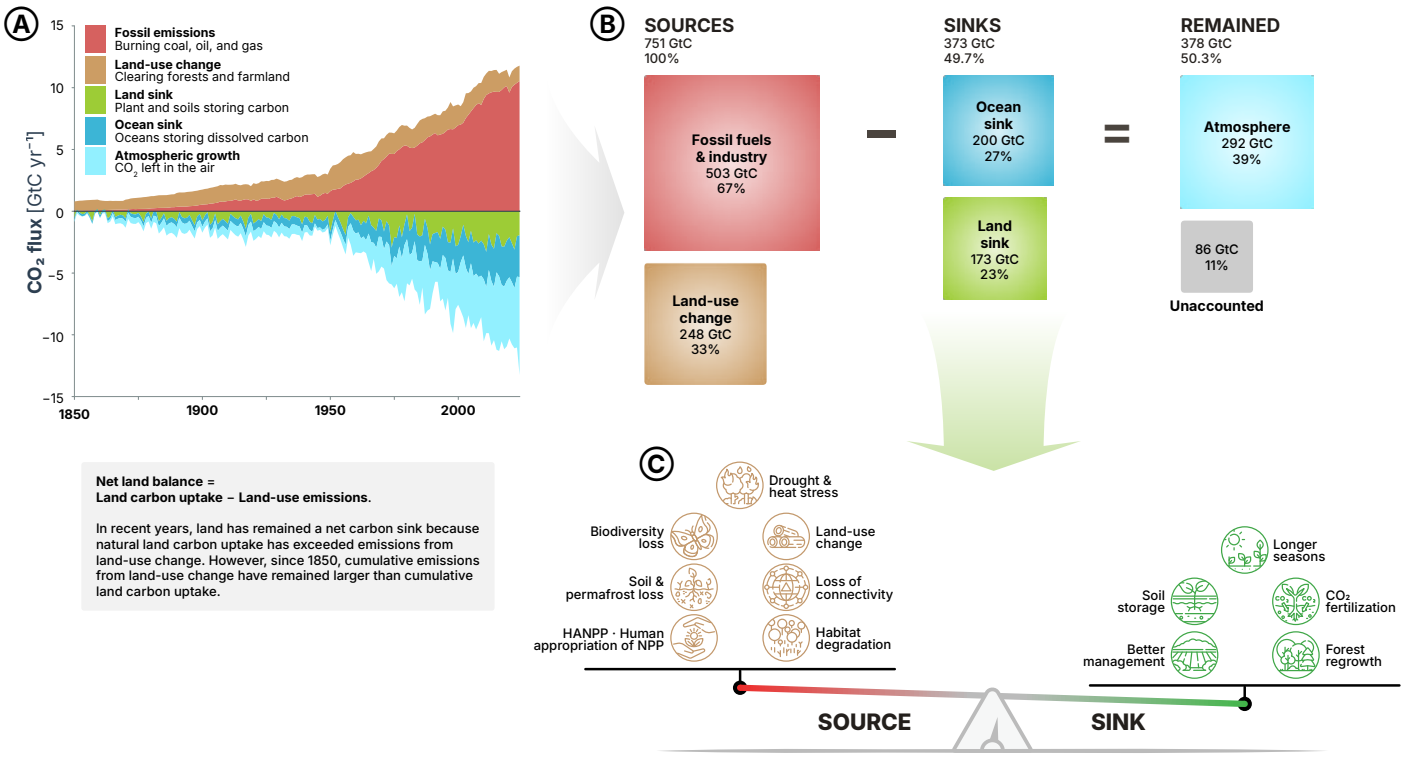
Many models rely on a small number of average representative plant types rather than locally adapted, demographically structured, species-rich communities.[118] In practice, this often means simplified tree

morphology, forest structure, and "big leaves" operating on grid cells that can span tens to hundreds of kilometers.[116–118] A whole biome may be represented by an average plant with broadly constant traits over space and time. These simplifications can still reproduce reasonable large-scale biome patterns, but they smooth away exactly the ecological frictions that matter for resilience: local adaptation, dispersal limits, recruitment failure, age structure, pests, hydraulic failure, cumulative damage, and mortality.[99,103,116–120]

This makes many modeled ecosystems behave like fertilized, teleporting, generalist biomass blobs. Modeled vegetation can creep into suitable climate space, respond smoothly to elevated CO_2, and recover after disturbance more easily than real ecosystems. Real species depend on seed sources, establishment conditions, landscape connectivity, soils, mutualists, and community reassembly.[96,99,101,103,118–120] Real forests also do not fail as one collective biomass. Trees die as individuals, through interacting water, carbon and defense failures, including xylem embolism and hydraulic failure, carbon starvation, impaired defense against insects and pathogens, heat stress, fire, and repeated drought. These mortality spirals are much harder to represent than gradual changes in average productivity.[99,101,103]

Such simplifications become especially problematic under extreme events. Observations show that droughts and heatwaves can have strong and persistent effects on productivity, mortality, and recovery.[94–96] Yet model evaluations repeatedly point to difficulties in reproducing the magnitude, duration and legacy effects of such events.[116,117] Climate models can capture broad changes in many extremes, especially heat, but droughts, storms, and circulation-driven compound events are harder to capture. If the physical event is underestimated, or if the modeled ecosystem response is too resilient, carbon losses and recovery times will be underestimated. The greatest risk arises when both biases occur together: underestimated extremes acting on overly resilient ecosystem models.[86,112]

Some missing processes might also make models underestimate resilience. Vegetation diversity, local adaptation, acclimation, selective survival, and suc-



● **FIGURE 12:** The global carbon budget and the fragile land sink. Panel A shows annual anthropogenic CO_2 emissions and their partitioning between atmospheric growth, ocean uptake and land uptake, based on the Global Carbon Budget 2025.[85] Positive values indicate emissions from fossil fuels and land-use change, while negative values show the fraction of emissions taken up by land and ocean sinks. Panel B translates this accounting into a simplified balance: Anthropogenic sources are partly offset by ocean uptake and land uptake excluding direct land-use change, with the remainder accumulating in the atmosphere; the budget imbalance is shown as a residual accounting term, not as a physical sink. Panel C zooms into the green land-sink term. This inset is conceptual and not to scale. It shows that land uptake excluding direct land-use change is not one process, but the residual of competing gains, limits, and losses. Gains such as CO_2 fertilization, longer growing seasons, forest regrowth, improved management, and soil carbon storage strengthen uptake. At the same time, drought and heat stress, soil and permafrost carbon loss, biodiversity loss, habitat degradation, loss of connectivity, and human appropriation of plant productivity weaken sink capacity and recovery. The key message is that the land sink is still tilted toward uptake, but only slightly: The global carbon buffer depends on ecological processes that are increasingly under stress.

cession can buffer ecosystems in some contexts.[45] But these processes are not free-floating safety mechanisms. They are slow, uneven, and constrained by dispersal, seed supply, soils, mutualists, competition, disturbance history, and fragmentation.[96,101,103,109,118–120] Local adaptation is especially ambiguous: It can increase fitness under familiar conditions, but also make real populations vulnerable when climates, soils, seasonal rhythms, and biotic interactions shift beyond past experience. If models currently reproduce broad biomass and productivity patterns without representing these details, this does not mean the details are unimportant. It may simply mean that today's large patterns can be approximated without the ecological machinery that will determine future sensitivity.

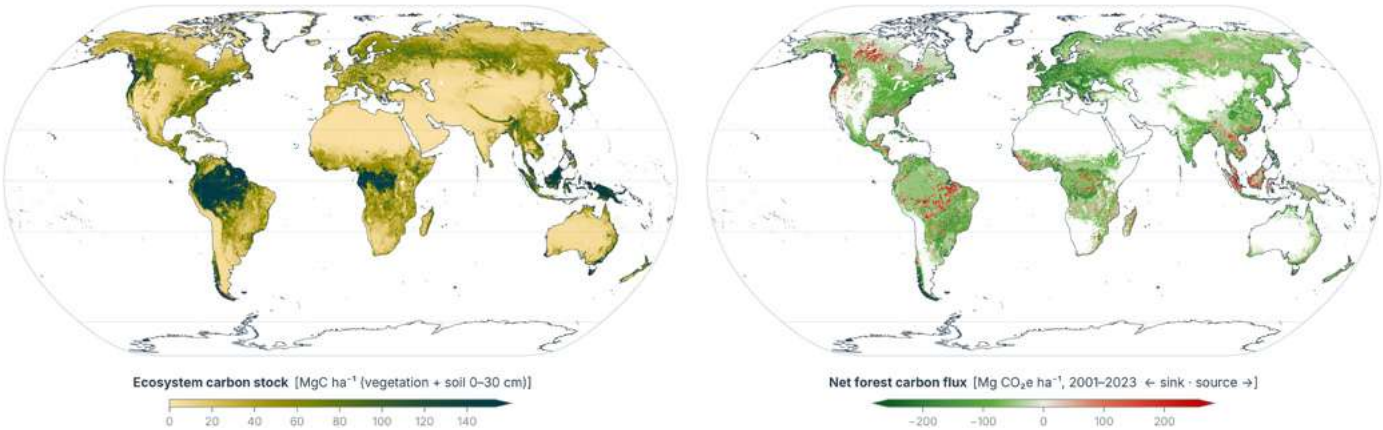
The conclusion is not that Earth system models are unreliable. They remain indispensable tools. The concern is more specific: Current models may overestimate the resilience of the land carbon sink because they represent ecosystems as more continuous, more flexible and more recoverable than they are in reality. In that case, projections can be broadly useful and still too optimistic about how long the living land system can keep buffering climate change.

Implications for Earth resilience

The limitations and potential over-optimism of current land-carbon modeling matter, because many mitigation scenarios and remaining carbon budget estimates rely on land carbon sinks remaining functional throughout the transition to net-zero emissions.[86,116] If this assumption proves too optimistic, the effective remaining carbon budget would be smaller than expected, warming during the transition could be higher, tipping risks would increase, and reliance on future carbon dioxide removal would grow despite uncertainties about feasibility, permanence, land competition, and biosphere integrity.[49,86,102,115,121,122]

Within the Planetary Boundaries framework, this highlights the tight coupling between **Climate Change, Change in Biosphere Integrity, Land System Change, Freshwater Change,** and **Modification of Biogeochemical Flows** **(SEE ALSO CH. 2.2)**.[10,11] Human appropriation of net primary production, land degradation, soil disturbance, biodiversity loss, and disrupted vegetation-water interactions directly undermine land carbon storage.[104–108,110,123] Healthy ecosystems store carbon while regulating soil moisture, evapotranspiration, cooling, and moisture recycling. Protecting and restoring them is therefore not only a matter of conservation, but part of maintaining Earth-system stability.[122]

In summary, Earth resilience cannot be assessed by climate forcing alone. It also emerges from the integrity of living systems that regulate carbon, water, and energy flows. Maintaining a stable climate trajectory requires safeguarding these systems and acknowledging the limits of current models in representing their response to rapid and compounding change.[49,124]



● **FIGURE 13:** Spatial patterns of forest carbon stocks and net forest carbon fluxes. The left-hand map shows ecosystem carbon stocks in vegetation and upper soil layers, highlighting regions where large carbon stores are concentrated and where degradation or disturbance could turn existing carbon assets into future liabilities. The right-hand map shows net forest carbon fluxes from Global Forest Watch / Harris et al.[125] It represents the balance between forest carbon removals from growth and regrowth and forest carbon emissions from deforestation and stand-replacing disturbances. This is not a complete map of the global terrestrial land carbon sink: Full land carbon fluxes could look different when non-forest ecosystems, soils, peatlands, permafrost, lateral fluxes, and ecosystem respiration are included. Nevertheless, it gives a sharp and intuitive picture of where living forests are currently acting as carbon sinks or sources, illustrating that the forest component of the land sink is spatially uneven and linked to land use, ecosystem integrity, disturbance, and climate stress.

4.2 Seafloor Integrity: Why the Bottom of the Ocean Matters

Guest authors: Jacob Geersen, Leibniz Institute for Baltic Sea Research Warnemünde
Nele Matz-Lück, Walther Schücking Institute for International Law at Kiel University
Levke Caesar, Potsdam Institute for Climate Impact Research

"I believe there is not a portion of the ground but what the trawl destroys. I have dragged 50 miles off Aberdeen. I have got fast there and brought up coral about 2.5ft in circumference, lumps of soft coral, and I am prepared to say that whatever is in the way of the trawler will not escape." The statement of a Scottish fisherman, which was part of an article entitled "Bottom trawling: how to empty the seas in just 150 years" (The Guardian, 10 February 2014),[126] dramatically illustrates how anthropogenic pressures can modify the seafloor to a degree that it threatens its integrity.[1] Because when we disturb the seafloor, we do not just scrape mud. We damage habitats, alter nutrient cycling, and in some places may even weaken one of the ocean's long-term carbon stores.

The hidden foundation of the ocean

The ocean covers two-thirds of Earth's surface. Below the water, and thus veiled from our eyes, lies a world most people never see: the seafloor, on average nearly four kilometers down. The seafloor is difficult to access, and exploration requires seagoing expeditions and the use of highly specialized technologies. For decades, its remoteness has secured it from anthropogenic disturbance. Today, this protection is diminishing as technological advances bring the global seafloor within reach of humans.

At the same time, there is growing recognition that the seafloor is far from inert. It hosts vast and diverse ecosystems, maintains benthic food webs, and plays a central role in regulating how carbon and nutrients move through the ocean. Because of its sheer size, processes at the seafloor can scale up to global consequences. However, while many of the underlying processes have been identified, their exact interactions and thresholds are still being resolved. This makes it difficult to define clear limits or control variables that define a Safe Operating Space for seafloor integrity.

Protecting this crucial and underexplored part of the Earth system is urgent. In many cases, once disturbed, seafloor systems may not recover on human timescales. At the same time, scientific understanding and governance frameworks are struggling to keep pace with the growing demand for marine resources.[127]

The stabilizing effect of the seafloor for the Earth system

The seafloor as habitat: Benthic ecosystems
The seafloor is not empty. In many places it is living architecture composed of biogenic reefs, sponge grounds, kelp, shell habitats, burrowing communities, and microbial systems. These benthic ecosystems – communities of organisms living on or within the seabed – build food webs, recycle nutrients, and regulate how carbon is stored at the seafloor. Many benthic habitats are threatened by increasing human use of the seafloor. Today, bottom trawling physically disturbs around 1–2% of the global seafloor each year – an area about half the size of Europe. Although much of this disturbance repeatedly affects the same fishing grounds, it is concentrated on continental shelves, which cover only a small fraction of the global ocean but support much of its biological productivity, fisheries, nutrient cycling, and long-term carbon burial.[128] In the future, mining for deep-sea mineral resources could add substantial new areas of disturbance with more than 200 km^2 per polymetallic nodule mining operation.[129] The direct effects on the seafloor may be best understood by comparison to terrestrial deforestation: In places that are trawled frequently, structurally complex benthic landscapes that were once rich in biodiversity are turned into "marine deserts" of sand or mud.[130]

What is lost is not only biodiversity, but a whole ecological machinery: Burrowing animals, microbes, and sediment chemistry together regulate how nitrogen, phosphorus, and carbon move between sediments and the overlying water. When these exchanges are

1 **SEAFLOOR INTEGRITY** means that the seabed retains the physical structure, ecological communities, and chemical functioning needed to support the stability of the Earth system.

disrupted, the consequences can cascade to marine ecosystems and food webs.[131] Many shelf and coastal seas have already experienced the loss of their "marine forest", reducing habitat complexity, nursery areas for commercially important fish, biodiversity, sediment stabilization, and nutrient cycling, and leaving these ecosystems less resilient to future disturbances. By contrast, the deep sea has until recently remained largely beyond direct human disturbance. Experimental studies show that even limited disturbances here can suppress ecosystem functioning for decades[132] or even lead to their permanent loss.[133]

The seafloor as carbon store

Marine sediments form one of the largest active carbon reservoirs in the Earth system, with continental shelf sediments storing around 360 billion tonnes of organic carbon in their upper meter, accounting for 75–90% of global marine carbon burial.[134] Before the Anthropocene, these sediments were out of reach for humans and only subject to natural disturbance. In the modern ocean, however, some of these sediments are repeatedly suspended through anthropogenic stressors such as bottom trawling,[130] marine mining,[133] anchoring,[135] and shipping.[136] When sediments come into contact with oxygen-rich waters, the stored carbon can be broken down and released as CO_2. Global modeling suggests that bottom trawling may release 160–400 million tonnes of carbon per year, with part of this potentially reaching the atmosphere.[137,138] While these estimates are still uncertain, they highlight an important point: Anthropogenic processes that disturb seafloor sediments may weaken a natural carbon store that would otherwise keep carbon locked away for geologic times.

Together, these functions show why the seafloor matters far beyond the ocean bottom itself. It is habitat, carbon store, and biogeochemical processor at the same time. When its integrity is lost, biodiversity declines, carbon storage may weaken, food webs are disrupted, and nutrient cycling shifts. In other words, damage to the seafloor may not always remain veiled as the seafloor itself, but propagate through the Earth system.

Ways to protect the global seafloor

Protecting seafloor integrity requires a precautionary approach. Anthropogenic alteration of the seafloor may affect Earth system stability through impacts on carbon storage, nutrient cycling, marine food-web dynamics, and potentially atmospheric CO_2 concentrations. Scientific understanding of these processes, however, remains limited, particularly in the deep ocean, and the magnitude and spatial extent of the impacts are not yet resolved. Nevertheless, the loss of these functions may persist for decades to centuries, and in some cases recovery may not occur at all, underscoring the need for precautionary and carefully targeted management approaches.

Managing anthropogenic pressures – by limiting their spatial extent, frequency, or intensity – can help maintain the seafloor's role in supporting Earth system stability. A primary priority is to minimize physical disturbance in areas where the seafloor plays a particularly important role in Earth system functioning. These include continental shelves and other low-energy depositional environments where organic carbon accumulates and is stored over long timescales. Such regions are not only hotspots of biological productivity but also key sites for long-term carbon sequestration and nitrogen removal. At the same time, some seafloor areas should remain off-limits to destructive activities. In particular, ecosystems that are slow to recover, such as deep-sea habitats or fine-grained sediments rich in organic carbon, require strong protection. Applying the precautionary principle is especially important here, as scientific understanding of impacts and recovery remains limited.

Protecting seafloor integrity requires a precautionary approach.

Marine spatial planning offers an important tool to balance use and protection. However, effective planning must go beyond biodiversity alone and account for the seafloor's role in Earth system processes, including carbon storage and nutrient cycling. This requires integrating scientific knowledge about sediment vulnerability, recovery rates, and biogeochemical functioning into decision-making.

Finally, governance and monitoring need to keep pace with expanding human activities in the ocean. International agreements and conservation targets are beginning to address these challenges, but significant gaps remain – particularly in areas beyond national jurisdiction and in the deep sea. Strengthening protection, improving monitoring, and closing knowledge gaps are essential steps toward safeguarding seafloor integrity.

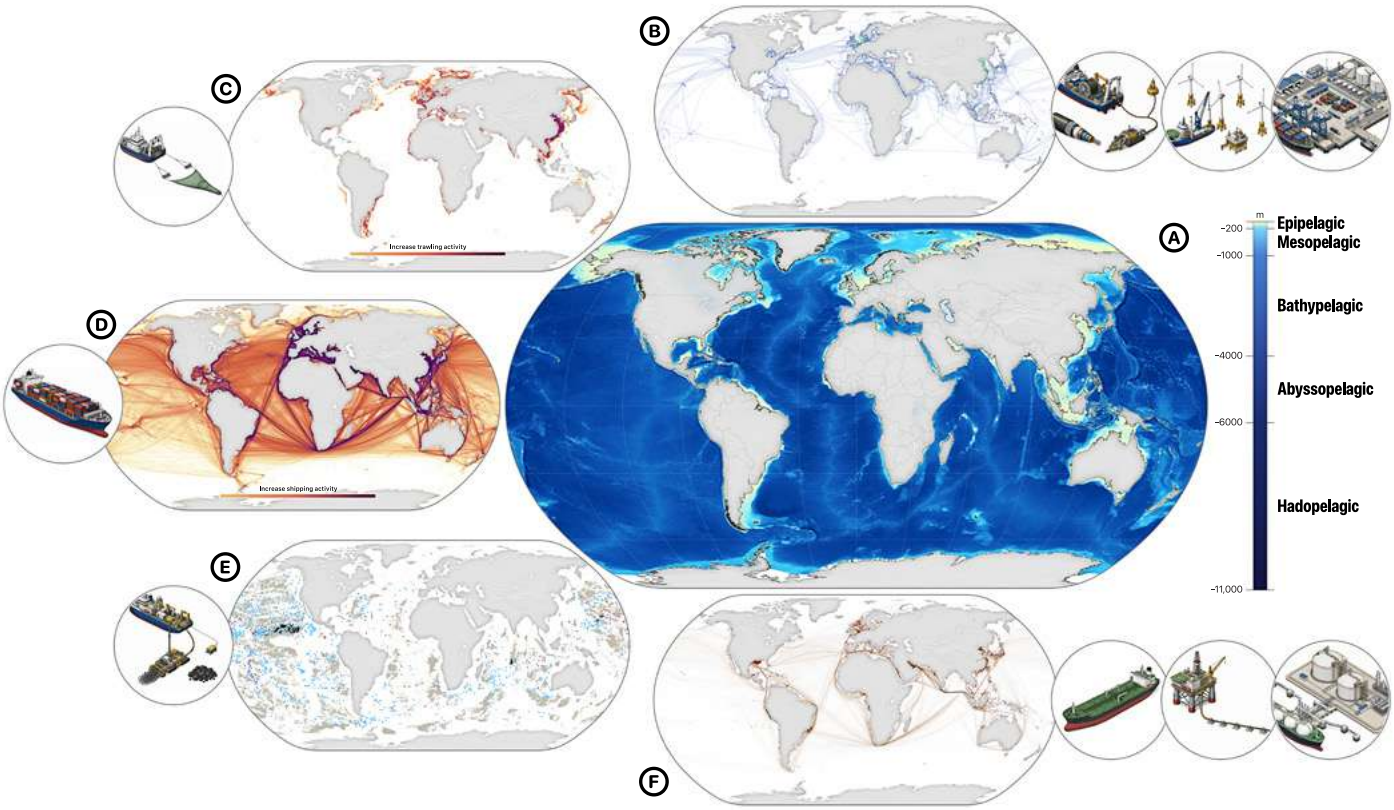
Governance of seafloor integrity

Legal governance of marine spaces depends upon the relevant maritime zone. The different zones are

established by the UN Convention on the Law of the Sea (UNCLOS) and are recognized by customary international law. They indicate who enjoys the competencies to enact and enforce laws for the use and protection of the marine environment, including the seafloor.

The seafloor up to the outer boundary of the territorial sea – a maximum of 12 nautical miles from a state's coast – is part of the territory of that state, which enjoys full sovereignty over the waters, the seabed, and the subsoil. It can therefore enact and enforce national laws to protect the seafloor from damaging activities and pollution.

Beyond the territorial sea, the legal picture changes. In the Exclusive Economic Zone (EEZ) and, particularly, concerning activities on the continental shelf, coastal States hold exclusive rights over seabed resources and are exclusively responsible for installations and structures, such as offshore wind parks. Yet, these zones do not form part of their territory.



● **FIGURE 14:** Human pressures on the global seafloor and the water column. Six global maps illustrating the spatial extent of human activities and industrial interests in the marine environment, from the coastal shelf to the abyssal plains. (A) Global bathymetry and pelagic depth zones, highlighting the principal vertical domains of the water column, together with major basins, mid-ocean ridges, and oceanic trenches.[141] (B) Non-hydrocarbon marine infrastructure including submarine telecommunications cables (blue lines),[142] major commercial ports (blue dots),[143] offshore wind farms and their associated vessel activity (green density),[144] together with major sea-crossing bridges and submerged tunnels.[145] Offshore wind farms remain largely confined to the epipelagic shelf (typically <60 m for fixed foundations, extending to several hundred meters for floating systems). Combined with shipping lanes and coastal engineering, this network of non-extractive built infrastructure spans the full water column from the shoreline to the deep ocean floor (0 to >6,000 m). (C) Bottom-contacting fishing effort: trawlers and dredges. Apparent fishing effort (hours) by industrial bottom trawlers and dredgers, 2020–2025, based on vessel tracks derived from Automatic Identification Systems (AIS).[146] Bottom trawling currently impacts the seabed from the coastline to roughly 4,000 m depth, and the operating depth has been steadily increasing as continental shelves are depleted and gear is adapted for deeper grounds. The footprint highlights chronic seabed disturbance along continental shelves, slopes, and seamounts. (D) Global shipping density. Cumulative density of commercial vessel traffic, revealing the principal trans-oceanic shipping corridors and choke points.[146–148] Although vessels themselves operate at the surface (epipelagic), shipping lanes are sustained by a coastal-to-deep-sea infrastructure footprint (ports, dredged channels, anchorages, cables, and pipelines) extending from 0 to more than 6,000 m. (E) Polymetallic nodule fields and exploration contracts. Composite map of abyssal areas geologically favorable to manganese-nodule formation (beige areas);[149] documented nodule occurrences enriched in iron (blue dots) and manganese (red dots);[150] and polymetallic-nodule exploration contract areas issued by the International Seabed Authority in the high seas (black polygons).[151] Whereas seabed mining as a whole could potentially affect any depth from the shore to 6,000 m, commercial interest in polymetallic nodules is concentrated in the abyssopelagic zone, between approximately 4,000 and 6,000 m. (F) Offshore hydrocarbon system: extraction, transport, and export. End-to-end footprint of the marine hydrocarbon value chain, from wellhead to liquefaction terminal: offshore oil-and-gas platforms and their associated vessel activity (brown density, 2017–2021);[144] submarine oil and gas pipelines (red lines);[152] LNG export and import terminals (red dots) and the global density of LNG tanker traffic linking them.[153] The hydrocarbon system reaches from coastal LNG terminals through the epipelagic, mesopelagic, and bathypelagic zones into the abyssopelagic, with platforms now operating at depths exceeding 3,000 m.

States enjoy only sovereign rights, not full sovereignty. Both the EEZ and the continental shelf measure up to 200 nautical miles. While the continental shelf can be extended in certain circumstances, the EEZ cannot. Where the EEZ and continental shelf coincide, the coastal State may regulate not only general environmental protection but also fishing practices that damage the seafloor, as well as the exploitation of non-living seabed resources.

Beyond zones of full or partial national jurisdiction, the deep seabed begins: "the Area". UNCLOS designates the Area as the "common heritage" of humankind. States may not appropriate its mineral resources unilaterally. The International Seabed Authority (ISA), established by UNCLOS, holds the mandate to license seabed activities and to develop binding rules – the so-called Mining Code – governing conditions for access and liability. The ISA is only responsible for mineral resources and has no general mandate for seafloor protection and the regulation of bottom trawling. So far, consensus on commercial mining regulations has proved elusive, and the ISA has only issued exploration licenses. It has set aside areas of particular environmental interest for which no licenses are granted, although its mandate is restricted to mineral resources and does not extend to other potentially damaging activities. Over 40 states have called for a moratorium on commercial seabed mining pending further environmental research.

The most recent addition to the legal framework is the Agreement on Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ), or the High Seas Treaty, which entered into force in January 2026. It aims to protect marine biodiversity beyond national jurisdiction, including the deep seabed, among other things by enabling the creation of marine protected areas and strengthening environmental impact assessment requirements. Its practical effectiveness, however, depends on political will and concrete implementation. For the deep seabed, close cooperation with the ISA will be required.

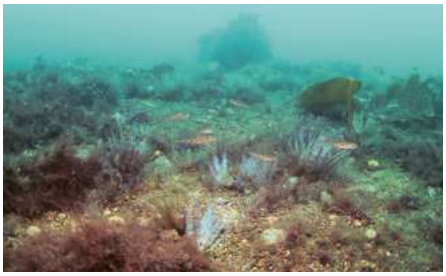
The main governance challenges are structural. Fragmentation between additional legal regimes – covering fisheries, shipping, seabed mining, and biodiversity in separate silos – makes integrated governance of cumulative impacts on the seafloor especially difficult. Monitoring and enforcement capacity is also highly uneven across States. The recent US executive order claiming the right to issue unilateral deep seabed mining licenses under a 1980 domestic statute – bypassing the ISA entirely – illustrates a broader risk: If unilateral licensing spreads, the "common heritage" principle and the institutional architecture built around it could be fundamentally undermined at the very moment when agreed international standards are most urgently needed.

The formal legal role of non-State actors remains limited, since international law binds States rather than individuals or companies directly. Nevertheless, civil society advocacy, scientific advice, and corporate due diligence can exert real influence. Ultimately, however, effective protection of the seafloor beyond national jurisdiction remains predominantly a question of multilateral governance and political commitment. Protecting seafloor integrity will therefore require stronger international cooperation, including effectively managed marine protected areas, safeguards against destructive activities in vulnerable habitats, cumulative-impact assessments, and a precautionary approach to emerging industries such as deep-sea mining.

Case study

Loss of seafloor integrity in the Baltic Sea

The Baltic Sea has a long history of anthropogenic disturbance, which began earlier than in most other oceans and marginal seas.[139] Today, the health state of the Baltic Sea is disastrous. Considering morphology, biogeochemistry, and the benthic ecosystem, there is not a single square meter of Baltic seafloor that is not anthropogenically altered. Decades of bottom trawling, eutrophication and oxygen depletion have transformed large parts of the Baltic seafloor, reducing habitat quality, biodiversity and benthic ecosystem functioning. These changes reinforce one another, making recovery increasingly difficult even if individual pressures are reduced.[139,140] Studying the loss of seafloor integrity in the Baltic Sea, and its link to declining ecosystem health, can provide insight into how environmental conditions and marine ecosystems may change more broadly in the Anthropocene, as increasing technological access brings larger parts of the global seafloor within reach of human activities.



● **FIGURE 15:** In bottom-contact fishing, weighted nets are dragged across the seafloor at speed, destroying bottom-dwelling life indiscriminately and swirling up great amounts of sediment. Top: Photographed from inside a trawl net, which is churning up the sediments as it is being dragged across the seafloor. Middle left: Intact seabed off the island of Arran, Scotland, with juvenile cod swimming over a healthy seagrass meadow. Middle right: The same area, recently devastated by scallop dredge fishing. Bottom: Aerial view of churned up sediments from bottom-contact fishing. Top and bottom images as featured in Ocean with David Attenborough; credit: Open Planet Studios, Silverback Films, and the Open Planet library. Middle images, credit: Howard Wood/COAST.

4.3 Novel Entities: Known Impacts and Unknown Planetary Threats

Guest authors: Miriam L. Diamond, Department of Earth Sciences & School of the Environment, University of Toronto
Anna Shalin, Department of Earth Sciences, University of Toronto
Zhanyun Wang, Department of Green Technology & Danish Institute for Advanced Study, University of Southern Denmark

Can't live without them, but some can't live because of them

Novel Entities present a paradox – many are essential and irrevocably embedded in modern society. And yet many are also causing short- to long-term, irreversible impacts, including serious harm to ecosystems that provide critical Earth system functions.

Novel Entities comprise a very large and diverse basket of "new", human-synthesized chemicals and materials such as pesticides, plasticizers, per- and polyfluoroalkyl substances (PFASs) and plastics that have become enmeshed in daily use, especially since the 1950s. Depending on the definition, they also include naturally occurring metals and other elements whose natural cycling and chemistry humans have altered,[154,155] as well as genetically modified organisms. In this article, we will focus on human-synthesized or -mobilized chemicals and materials.

To date, hundreds of thousands of chemicals have been registered for use globally, with new ones continuously entering the market. Materials, such as plastics, are diverse and complex as well. The rapid rise in the number and diversity of Novel Entities contributes to the "great acceleration" that is modifying the planet.[8] There is no place on Earth untouched by Novel Entities, from the bottom of the sea to orbiting "space junk".

Too little is known about the vast majority of Novel Entities, even including their identity, let alone their safety. Nevertheless, growing evidence shows that many Novel Entities seriously impact the Earth's biophysical processes at local to planetary scales, with concerns mounting over the extent and irreversibility of those impacts. ● **FIG. 16** summarizes some of the better-known impacts on ecosystems and human populations. It also highlights the considerable unknowns and uncertainties along the pathway from the production of Novel Entities to their presence in the environment, associated exposures, and resulting impacts. Below, we highlight key lessons learned from those impacts to ecosystems and present some solutions for consideration.

Novel Entities are eroding ecosystem health and resilience

Novel Entities cause impacts along their life cycle, from resource extraction and manufacturing to their use, and finally their disposal. Those impacts come from physical, chemical, and biological disruptions, which may interact with other boundaries – notably **Climate Change**, **Stratospheric Ozone Depletion**, **Atmospheric Aerosol Loading**, **Change in Biosphere Integrity**, **Land System Change**, and **Modification of Biogeochemical Flows**. For example, Novel Entities include fluorinated gas refrigerants that play a key role in accelerating **Climate Change**, and in some cases also contribute to **Stratospheric Ozone Depletion**.

Furthermore, evidence is clear and compelling that pollution from many Novel Entities is toxic to the biosphere, disrupting ecosystem functioning, and reducing the resilience of ecosystems to respond to other assaults from, for example, **Climate Change** and **Ocean Acidification**. Chemical pollution has been named as one of the five major drivers of global biodiversity loss[156] by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Nearly 14% of the 84,000 animal species on the "Red List" of threatened species kept by the International Union for Conservation of Nature (IUCN) have been considered to be affected by pollution.[157] Human populations are also widely exposed to Novel Entities, with mounting evidence of widespread harm.

There is no place on Earth untouched by Novel Entities, from the bottom of the sea to orbiting "space junk".

Some of the impacts to ecosystems lead to extreme disruption. For example, over 45,000 sites worldwide are disturbed by mining activities, with thousands more disturbed by oil and gas extraction, and waste dumping and burning. In mining and oil extraction, these disruptions often arise from bringing toxic substances to the Earth's surface and from the use of hazardous chemicals and materials in the extraction process, alongside physical disturbance of the land. These activities contaminate surrounding air, soils, and water, poisoning nearby ecosystems and rendering them unusable for agriculture and human habitation.

Polychlorinated biphenyls (PCBs), chemicals that were widely used in electrical transformers and capacitors between the 1940s and 1980s, are now contributing to the slow demise of Orca populations.

Additionally, there is a long list of Novel Entities that are slowly eroding ecosystem integrity and resilience. For example, the widespread use of agricultural pesticides has been linked to declining populations of pollinators, other "non-target" insects, amphibians, and aquatic biota, with cascading effects on insectivorous birds.[158–161] Polychlorinated biphenyls (PCBs), chemicals that were widely used in electrical transformers and capacitors between the 1940s and 1980s, are now contributing to the slow demise of Orca populations.[162]

Due to the complexity of ecosystem processes, some impacts take decades to become evident. For example, despite early observation of acid rain in the mid 1800s, it took nearly a century for scientists to identify and understand its connection to industrial emissions from mining, mineral processing, and fossil fuel combustion. By then, acid rain had caused large-scale declines and even collapse of some freshwater fish communities, particularly in Northern regions where clear waters lack buffering capacity. Fortunately, many of these declines have now been reversed by concerted efforts to control those industrial emissions. But acid rain from past and continuing emissions is still reducing the growth and resilience of some forests, including reduced carbon sequestration, as acids have depleted nutrients in soils. These changes are taking decades to reverse.[163]

Plastics raise a new set of concerns. Every year, between 19 and 23 million tonnes of plastic waste enter streams, lakes, and oceans.[164] No place on Earth remains untouched by plastic pollution, and this pollution will persist because of the extraordinary longevity of plastics.[165] Most plastics fragment over time, but take hundreds to thousands of years to mineralize into CO_2. Large plastic debris threatens marine birds, turtles, and mammals with entanglement. Small plastic debris can accumulate in the stomachs of some marine birds, impairing feeding, which can lead to starvation. Very small particles, known as micro- and nanoplastics, are now in virtually every organism, including humans. The impacts of micro- and nanoplastics remain insufficiently understood – but this uncertainty is itself a serious concern, given their growing presence and potential risks to ecosystems and human health. This is partly due to the release of many plastic additives and other chemicals therein, only some of which have been well-researched in terms of toxicity. Initial evidence also suggests that plastic debris might interfere with the Earth's natural carbon cycling and the biological carbon "pump",[166] which moves carbon from the surface ocean to deep waters and ultimately to the seafloor. This potential impact is under further investigation.

Taken together, ubiquitous pollution from Novel Entities, including plastics, is challenging the functioning of global ecosystems that are already severely impacted by **Change in Biosphere Integrity, Climate Change,** and **Land System Change**, pushing them toward or beyond the Planetary Boundary. Importantly, the illustrative examples discussed above represent only the tip of the iceberg. Many other known impacts exist, and still more are likely to arise in the future since most Novel Entities and their effects remain poorly understood. Furthermore, these examples do not account for the *interactions* among different Novel Entities. The overall impacts of Novel Entities are therefore very likely more extensive and severe than observations of better-known ones currently suggest.

Challenges in reversing the global impacts of Novel Entities

The danger of many Novel Entities lies in their staying power. Some resist degradation to a remarkable degree, while others only partially degrade, forming additional chemicals and materials that can persist for decades. Once released, they can spread across the globe, accumulating in the environment as production and use continue to increase.

Among chemicals infamous for their persistence, global distribution and toxic effects are persistent organic pollutants (POPs). PCBs, among the most

prominent examples of POPs, illustrate how long these impacts can endure: Although most production stopped by the 1980s, they remain at high levels in the environment today and continue to contribute to the decline of long-lived whale populations. Soils to which DDT was applied decades ago can still retain high concentrations, which move through the food web to harm bird populations.[167] Many PFASs contaminate surface and groundwater worldwide, with this pollution expected to last for centuries to millennia, risking very long-term harm to exposed ecosystems and human populations.

Toxic metals are inherently persistent and can pose risks. For example, just in Europe, a million wildfowl are estimated to die annually from lead exposure leaching from spent ammunition, with over three million more experiencing sub-lethal effects.[168] Mercury provides another example: Human activities have tripled atmospheric mercury levels since 1850, increasing long-term exposures to global wildlife and causing effects such as lower reproductive success[169] and behavioral changes in some populations.

Even natural materials, subject to chemical alteration by humans, can persist in the environment and pose a long-term source of exposure and potential risk to ecosystems. Human-modified indigo denim fibers from blue jeans are found in the sediment of Arctic waters, thousands of kilometers from their point of release,[170] where they can enter the aquatic food chain and could cause harmful effects,[171] partly due to the chemicals they carry.

Poorly reversible impacts can also come from the evolutionary pressure that chemicals can exert on ecosystems. Biocides and antimicrobials, such as antibiotics used in humans and farm animals, are increasing the abundance of antimicrobial resistant genes in surface water ecosystems receiving treated and untreated wastewater. Globally, antibiotic concentrations exceed safe thresholds in an estimated 6 million kilometers (at low flow) of rivers from human antibiotic consumption alone.[172]

Even the more short-lived Novel Entities provide significant challenges. Economic, political, social and technological factors may be very resistant to change, and "lock-in" continued production, release, and destructive impacts.[173,174]

Overall, society's ability to reverse the global impacts of Novel Entities is limited. Many persist in the environment, cause damage that outlasts their release, or are sustained by social and industrial systems that are hard to unwind. These conditions demand early and decisive action to reduce impacts, even while major knowledge gaps remain about the full range of Novel Entities and their impacts on the Earth system.

Society can reduce harms from Novel Entities

The Planetary Boundaries are intended to be guardrails that ensure Earth system processes remain in a Holocene-like, civilization-friendly state. Evidence continues to mount that global pollution by Novel Entities is approaching or exceeding these guardrails.[175,176] But it is not inevitable that societies continue to poison themselves and their environment. After over a century of inventing, producing, using, and disposing of chemicals and materials through a largely technology-centered approach, societies must fundamentally rethink their relationship with Novel Entities. This broader rethinking can begin with specific applications, asking where hazardous chemicals and materials are truly necessary and where they can be avoided or replaced.

Overall, society's ability to reverse the global impacts of Novel Entities is limited.

Pulling back from current unsustainable practices to safer conditions will require ambitious changes. Fortunately, some solutions are available today. Actions can start with reversing the trend of ever-increasing rates of Novel Entity production, which currently exceed the rate of population growth. For example, the production of basic petrochemicals, from which many industrial chemicals and plastics are derived, doubled between 1990 and 2010. Continuing business as usual, production of these basic petrochemicals could more than triple by 2030 compared with 2010.[177] However, global production has recently stagnated because of structural overcapacity,[178] highlighting the potential to reduce production to better align with actual demand. Part of the demand can be further reduced by addressing overconsumption in high-income countries. For example, the material footprint of high-income countries is six times higher than that of low-income countries. Notably,[179] this overconsumption among high-income countries comes with disproportionate environmental impacts in lower-income countries.[180,181]

Pulling back from current unsustainable practices to safer conditions will require ambitious changes. Fortunately, some solutions are available today.

Next, the rate of Novel Entities proliferation needs to be tamed. Currently, more than 350,000 individual chemicals and mixtures have been registered for large-scale production and use in different parts of the world,[182] with new chemicals and materials continually introduced to the market. This proliferation could be addressed through simplification, i.e., using fewer and less diverse Novel Entities to achieve the same functions. One potential pathway is to advance the development of Novel Entities that are *Safe and Sustainable by Design* (SSbD),[183] coupled with effective mechanisms to phase out other chemicals and materials used for the same applications, particularly those that are known to be problematic.

Determining which Novel Entities may continue to be used, and for which applications, will be challenging. However, we take inspiration by seeing the progress with POPs listed under the Stockholm Convention – through dedicated restriction/elimination efforts, levels of these chemicals are declining worldwide.[184] This approach needs to be taken further to reduce, or better yet, eliminate the non-essential use of other hazardous Novel Entities. The concept of "essential use" was first introduced in the 1970s during discussions about restricting the use of ozone-depleting substances. It was then incorporated into the Montreal Protocol that has effectively reduced the production of ozone-depleting substances. Recently, the essential use concept has been introduced to guide the phase-out of PFASs,[185] and could be applied to other hazardous chemicals and materials.

In closing, the evidence is staring humanity in the face – many Novel Entities are causing significant harm to the Earth's biophysical processes, including ecosystems, and hence are threatening planetary health. The situation is worsening and demands urgent action. More evidence can strengthen societies' understanding of the matter, but it should not be used to delay actions. Rather, greater ambition and decisive measures are needed now to curb these threats and to pull humanity back from breaching this Planetary Boundary. In this context, less can indeed be more.

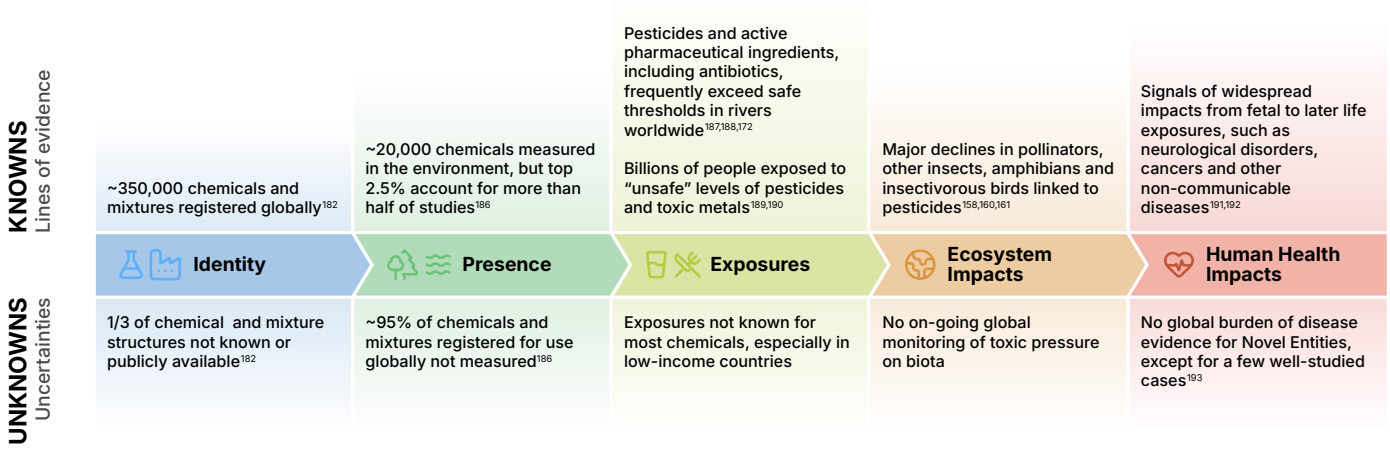
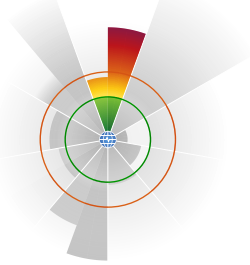


FIGURE 16: Novel Entities pose significant threats to the functioning of the planet, as well as for human well-being. Much is already known about widespread contamination with various substances, and observations of additional destructive impacts are emerging. However, some of the greatest risks lie in the "unknowns": impacts of pollution that we are not yet aware of, but which may already be causing grave harm, or may do so in the future. By the time these effects become widely recognized and understood, it may be too late to reverse them.[158,160,161,172,182,186–193]

5 | Planetary Boundary Information Sheets

Photography by Mattias Klum

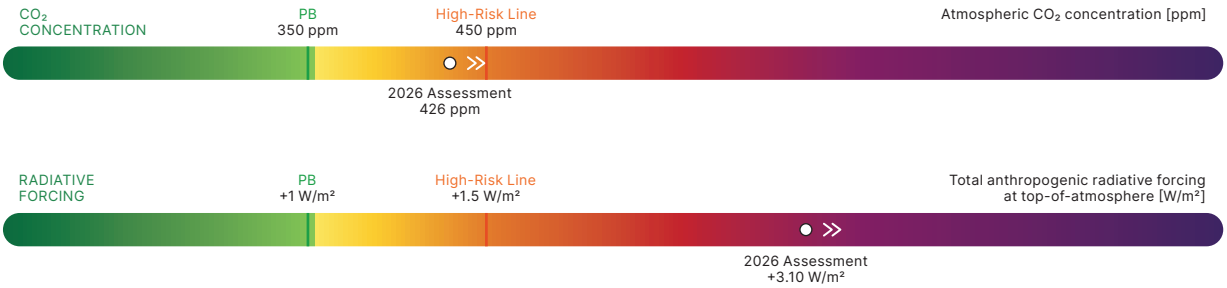
5.1 Climate Change



MAIN TAKEAWAY

Climate Change is disrupting the Earth's climate system in ways that threaten the foundations of human well being. By burning fossil fuels, clearing forests, and altering the land, humanity is releasing large amounts of greenhouse gases that trap extra heat in the atmosphere. This is pushing the planet beyond its natural limits. As a result, global temperatures are increasing, ice sheets are melting, and weather patterns are becoming more extreme. Sea levels are rising, and ecosystems are under stress.

These changes increase the risk of crossing dangerous tipping points – irreversible shifts in Earth's systems that could lock in long-term damage. Communities around the world are already experiencing more heatwaves, droughts, floods, and storms. Without urgent action, continued climate disruption risks triggering irreversible changes in Earth's systems, undermining ecosystems, human health, and societal stability for generations to come.



Definition

Climate Change refers to long-term shifts in temperature and weather patterns. The Planetary Boundary for **Climate Change** is defined to avoid transgressing levels of climate-system change beyond which the risks of triggering irreversible changes, such as large-scale melting of polar ice sheets, increase significantly. A necessary condition for the overall stability of the climate system is to limit the accumulation of heat within the Earth system. This accumulation results from persistent perturbations to Earth's energy balance, i.e., the balance between incoming solar radiation and outgoing energy. Today, human activities are the dominant cause of these perturbations, most notably through the emission of greenhouse gases, such as CO_2, which reduce the loss of heat to space and thereby destabilize the climate system.

2026 Status

The atmospheric concentration of CO_2 (426 ppm) and the total anthropogenic radiative forcing at the top of the atmosphere (+ 3.10 W/m²) have long **exceeded their safe levels** (350 ppm and 1 W/ m², respectively). This transgression is dangerously increasing global temperatures, intensifying climate impacts, and increasing the likelihood of crossing critical tipping points in Earth's climate system.

CONTROL VARIABLE

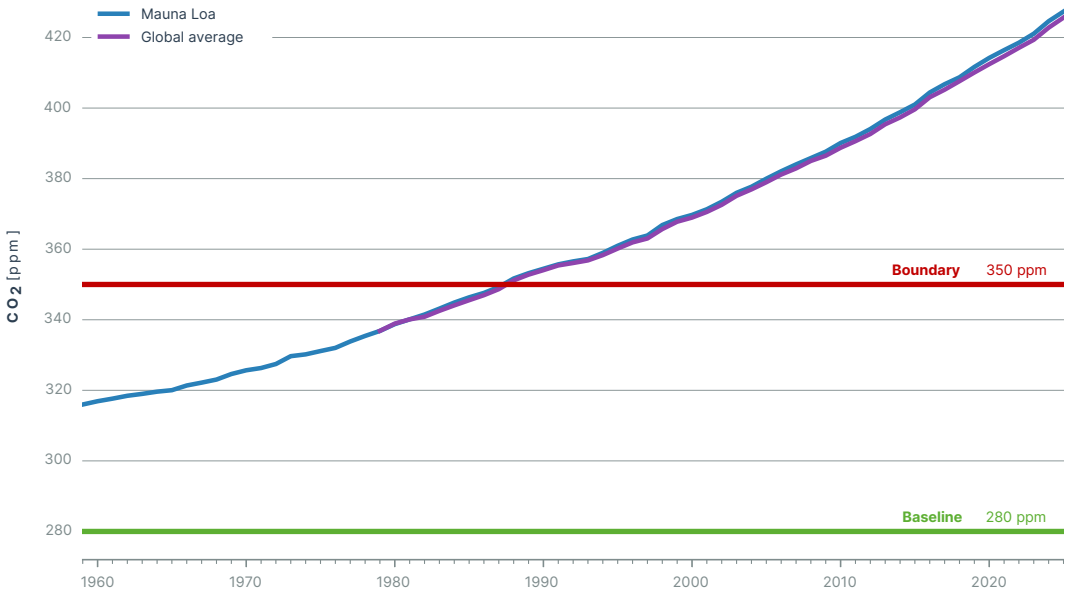
Atmospheric CO_2 Concentration (CO_2)

DEFINITION Atmospheric CO_2 is a primary greenhouse gas emitted by human activities such as fossil fuel combustion, deforestation, and cement production. It is a key driver of Climate Change.[11] CO_2 is relatively straightforward to monitor through atmospheric measurements, satellite observations, and carbon budget assessments.

UNIT Parts per million (ppm)

HISTORICAL RANGE Over the course of Earth's history, CO_2 levels have naturally fluctuated between about 180–200 ppm during ice ages and around 280 ppm during the pre-industrial Holocene period.[194]

PLANETARY BOUNDARY (PB) Scientists have proposed a PB for CO_2 at 350 ppm, based on paleoclimate evidence and climate modeling. This threshold represents a point beyond which the risks of triggering irreversible changes, such as large-scale melting of polar ice sheets, increase significantly.[71,195–197] It also aligns with the internationally recognized goal of limiting global warming to 1.5°C above pre-industrial levels, as agreed upon in the Paris Climate Agreement.[10]



● **FIGURE 17:** Atmospheric CO_2 concentration far exceeds the safe level. This figure illustrates the steady increase in the atmospheric CO_2 concentration, as one of the Climate Change boundary's control variables. The blue line represents annual mean values from 1959 to 2025 at the Mauna Loa Observatory in Hawaii, operated by the National Oceanic and Atmospheric Administration (NOAA).[198] The dark violet line shows globally averaged CO_2 concentrations from multiple international monitoring sites,[198] including Mauna Loa. The green and red lines indicate the baseline (safe) value (280 ppm) and the Planetary Boundary threshold (350 ppm) for this control variable, respectively.

KEY TAKEAWAY: CO_2 continues to rise and remains the dominant driver of climate change, with current levels approximately 50% above pre-industrial concentrations.

CONTROL VARIABLE

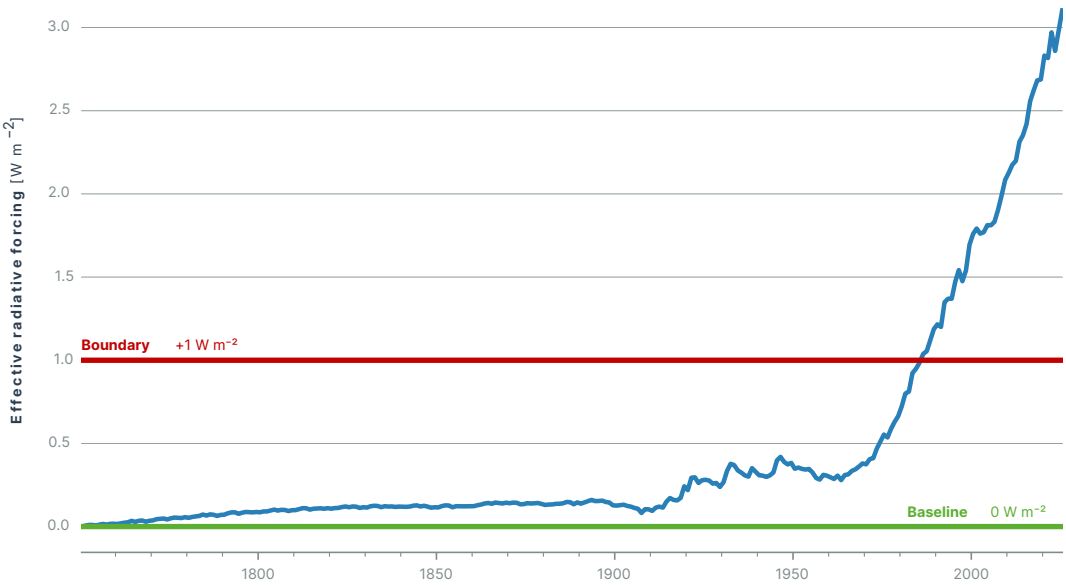
Total Anthropogenic Radiative Forcing at the Top of the Atmosphere (TOA)

DEFINITION The net radiative forcing sums up all the ways human activities impact the global climate. This includes emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as aerosols and land-use changes. Radiative forcing is a key measure of how much additional heat energy is added to the Earth system. It integrates the effects of all human activities that influence the planet's energy balance and therefore represents the overall strength of human-induced climate change.[11] While changes in TOA fluxes can be measured via satellites, estimating the human-caused component depends on climate models. This makes it a powerful, system-level signal, but also more abstract and less directly observable than CO_2 or temperature.

UNIT Watts per square meter (W/m²)

HISTORICAL RANGE During the pre-industrial Holocene, the radiative forcing remained relatively stable with small fluctuations due to land cover changes and volcanic activity,[199,200] indicating a stable energy balance under which human civilizations developed. Significant positive forcing began with the Industrial Revolution, as greenhouse gas concentrations rose due to fossil fuel combustion and land conversion.[201]

PLANETARY BOUNDARY (PB) Scientists have proposed a PB for total anthropogenic radiative forcing at +1.0 W/m², relative to pre-industrial levels. This threshold is based on the climate system's sensitivity to greenhouse gas forcing, observed responses of polar ice sheets to warming, and growing evidence of climate instability at forcing levels above +1.5 W/m².[9] Exceeding this boundary increases the risk of irreversible climate impacts and triggering long-term destabilizing system feedback loops.



● **FIGURE 18:** Disturbance of our planet's energy balance. This figure shows the global average of human-induced radiative forcing at the top of the atmosphere from 1750 to 2025.[21,202] The values were calculated using observational data and established climate models, based on methods from the IPCC. The green line marks the safe baseline (0.0 W/m²), and the red line indicates the Planetary Boundary (+1.0 W/m²).

KEY TAKEAWAY: Human activities have significantly increased net radiative forcing to three times the safe limit, exerting a persistent warming influence on the Earth system and pushing well beyond the safe threshold.

Key Drivers

Climate Change is caused by a mix of natural and human influences, but human activity is by far the dominant cause of recent warming.[203] The most important human drivers are those that disturb Earth's radiative balance, i.e. the difference between incoming energy from the sun and outgoing energy from Earth. A key driver is the release of greenhouse gases, which trap heat within the Earth system. The main gases are carbon dioxide (CO_2), released by burning fossil fuels like coal, oil, and gas (SEE ● FIG. 17); methane (CH_4), connected to agricultural activities, fossil fuel extraction, and landfills; and nitrous oxide (N_2O), mostly from fertilizer use (SEE ● FIG. 21).[204,205] These gases stay in the atmosphere for years or even centuries, steadily warming the planet.[206] Water vapor is also a powerful greenhouse gas, although it mostly increases via a feedback process when the planet gets warmer, primarily due to the increase in CO_2.[207]

Other human activities affect the climate too. Aerosols – tiny particles from burning fuels or biomass – can cool or warm the atmosphere depending on their type and location.[208] Land-use changes, such as deforestation and urban development, reduce the planet's ability to absorb CO_2 and change how sunlight is reflected or absorbed by the surface.[209]

These changes are closely linked to major sectors of the economy. Energy production, transportation, and agriculture are among the largest sources of greenhouse gases.[209] Decisions that societies make in areas such as electricity production, food production, and transportation therefore have a major impact on the climate.

Impacts

As more heat is trapped in the Earth system, temperatures rise in the atmosphere, oceans, and on land (SEE ● FIG. 20). This leads to more extreme weather, including heatwaves, floods, droughts, and heavy rainfall.[211] Human-driven climate change now far exceeds natural variability.[212]

Ecosystems are under growing pressure. In the oceans, warming and acidification disrupt food webs and force species to migrate.[213] On land, ecosystems are degrading, and species are struggling to adapt.[214] Agriculture and food security are increasingly vulnerable. Shifting rainfall patterns and rising temperatures affect crop yields and water availability, threatening livelihoods and regional stability.[215,216] Melting land ice and rising sea levels put coastal areas and island nations at risk. As ice and snow reflect more sunlight than the surface beneath them, further warming is accelerated, bringing us closer to potential tipping points.[212]

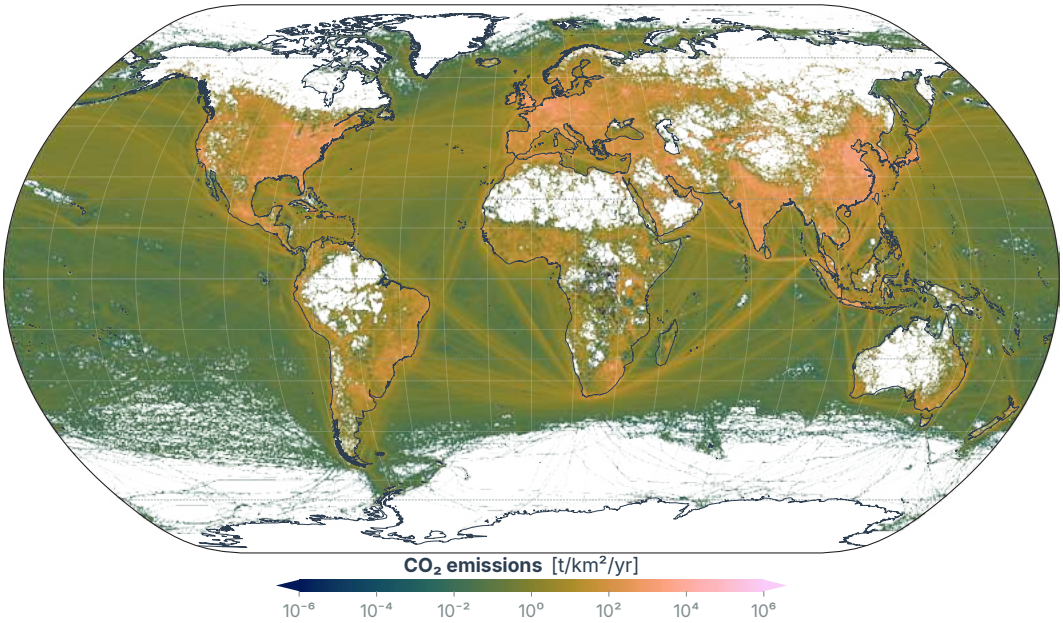
Climate Change also impacts human health, increasing exposure to heat stress, air pollution, and disease.[217] Social systems, from infrastructure to economies, face mounting pressure from more frequent and intense climate shocks.

Because **Climate Change** strongly influences all other Planetary Boundaries,[39] breaching this threshold puts the entire Earth system at risk. Staying beyond the safe zone increases the chance of irreversible changes that could affect life on Earth for generations to come.

Current and Future Research

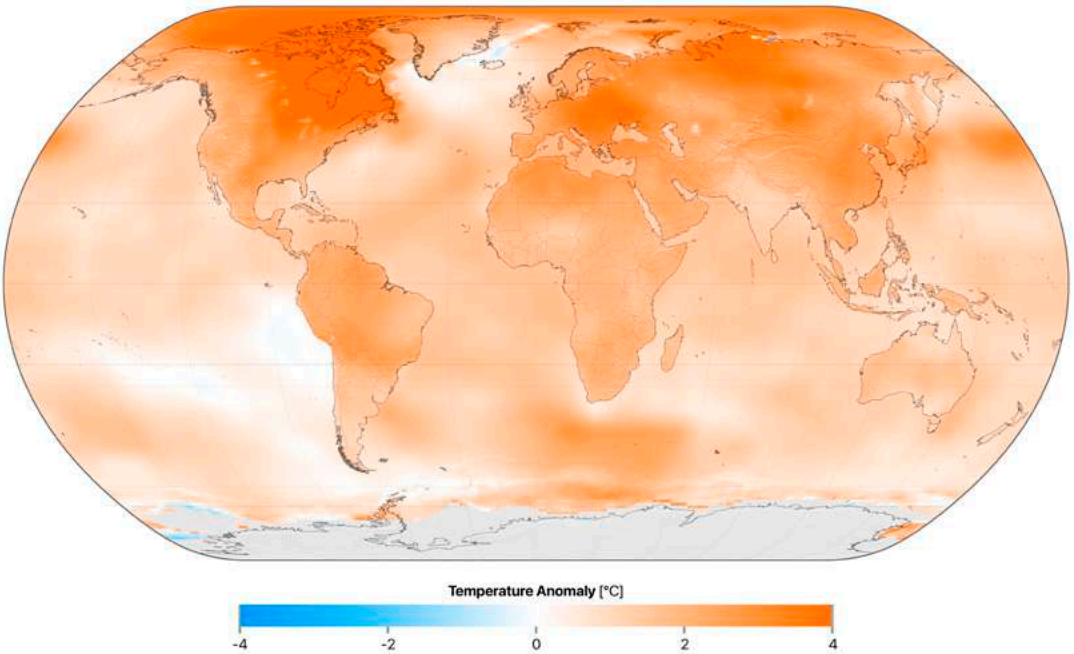
CO_2 concentration and net radiative forcing provide a robust picture of how humanity is disturbing the global climate system. At the same time, other variables may be better suited to tracking regional climate risks, specific drivers, or early-warning signs of impacts. For example, recent research highlights the critical role of non-CO_2 greenhouse gases, especially methane (CH_4) and nitrous oxide (N_2O). Although they occur in lower concentrations than CO_2, they have much stronger warming potentials per molecule: CH_4 is 28 times more potent over a 100-year period, and N_2O is 265 times more potent.[223] CH_4 is mainly emitted from agriculture, fossil fuel operations, and land use, and has an atmospheric lifetime of about a decade. N_2O is longer-lived and linked to nitrogen fertilizers and industrial processes. These differences in potency, source, and lifetime are reflected in recent estimates of gas-specific temperature contributions (SEE ● FIG. 21).

This growing recognition supports the case for complementary control variables, such as global mean surface temperatures,[55] which are widely used in policy contexts and underpin the Paris Agreement's 1.5°C and 2°C targets. Yet temperature is a lagging indicator, responding to past emissions with a delay. This delayed response – sometimes referred to as *committed warming* – can be a limitation when early detection of changes in the climate system is needed. Such a leading indicator of future warming is the Earth energy imbalance at the top of the atmosphere (SEE ● FIG. 22). The Earth's energy imbalance measures the energy difference between incoming and outgoing radiation. It indicates how far the Earth is out of equilibrium and consequently, the magnitude of additional warming that is already committed.



● **FIGURE 19:** Where climate change begins – Global patterns of fossil CO_2 emissions. The map shows fossil CO_2 emissions intensity in 2025, expressed as tonnes of CO_2 per square kilometer per year on a 0.1° × 0.1° grid. This data from Climate TRACE combines satellite observations with AI models to measure emissions from thousands of individual facilities worldwide.[210] Emissions are most intense in areas with dense industrial activity, urbanization, and fossil fuel use.

KEY TAKEAWAY: Fossil CO_2 emissions are highly uneven across the globe – concentrated in heavily populated areas, with further hotspots such as industrial operations, resource extraction, and shipping.



● **FIGURE 20:** How Earth's temperature has changed since the late 19th century. This map shows how the Earth's surface temperature[218] changed in 2024 compared to the average from 1880 to 1899, before modern climate change began. Red areas are warmer, while blue areas are cooler.

KEY TAKEAWAY: The map reveals a clear global warming trend, with almost every region showing increased temperatures. Land areas have warmed faster than oceans, and the Arctic is heating up more than twice as fast as the global average – a well-known effect called Arctic amplification.

Other candidates include ocean heat content, which integrates the vast majority of excess energy trapped in the climate system. While scientifically robust, it is harder to measure comprehensively and lacks the intuitive clarity of temperature or CO_2. There's a trade-off between how useful a climate measure is for policy and how fully it reflects the physical reality when comparing different control variables. None of these alternatives fully replace the current control variables, but they offer complementary insights. Some may be more useful for communicating risk, guiding policy, or monitoring specific sectors or regions.

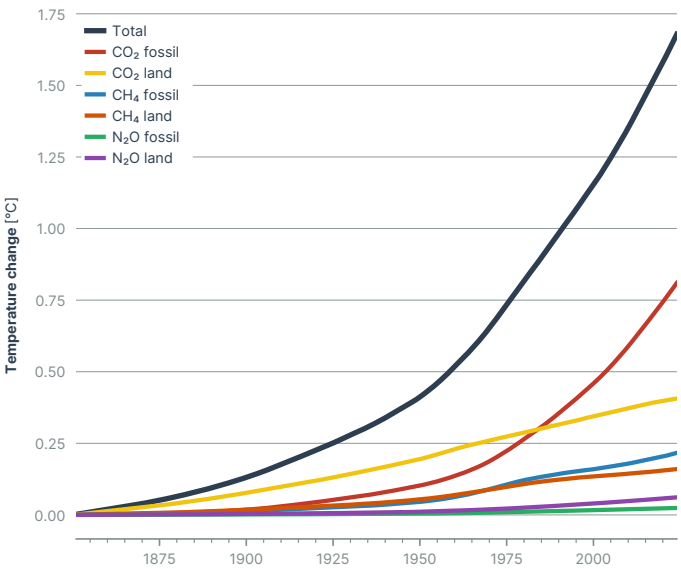
At the regional scale, there is growing interest in early-warning indicators that could flag loss of resilience in critical parts of the Earth system – the Greenland and West Antarctic ice sheets, the Amazon rainforest, or the Atlantic Meridional Overturning Circulation (AMOC), for instance.[71]

These regions may approach tipping points before global averages shift significantly. Although region-specific variables are not suited to defining the global climate boundary, they could play a role in a layered monitoring approach, or even define regional boundaries relevant to ecosystem-based governance or adaptation strategies.

In summary, current research focuses on finding a balanced approach, one that allows for quantitative results while still capturing the full complexity of systems, ensures global standards without losing local relevance, and maintains scientific rigor while being practical for policymakers. While atmospheric CO_2 and radiative forcing remain strong foundations for defining the climate boundary, the case is growing for a suite of complementary indicators to improve our ability to detect, understand, and respond to climate risks in a rapidly changing world.

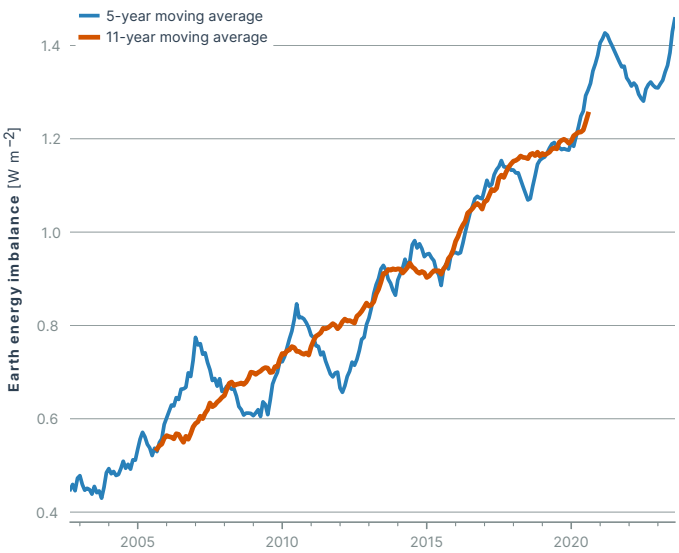
Data Sources

- CO_2 Emissions data from Climate TRACE (2026), accessed 17 April 2026.
- Data on global temperatures from Berkeley Earth.[218,224]
- Data on CO_2 concentrations from Lan et al. (2025),[198] accessed 10 April 2026.
- Data on anthropogenic TOA radiative forcing: Forster et al. (2025),[21] and Smith et al. (2026).[202]
- Other Greenhouse gases: Data adopted from Jones et al. (2023)[219] and Jones et al. (2025).[220]
- Data on Earth energy imbalance from CERES-EBAF: Loeb et al. (2018).[221,222]



● **FIGURE 21:** Different gases and sectors contribute unevenly to climate change. The figure shows the temperature contributions from individual greenhouse gases (CO_2, CH_4, and N_2O) over time, with contributions separated by source category (fossil fuels & industry vs. agriculture & land use).[219,220] These visualizations reinforce the importance of a multi-gas perspective in understanding climate forcing.

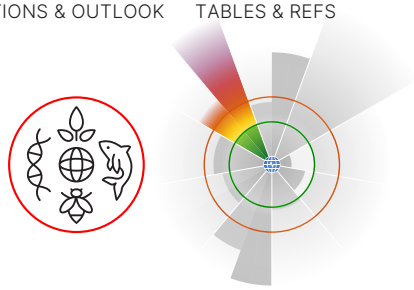
KEY TAKEAWAY: Most of the warming is caused by CO_2 from fossil fuels, but other gases like methane and emissions from agriculture also play a major role – showing why tackling all greenhouse gases is essential.



● **FIGURE 22:** An indicator for the committed warming "in the pipeline". The figure shows the global mean net energy flux into the Earth at the top of the atmosphere based on satellite measurements and analyses of the ocean heat content.[221,222] The red curve shows the 11-year centered moving average, which corresponds to the length of a solar cycle, the blue curve shows the 5-year centered moving average. Currently, the Earth receives more energy from the sun than it radiates back into space, causing temperatures to increase. This imbalance will drive further warming as long as it persists. A larger imbalance indicates greater future warming that is already committed but not yet realized.

KEY TAKEAWAY: The difference between incoming and outgoing radiation has steadily increased. The Earth is moving further from radiative equilibrium and the already committed warming continues to rise.

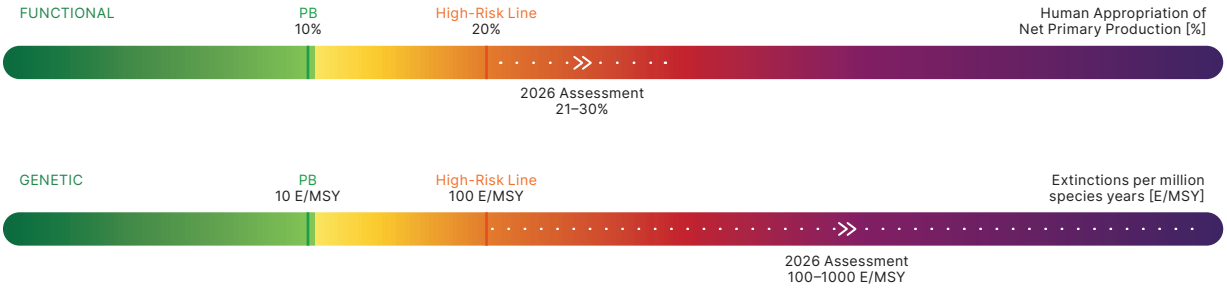
5.2 Change in Biosphere Integrity



MAIN TAKEAWAY

Biosphere Integrity refers to the collective capacity of ecosystems across the planet to support life and maintain the overall health and stability of the Earth system. This depends on the composition and diversity of species, and their interactions as ecosystems. Human activities are putting increasing pressure on Biosphere Integrity through land-use change such as the expansion and intensification of agriculture and livestock production, as well as urban and industrial development, overexploitation of natural resources (like overfishing), the spread of invasive species, and various forms of pollution.

These pressures are further intensified by disruptions in other Planetary Boundaries, including **Climate Change**, **Modification of Biogeochemical Flows** (e.g. fertilizer pollution), and **Novel Entities** (e.g. chemical pollution by toxins and plastics). Today, the Planetary Boundary for Biosphere Integrity is strongly transgressed. When Biosphere Integrity is compromised, Earth system resilience is weakened, threatening the essential conditions that support human life on our planet.



Definition

The Planetary Boundary for **Change in Biosphere Integrity** is defined to safeguard the biosphere's ability to uphold the necessary conditions for life on Earth. This includes the preservation of stable nutrient, energy, water and species flows within and across interconnected, healthy ecosystems. Alarmingly high extinction rates along with the loss of habitats manifest in declining genetic diversity and functional intactness of ecosystems. This threatens the biosphere's ability to regulate and stabilize the state of the planet.

2026 Status

Both control variables for this boundary – genetic diversity and the decline in the functional integrity of the biosphere – have **exceeded their safe levels**. Worldwide, species are going extinct at an alarming rate of above 100 extinctions per million species-years (E/MSY), while the Planetary Boundary is at 10 E/MSY (● FIG. 23), and humans are using 21–30% of the available energy from nature – more than double the Planetary Boundary of this control variable (PB: 10%, ● FIG. 24 AND 25). There have been no new estimates for genetic diversity since the last Planetary Health Check. Additional datasets for the biosphere's functional integrity have been integrated. These report varying values of HANPP, but consistently place the level of transgression within the High-Risk Zone.[10,105,225–227]

CONTROL VARIABLE

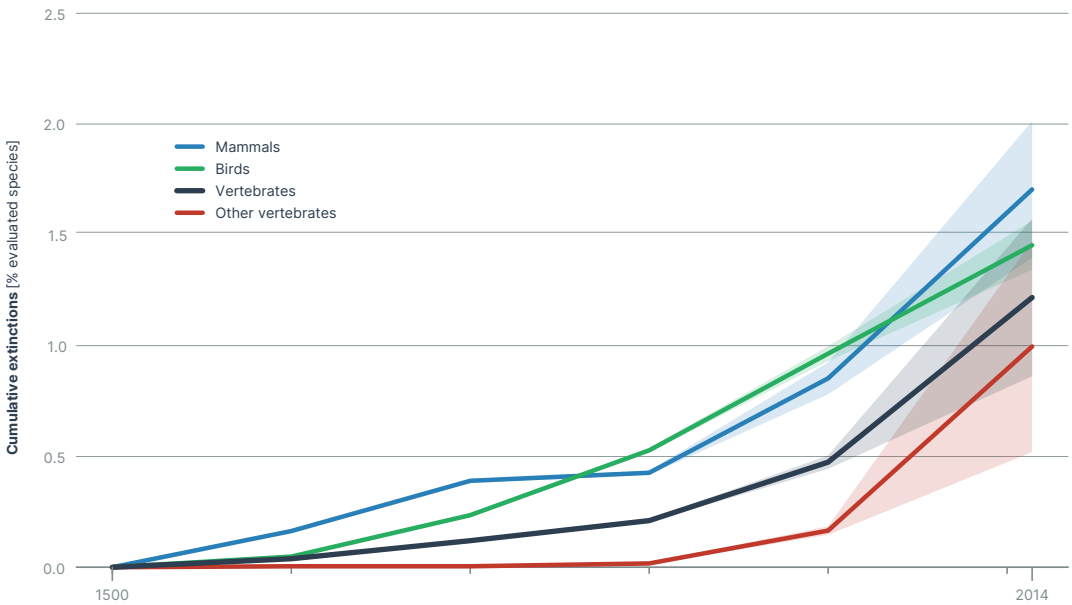
Genetic Diversity: Species Extinction Rate

DEFINITION The decline in genetic diversity, along with the loss of their habitats, threatens the biosphere's ability to co-regulate the state of the planet by impacting the energy balance and chemical cycles on Earth. The **Species Extinction Rate** describes the speed at which the number of species (species richness) is reduced. High species extinction rates negatively impact ecosystem resilience because fewer species can lead to changes in ecological processes and species interactions that maintain ecosystem stability. Species extinction rates are used provisionally as a proxy for loss in genetic diversity and may be refined as more data becomes available.

UNIT Extinctions per Million Species-Years (E/MSY). For example, if 1 species out of 1 million species goes extinct every year, the extinction rate would be 1 E/MSY.

HISTORICAL RANGE The background (i.e. normal) rate of extinction loss is estimated to be 1 E/MSY.[228]

PLANETARY BOUNDARY (PB) The PB is set at 10 E/MSY[11] because, according to latest expert advice, losing species at a rate 10x faster than the natural background rate is what the Earth system can tolerate. The boundary has a wide range of uncertainty (10–100 E/MSY), with the safe threshold reflecting uncertainty and precaution to account for potential knowledge gaps and to minimize the risk of significant Earth system changes.



● **FIGURE 23:** Species extinctions accelerating globally. Increasing species extinction rates are exemplified by extinctions of closely related species with likely common ancestors (genera) per century according to data from Ceballos & Ehrlich (2023).[229] This graph shows that at least 73 genera of vertebrates became extinct over the last 500 years. Complementary estimates for vertebrates and selected terrestrial invertebrate biological groups (taxa) indicate a total extinction rate of up to 100 E/MSY.[10,230–232]

KEY TAKEAWAY: The significant and steadily increasing loss of global biodiversity raises concerns that Earth's biosphere is losing resilience, adaptability and hence its ability to buffer against other Planetary Boundary transgressions.

CONTROL VARIABLE

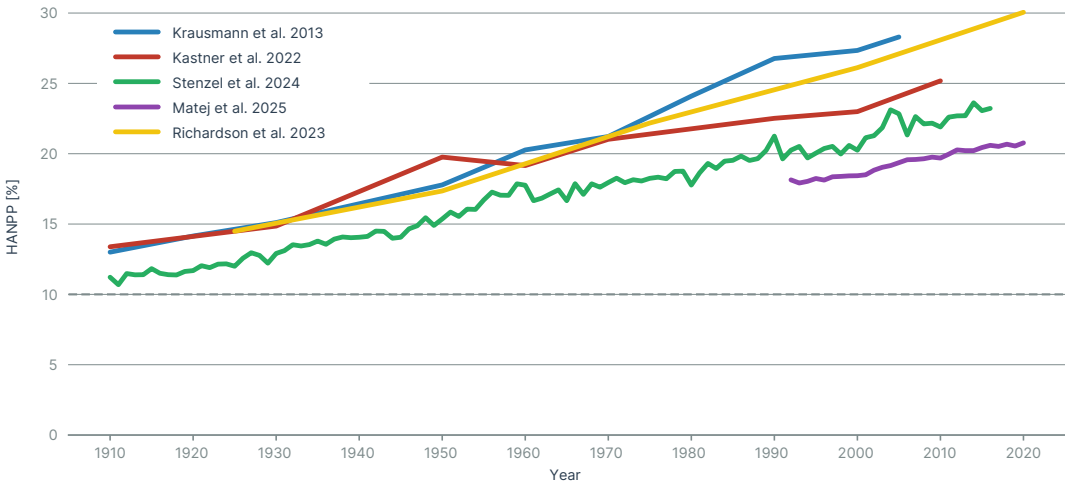
Functional Integrity: Human Appropriation of Net Primary Production (HANPP)

DEFINITION Net primary production (NPP) is the rate at which plants and other photosynthetic organisms produce biomass (organic carbon) in an ecosystem, after accounting for the carbon they use for their own respiration (gross primary production minus respiration). NPP is a fundamental measure of ecosystem productivity and health. It serves as a proxy for the energy flow into the biosphere that all life processes depend on. Human appropriated NPP (HANPP) measures the extent to which human activities, such as agriculture, forestry, and urbanization, appropriate NPP for human use by (1) inhibiting net primary production and (2) withdrawing energy by harvesting products for human use and consumption.

UNIT HANPP is measured in petagrams of carbon appropriated per year. In the context of Planetary Boundaries, HANPP is reported as a fraction of the natural Holocene reference NPP (i.e. energy flows into the biosphere without humans).

HISTORICAL RANGE Without any human activity, HANPP would be zero. For low-impact early human societies, it would be close to zero.

PLANETARY BOUNDARY (PB) The PB is provisionally set at less than 10% of the Holocene reference NPP, and shifts into the zone of high risk at 20%. These thresholds are based on observational data and on ecological models that indicate negative trends in several critical metrics of biosphere functioning.[10,106] As NPP is the basis for the energy and materials flow that underpins the biosphere's functioning,[233] today's impact of HANPP reflects the significant declines seen across major indicators of ecosystem health.



● **FIGURE 24:** The energy we take from nature and use for our purposes. The plot displays the control variable "human appropriation of net primary production (HANPP)", expressed as the percentage of the potential net primary productivity (NPP). The dashed line shows the Planetary Boundary of about 10% HANPP based on Richardson et al., 2023.[10] The displayed datasets differ methodologically, yet consistently indicate that current HANPP levels lie within the High-Risk Zone (>20%).[10,105,225–227] Stenzel et al. (2025) is based on a purely model-driven approach (LPJmL), while Krausmann et al. (2013), Kastner et al. (2022), and Matej et al. (2025) follow inventory-based approaches combined with LPJ-GUESS estimates of potential NPP. Richardson et al. (2023) combines HANPP shares from Krausmann et al. (2013) with a Holocene-like potential NPP derived from LPJmL and CLIMBER-X simulations. The lower HANPP values in Matej et al. (2025) compared to Kastner et al. (2013) mainly result from the exclusion of deforestation and reduced grazing demand in the underlying assumptions.

KEY TAKEAWAY: The current HANPP has exceeded safe levels since at least the early 20th century.

Key Drivers

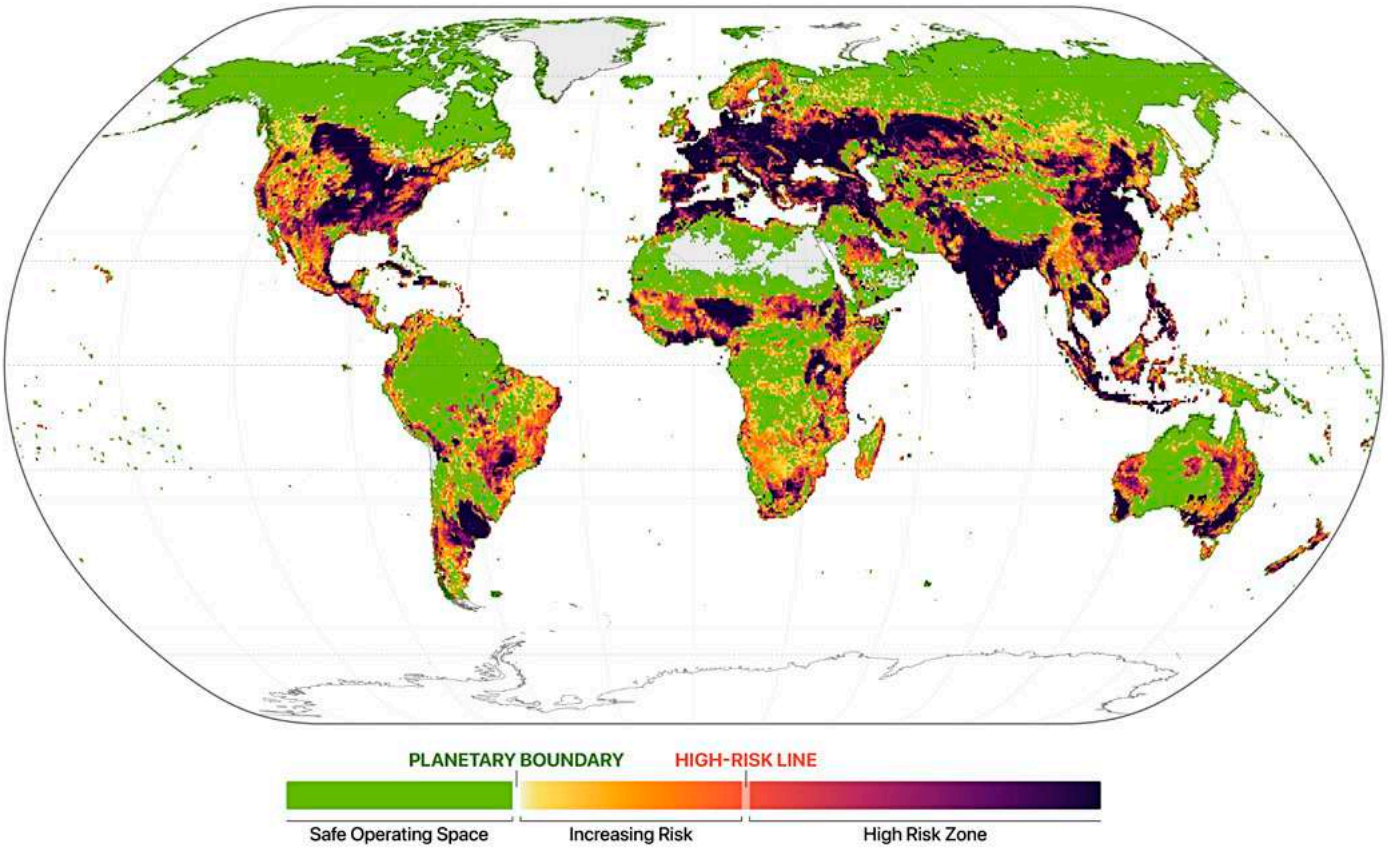
Change in Biosphere Integrity not only reflects the health and resilience of Earth's ecosystems for maintaining biodiversity and ecological functions but also regulates and interacts with most other PB processes, making it essential for the stability of the entire Earth system. This boundary is defined by two control variables: Species Extinction Rate (proxy for Genetic Diversity) and HANPP (proxy for Functional Integrity).

The primary drivers of species loss include the rapid expansions of agricultural and range lands into intact nature, along with the landscape fragmentation that this expansion causes. Species loss is also driven by direct exploitation of ecosystems through human activities such as fishing and logging.[234] **Climate Change**, pollution, and the introduction of invasive species further exacerbate these pressures.[234] These stressors often interact in complex ways, introducing significant uncertainty into predictions of future biodiversity loss.[235,236]

Human appropriation of net primary production (HANPP) for human consumption such as food, fuel, fodder, and fiber has been exceeding sustainable levels for over a century **(● FIG. 24)**.[10] This extraction of energy from the biosphere varies across different ecological regions (biomes) **(● FIG. 25)**; on land, it involves harvesting plant materials and converting natural ecosystems into managed lands.[226] This diminishes the energy available to natural ecosystems, affecting their functioning as vital components of the Earth system. In marine ecosystems, energy extraction primarily occurs through fishing activities, which alter ecosystem dynamics[10,237] **(SEE ALSO CH. 4.2)**.

Impacts

The impacts of losing the integrity and functioning of the biosphere are hard to overstate. The biosphere plays a crucial role in regulating biogeochemical processes and energy balances. Changes in species



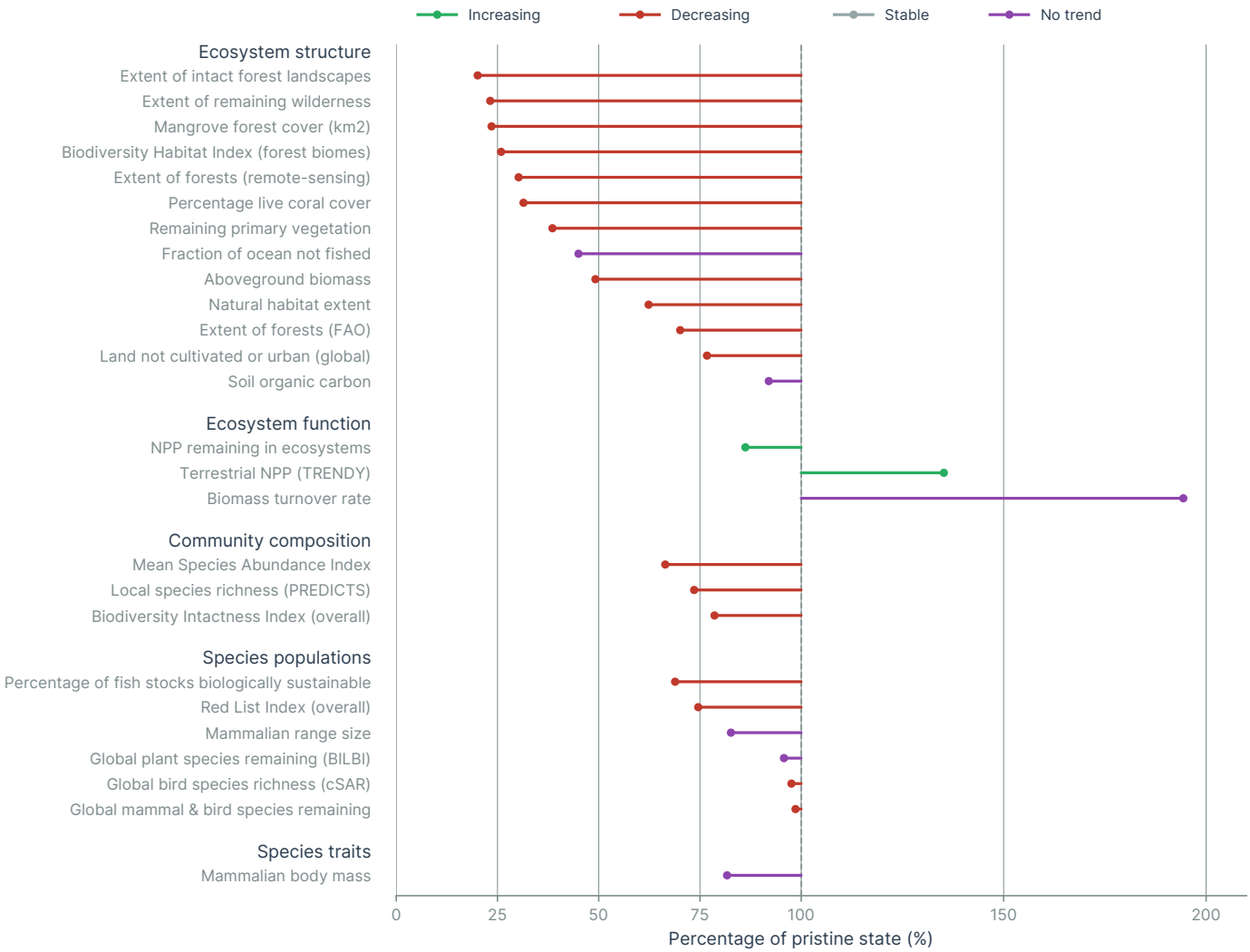
● **FIGURE 25:** Global risk map of Change in Biosphere Integrity – HANPP. Transgression is based on the HANPP control variable. All values shown on the map refer to the year 2010. Based on data from Kastner et al. 2022.[105]

KEY TAKEAWAY: Most boundary transgressions occur in large, continuous regions with high land-use intensity. In contrast, areas in regions without transgressions, such as the Amazon, the Congo Basin, and boreal forests, are primarily natural or semi-natural.

diversity, ecosystem composition and the disruption of ecological interactions can strongly reduce the biosphere's capacity to regulate these processes.[238] There is strong evidence that the biosphere plays an important mediating role in tipping point dynamics, helping to stabilize both the climate and freshwater systems. For instance, forests regulate regional precipitation through evapotranspiration and moisture recycling, while wetlands and peatlands act as long-term carbon sinks that reduce atmospheric greenhouse gas accumulation. Loss and degradation of these ecosystems can thus weaken biosphere buffering capacity and amplify tipping point dynamics. At finer scales, the loss and fragmentation of natural habitats through land-use change can reduce ecosystem services that contribute to human well-being. Strongly managed agricultural landscapes provide one example, where biodiversity is often already depleted, further limiting services such as pollination and pest regulation. It is estimated that approximately 60% of agricultural lands lack sufficient biodiversity to provide these services.[239] This is alarming as pollinators are necessary for more than 75% of food crop species,[240] including many that are central to current human diets.[241] Beyond this, ecosystem degradation also threatens to deprive societies of irreplaceable sources of feed, energy, materials, and medicines,[234] while also reducing CO_2 sequestration capacity and thereby potentially accelerating climate change.[107,234]

Current and Future Research

Current assessments of **Change in Biosphere Integrity** rely on a limited set of control variables that capture only selected dimensions of biosphere integrity rather than nature's full complexity. Here, we outline ideas how to overcome current shortcomings in the future.



● **FIGURE 26:** IPBES indicators show that human activities have significantly altered nature since prehistory. Indicators of ecosystem structure, ecosystem function, community composition, species population, and species traits reveal substantial reductions in many facets of nature relative to pristine conditions.

KEY TAKEAWAY: Multiple indicators consistently show that nature has been substantially degraded and continues to deteriorate.

Augmenting HANPP with the multidimensional ecosystem indicator EcoRisk

While **HANPP** is essentially a pressure metric, capturing the degree of human colonization and disruption of the biosphere, it misses crucial changes in ecosystem functioning, such as shifts in vegetation structure and total biomass storage, or biosphere mediated disruptions of water, carbon, and nitrogen biogeochemical cycles. To address this, the novel biosphere integrity metric **EcoRisk** was developed by Stenzel et al. to quantify changes in biogeochemical cycles as a proxy for the risk of ecosystem destabilization, based on simulations with the Dynamic Global Vegetation Model LPJmL5.[242]

EcoRisk indicates that many ecosystems have significantly degraded compared to the pre-industrial state. Regions with high risk of destabilization include areas of intense land use and deforestation, as well as climate-sensitive zones such as deserts (● FIG. 27). In order to make Planetary Boundaries more operational at the scales at which land-use decisions and ecosystem change occur, local thresholds for both metrics have been derived through comparison with other biosphere integrity indicators, further described in the original publication.[225] Globally aggregated, 60% of the ice-free land surface is currently transgressing these local boundaries, with 38% already being at high risk of degradation.[225]

Linking IPBES Indicators to Biosphere Integrity

While the current control variables for this boundary capture key aspects of biosphere integrity, they represent only parts of the biosphere. Ongoing work seeks to extend the quantification of biosphere integrity by considering additional variables. In this context, the indicator system and global assessment reports of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) provide a potential starting point. The last IPBES global assessment report from 2019[106] evaluated the state of nature using indicators based on Essential Biodiversity Variables (EBVs),[243] such as ecosystem structure, community composition, and species populations. Collectively, these indicators reveal substantial deviations from pristine natural conditions used as the baseline, with reductions down to 25% and increases exceeding 200% of baseline levels, and trends indicating continued divergence (● FIG. 26).[244] This shows that biosphere integrity is being compromised across a wider and deeper set of ecological dimensions than captured by existing control variables, with degradation both substantial and ongoing.

The next global assessment report by IPBES, scheduled for 2028, is expected to address several gaps and challenges, including more comprehensive consideration of oceans, neglected components of biodiversity, and the integration of multiple worldviews and knowledge systems.[245] While IPBES indicators provide a promising basis for exploring additional variables, it is necessary to evaluate which of them are suitable for the Planetary Boundaries framework – for example, whether they capture processes that operate at a global scale or influence Earth system dynamics. To address this, members of the PBScience Initiative are currently developing decision principles to determine control variable suitability, based on which the inclusion of additional control variables will be considered.

The role of the ocean

The Planetary Boundaries framework does not yet include a comprehensive assessment of marine life. Ongoing efforts by members of the PBScience Initiative and collaborating ocean scientists aim to refine existing control variables for Genetic Diversity and Functional Integrity to adequately reflect both terrestrial and marine biosphere integrity. This refinement is essential to better reflect the role of the ocean in maintaining the Earth system in a Holocene-like state.

A key limitation of **the genetic component** is that extinction rates may be a poor proxy for marine genetic diversity. Currently used extinction rate estimates are mainly based on data from vertebrates, and only from selected terrestrial invertebrate taxa. This is not representative of marine ecosystems because they are significantly shaped by distinct higher-level taxa, where invertebrates such as polychaetes, crustaceans, or echinoderms are the most species-rich groups. In addition, 91% of the expected 2.2 million species are still undescribed.[246] Even if ongoing explorations could close the knowledge gap, new data come with a lack of historical information which makes the exact estimation of extinction rates for marine biodiversity impossible. Hence, an adequate reflection of marine biodiversity loss depends on a broader coverage of taxa and an alternative metric.

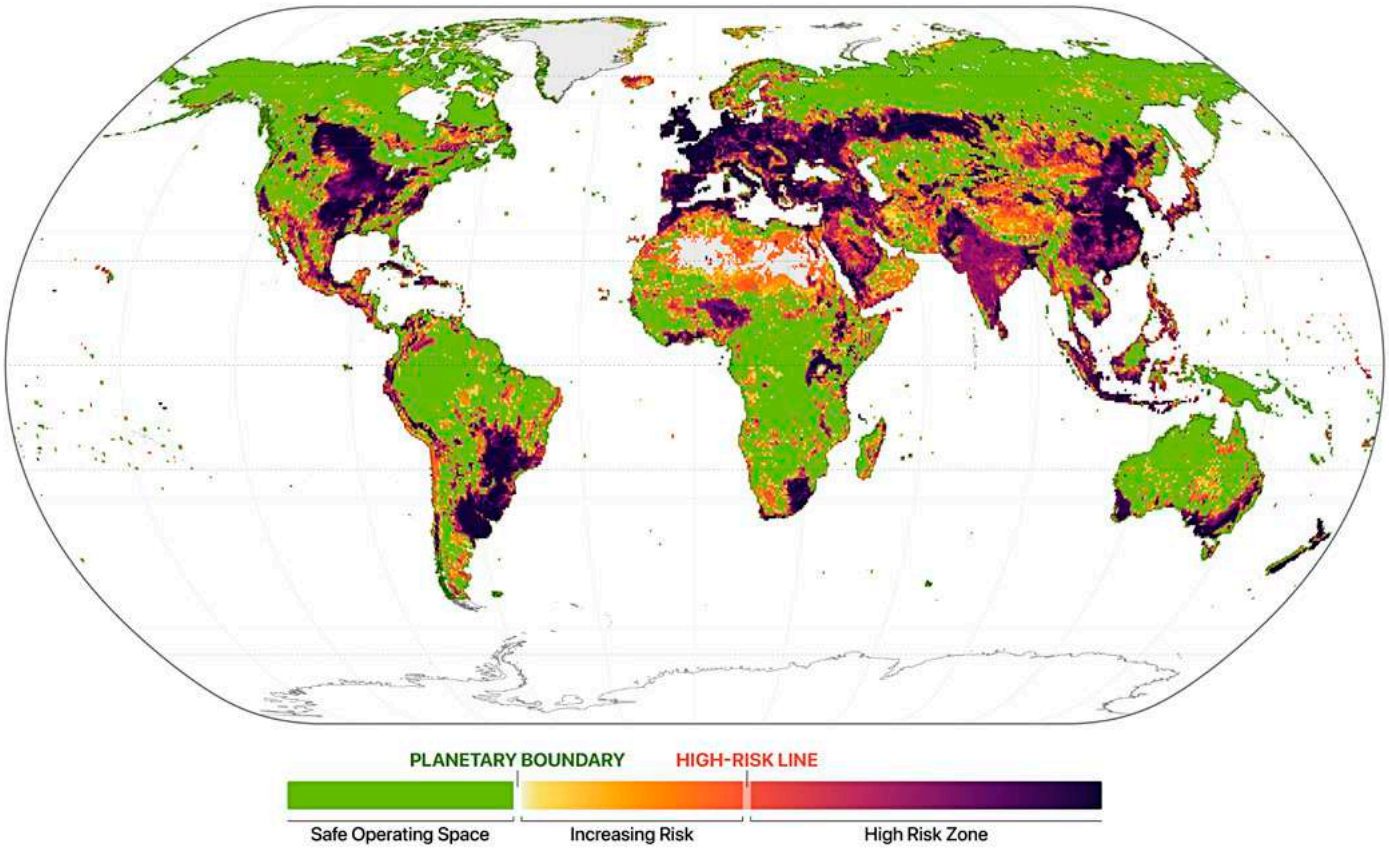
Furthermore, **the functional integrity of marine life** is not yet represented in the framework. Marine biosphere functions contribute to Earth-system stability through their role in regulating energy flows and biogeochemical cycles, especially carbon uptake and long-term storage through the biological carbon pump. The biological carbon pump is therefore a key function to assess, although its different components remain poorly constrained and historical baselines are uncertain.[247,248]

Two major anthropogenic pressures are especially relevant in this context: coastal habitat disturbance and fishing. Coastal disturbance can reduce carbon uptake and storage through the degradation or loss of mangroves, seagrasses, kelp forests, tidal flats and other productive coastal habitats.[249–251] This loss of coastal primary production is conceptually closer to terrestrial HANPP than fisheries harvest, which is mostly at higher trophic levels and should be treated differently. Thus, loss of coastal primary production could potentially be considered as an extension of HANPP to coastal systems. Coastal ecosystems, supported by this primary production, have an outsized importance, though their NPP is only a few percent of marine production.[252]

Fishing affects marine biosphere function not only through biodiversity loss and seabed degradation, but also by altering biomass, trophic structure, and size spectra.[253,254] Recent work suggests that the depletion of exploited fish biomass may affect the biological carbon pump. Exploited fish populations tend to be dominated by larger individuals, which produce larger and faster-sinking particles and carcasses. Reductions in their biomass can therefore alter the production and sinking dynamics of organic matter, influencing carbon transport to depth and its long-term sequestration.[253,255–257] However, the magnitude of this effect, its dependence on ecosystem structure, and appropriate Holocene or preindustrial baselines remain uncertain.[247,257] Coastal habitat loss and exploited biomass reduction therefore represent promising candidate directions for future marine functional-integrity control variables, but require further synthesis and model development before robust global thresholds can be defined.

Data Sources

- Cumulative (1500–2022) extinctions from Ceballos & Ehrlich (2023).[229]
- HANPP data from Krausmann et al. (2013),[226] Kastner et al. (2022),[105] Richardson et al. (2023),[10] Stenzel et al. (2025)[225] and Matej et al. (2025).[227]



● **FIGURE 27:** Global map of ecosystem destabilization risk based on the biosphere integrity indicator EcoRisk (status average 1987–2016 based on LPJmL model simulations). Regions with zero NPP are colored grey. Replotted from Stenzel et al. (2025)[225]

KEY TAKEAWAY: Many ecosystems have significantly degraded compared to the pre-industrial state. Unlike HANPP, EcoRisk also shows degradation in regions without human land use, such as deserts or polar regions.

5.3 Land System Change

MAIN TAKEAWAY

Forests play a vital role in stabilizing the Earth's climate, supporting biodiversity, and sustaining human well-being. Ongoing forest loss and other land system changes continue at alarming rates, driven by complex and region-specific pressures.

Agriculture is the leading direct cause of **Land System Change**, particularly livestock grazing and the expansion of cropland. Other significant factors include illegal logging, infrastructure expansion, weak governance, and climate change. Often, these points are interrelated and facilitate each other. In the Amazon, for example, deforestation typically starts with the extraction of illegal timber before land is finally converted into pasture.

The impact of deforestation is profound. It disrupts biodiversity, increases carbon emissions, alters rainfall patterns, and weakens soil and water systems. Deforestation also affects human health, for example by increasing the risk of malaria in affected areas. **Climate Change** and water stress further amplify this damage through heatwaves, fires, and manifestation of pests such as outbreaks of bark beetle. If land degradation continues, our chances of stabilizing the climate, securing freshwater resources, and protecting biodiversity will be weakened. To stay within the Safe Operating Space, we must urgently protect and restore ecosystems, keeping the land resilient, and ensuring that the Earth remains habitable for generations to come.

Definition

The Planetary Boundary for **Land System Change** defines the global threshold beyond which changes in land use – particularly deforestation, agricultural expansion, and urbanization – compromise the Earth's ability to maintain ecological stability, biodiversity, climate regulation, and essential ecosystem services. Transgressing this threshold increases the risk of irreversible changes to the structure and functioning of ecosystems. This in turn can weaken Earth's resilience and potentially trigger adverse feedback loops across multiple other relevant Earth system processes.

2026 Status

Globally, only 64% of the potential forest cover (the forest cover that would exist in the absence of human land-use changes) is still presently remaining. This is significantly below the anticipated safe threshold of 78%. Thus, the globally remaining forest area is well **outside of the Safe Operating Space**. Even when considered individually, most major forest biomes around the world have exceeded their boundaries to varying degrees **(SEE ● FIGS. 28 AND 29)**.

CONTROL VARIABLE

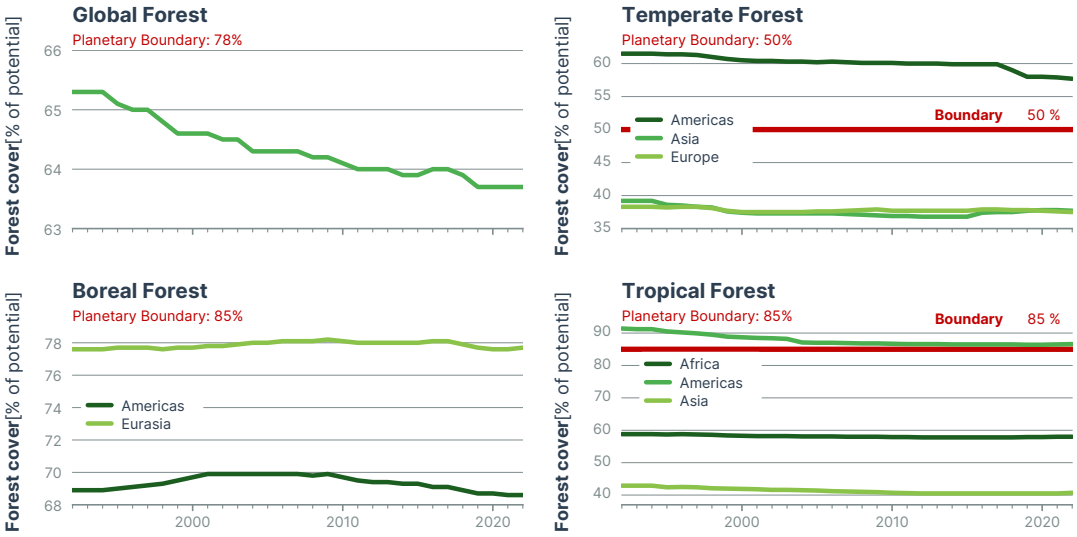
Forest Area

DEFINITION While different land types have distinct functions within the Earth system, forests are of particular importance to the climate system, due to their temperature- and moisture-regulating interactions with the atmosphere and their role in carbon and water cycling.[258] 'Remaining forest area' is the main component responsible for maintaining major global ecological functions, and is thus used as the control variable for this Planetary Boundary. It is expressed as a percentage of the forest cover that would exist in the absence of human land-use changes ('potential natural forest cover'). This is determined for the boreal, temperate, and tropical forest biomes (as contiguous area per continent) and then aggregated globally.

UNIT Percentage (%) of potential forest cover.

HISTORICAL RANGE The value of relative forest cover ranges from 100% (all forest relative to potential forest cover is remaining) to 0% (no forest relative to potential forest cover is remaining).

PLANETARY BOUNDARY (PB) The global Planetary Boundary threshold for **Land System Change** is set at 78% of the potential forest cover. Changed from the previous 75%, it is now calculated as the area-weighted mean of the contiguous biome thresholds: 85% for boreal and tropical forests (both 19.1 Mkm^2), and 50% for temperate forests (9.9 Mkm^2).[11] These thresholds are based on studies indicating that tropical and boreal forests exert a stronger influence on regional and remote climatic conditions than temperate forests.[258,259] The areas differ from the total areas in[260] or[258] because only contiguous forest cover is taken into account in the PB framework.



● **FIGURE 28:** Recent global forest decline. Annual mean forest cover, expressed as a percentage of potential forest cover, globally and for three different biomes (temperate, boreal, and tropical) between 1992 and 2022. Red lines show the thresholds for global, temperate, boreal and tropical forests of 78%, 50%, 85% and 85%, respectively. Data from Copernicus (2024) and Ramankutty & Foley (1999).[260,261]

KEY TAKEAWAY: As a result of land use change and, increasingly, climate change, forests across all major forest biomes have been steadily declining over the last few decades. Most regions have already significantly transgressed their biome-specific safe boundary thresholds. However, the status of the forest areas of the temperate and tropical Americas was reclassified to safe, as previous assessments had omitted two forest cover classes from the satellite-based analysis data.

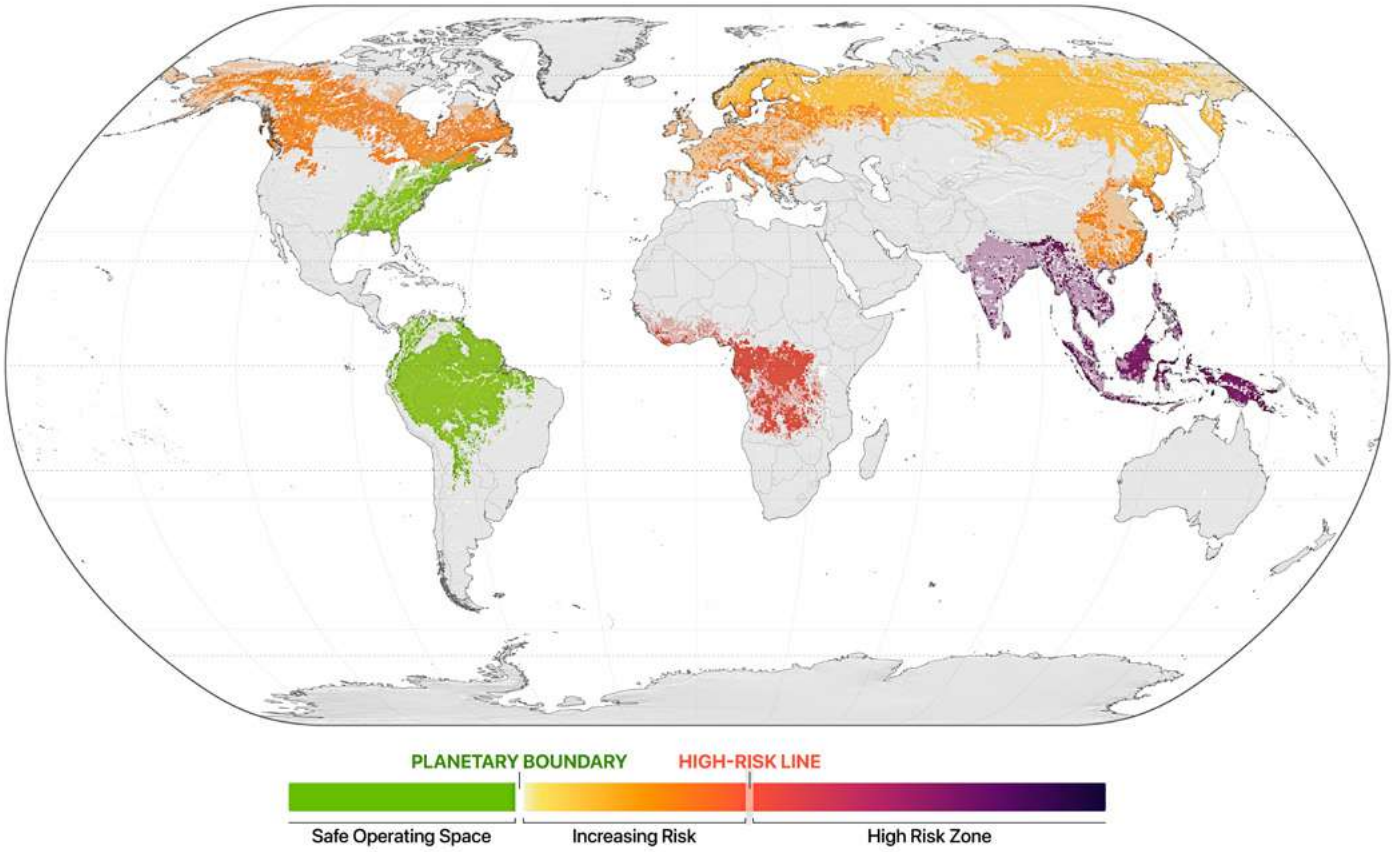
Key Drivers

The causes of deforestation vary greatly from place to place. Historically, forests have been cleared not for farming, but also to provide timber, to create settlements, and to open up landscapes for hunting.[265–267] Often, the initial reason for clearing a forest differs from the subsequent use of the land.

According to satellite data, nearly 90% of direct deforestation between 2000 and 2018 was followed by the expansion of agriculture, with around 52% attributed to crop cultivation and 38% to grazing. Cropland expansion is the leading cause of forest loss in Africa and Asia, whereas in the Americas and Oceania livestock grazing plays the major role.[268]

However, these figures do not tell the whole story. In many places, especially the Amazon, deforestation often begins with illegal logging, which is frequently linked to criminal networks involved in land grabbing and illegal timber trade.[269] Once the valuable trees are removed, the land is sold or used for other purposes, such as cattle ranching. In these cases, livestock grazing is not the root cause, but rather a final step in a series of destructive actions. Focusing solely on this would overlook the broader dynamics at play.

In tropical areas, both permanent agriculture and shifting cultivation also play a major role.[268,270] In Europe and parts of the tropics, forest degradation



● **FIGURE 29:** Global risk map of the Land System Change boundary transgression – Forest area. Transgression is shown for the major contiguous forest biomes as defined in Steffen et al. 2015.[11] Transgression is based on the control variable of remaining forest area. Lighter shades of a color indicate areas that were originally covered with forest but are now predominantly deforested. Areas without contiguous potential forest cover are shown in gray. This is based on data from Brun et al. 2022, Copernicus (2024) and Ramankutty & Foley (1999).[260–262]

KEY TAKEAWAY: Most large contiguous forest biomes of the Earth have transgressed the Planetary Boundary, although with varying degrees of transgression. Following the inclusion of two previously missing forest cover classes from the Copernicus dataset in our analysis, the tropical and temperate biomes of the Americas now have a slightly better status compared to previous assessments. However, this does not mean that these biomes are in a good condition. Our methodology does not capture forest degradation resulting from deforestation, extraction of resources or destruction from extreme weather events, which are amplified by climate change.[263] This means that we should not feel too confident about the apparent good state in the Amazon, since this system is likely still at risk.[264]

is often driven by the timber, paper, and pulp industries.[271] Many of these drivers are rooted in systemic issues – such as weak governance, poverty, unclear land rights, and political instability.[272,273]

Moreover, **Climate Change** and **Freshwater Change** are increasingly acting as indirect but powerful drivers of **Land System Change**, even in the absence of direct local anthropogenic land use change. Rising temperatures and shifting rainfall patterns, particularly reduced moisture transport in the atmosphere, can put stress on forest ecosystems and reduce their resilience.[274] In extreme cases, this can lead to large-scale forest dieback due to drought, flooding, or large-scale forest fires. In the boreal forests of Northern Canada and Siberia, for example, a massive increase of wildfires is occurring.[100] In temperate forests, warming and water stress have also been linked to an increase in disease outbreaks, most notably bark beetle infestations. Often triggered or amplified by heat and drought, these outbreaks can devastate large forest areas and interact with other disturbances such as wind-throw, creating cascading forest degradation.[275,276]

While on a global level, forest areas are decreasing, some areas are experiencing an increase in regional forest cover. One reason for this is the success of national reforestation programs.[277] Additionally, natural regrowth, triggered by recent climate change, is making new regions suitable for trees. Specifically in Arctic regions, which are warming faster, forests are shifting northward into areas that used to be too cold.[43] While this may seem like a positive development (it also counts positively for the boundary status), such shifts can disrupt local ecosystems, negatively affect albedo and the surface energy balance, and thereby reshape the distribution of species and ecological functions.

Overall, changes in forest cover are the result of complex chains of events, shaped by both the combination of human changes of local pressures and global processes. These changes are caused by consequences ranging from economic demand and governance failures to climate dynamics and cross-boundary feedback processes. Addressing these challenges requires an integrated approach that considers not only what is happening to forests, but also why and how different drivers interact with each other and the wider environment over time.

Impacts

Land systems and especially forests play a vital role in maintaining crucial Earth system functions, related to other Planetary Boundary dimensions. First and foremost, land systems act as a habitat and thus support biodiversity at the genetic, species, and ecosystem levels.[278,279] Consequently, forest loss endangers **Biosphere Integrity** and weakens the resilience of ecosystems to withstand other disturbances.

Forests are also essential carbon sinks. Above and below ground, a significant amount of atmospheric CO_2 can be stored, making terrestrial ecosystems a major component in regulating **Climate Change**.[280] When forests are removed, this function is lost, and the stored carbon is released, contributing to global warming and amplified temperature extremes. Interactions with the atmosphere also influence the local climate. For example, they modulate surface temperatures via latent heat fluxes and albedo.[281]

The Land System Change Planetary Boundary directly interacts with **Freshwater Change**, by regulating the quality and quantity of available freshwater. Vegetation plays a key role in the freshwater cycle, by controlling the partitioning of precipitation into soils, aquifers, and surface water bodies,[278] and by transporting moisture back to the atmosphere and to other regions via evapotranspiration.[282] Therefore, forest loss can contribute to altered rainfall patterns, reduced water availability, and increased runoff and erosion.

The root zone of vegetation also provides erosion protection and supports nutrient cycling through nitrogen fixation, thus interacting with the Planetary Boundary for **Biogeochemical Flows**.[283] The loss or degradation of this root structure can therefore accelerate soil degradation and reduce nutrient retention in ecosystems.[284]

Additionally, several potential tipping elements lie at the interface between the land system and the atmosphere **(SEE CH. 3.2)**. One critical example is the Amazon rainforest, which depends on recycling its own rainfall to maintain ecosystem stability. Continued deforestation and rising global temperatures could push up to 40% of the region toward a savanna-like state, with devastating consequences – including massive carbon emissions that would further fuel **Climate Change**.[71]

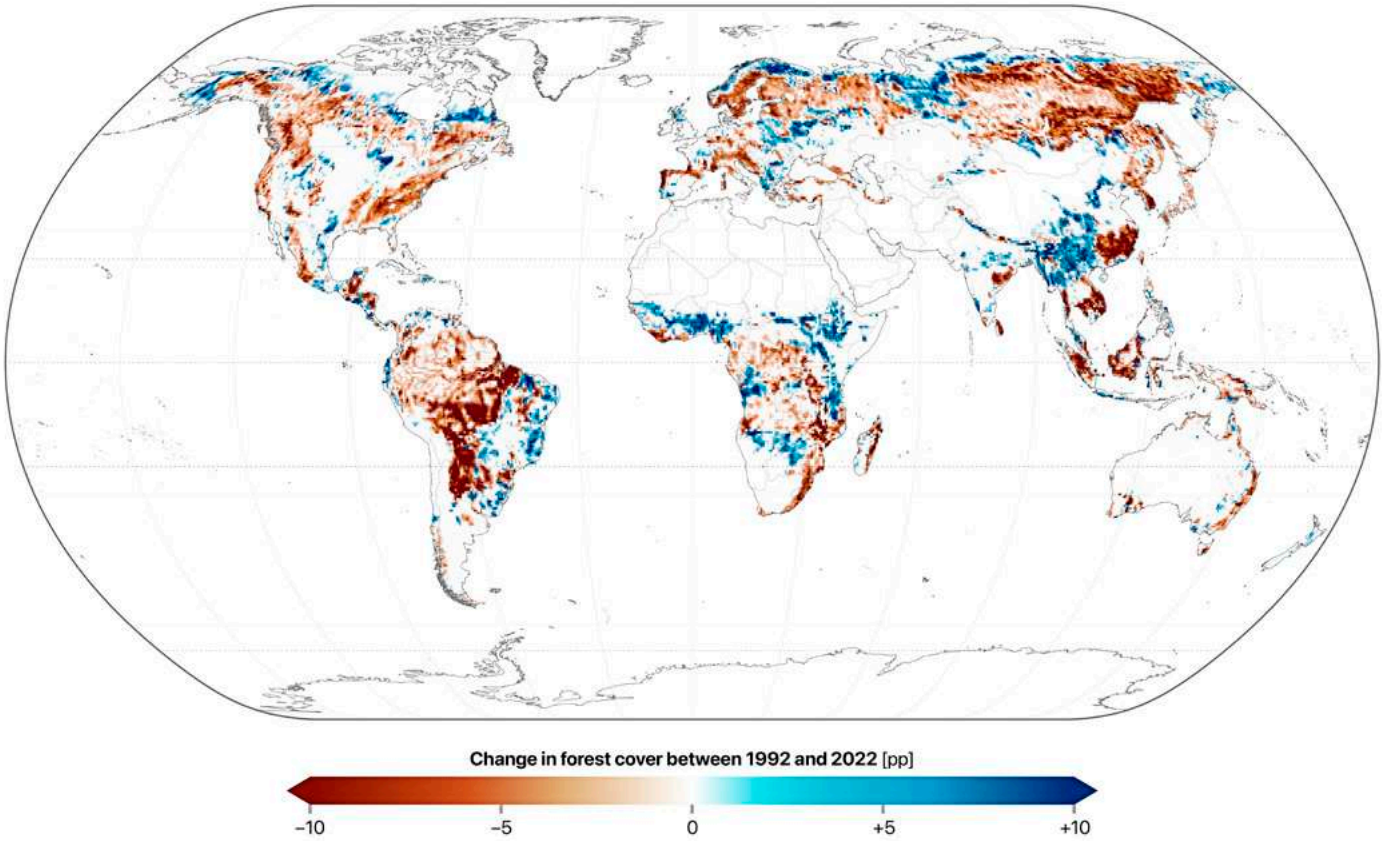
Beyond these direct environmental impacts, **Land System Change** also has serious implications for human well-being. For instance, forest loss has been linked to increased malaria rates among children in certain regions, likely due to the increase of pools of standing water, which are suitable habitats for mosquitoes.[285,286] The essential ecosystem services

provided by forests in tropical regions, including weather regulation, a stable freshwater supply, and support for biodiversity, are also critical for human societies, for example through the provision of livelihoods and food security.[287]

Current and Future Research

Within the Planetary Boundaries framework, the current control variable for **Land System Change** is based on the percentage of remaining forest cover, globally and for each biome. Biomes are large geographic regions characterized by specific climate conditions, plant life, and animal communities, here defined by the contiguous forest cover types in Ramankutty and Foley (1999) per continent.[260] However, different definitions exist.[288] This measure was originally selected for its simplicity, scientific basis, and data availability. Steffen et al. (2015),[11] proposed maintaining biome-level forest cover above critical thresholds as a means of preserving the functioning of large-scale Earth system processes, including carbon cycling, hydrological regulation, and biodiversity support. Thus, forest cover serves as a visible and measurable proxy for wider land system integrity.

However, recent research and experience have highlighted some limitations of this approach. The presence or absence of forests alone does not capture the ecological quality or functional integrity of these systems. For example, secondary or degraded forests often differ substantially from intact or old-growth forests in terms of biodiversity, carbon storage, water regulation, and resilience.[289–291] Forests may expand in some areas, but this does not necessarily signal the recovery of ecological function – especially when new forests are mono-cultures, poorly connected, or under ongoing stress.



● **FIGURE 30:** Global map of recent forest cover changes. The colors indicate the absolute change in forest cover between 1992 and 2022 (percentage change in 300m subpixels identified as forest within each cell area), with shades of blue representing an increase in forest cover and shades of red representing a decrease in forest cover (e.g., a change from 60% to 50% forest cover would be indicated by a value of -10%). Areas with no forest cover in both 1992 and 2022, or with no change in forest cover, are shown in white. Data from Copernicus (2024).[261]

KEY TAKEAWAY: Patterns of forest loss and gain have been heterogeneous, with prevailing net losses at the biome scale Contiguous pristine forests in the tropics and boreal zones, in particular, have suffered losses of primary forest, while temperate forests, often reflecting managed forestry, have mostly suffered from climate change impacts.

While most of the satellite data used for this year's analysis is not currently available beyond the year 2022, this year's report does include a few methodological improvements identified since last year:

Firstly, the potential forest cover class "Evergreen/Deciduous Mixed Forest/Woodland"[260] is now split into classes of 'boreal' and 'temperate' forest along the 6°C average annual temperature isoline (5-minute resolution aggregated from the 1km CHELSA variable bio01[262]) according to Holdridge's life zones.[292] This creates a more nuanced border between these biomes in Eurasia.

Secondly, previous assessments had omitted the tree type classification "*tree cover, mixed leaf type*" and "*tree cover, flooded, fresh*" from the ESA satellite forest cover.[261] These are now included, resulting in improved overall status and notably better representation of tropical and temperate forest in the Americas. Thirdly, the Planetary Boundary threshold value was changed from previously 75% to now 78%. This change occurred because some areas were accidentally counted twice when weighting the biome thresholds in previous assessments. Now the contiguous areas from the potential forest biomes are used: 19.1 Mkm each for boreal and tropical forests, and 9.9 Mkm for temperate forests.

These changes highlight the need to improve future Planetary Boundary assessments by including multiple datasets or more consistent methodologies to account for current uncertainties in forest areas.

In parallel, ongoing research is exploring if new or additional control variables could provide a more nuanced and functionally meaningful assessment of changes to land systems. These efforts aim to more accurately reflect the actual state and function of terrestrial ecosystems, by including indicators such as forest fragmentation, ecological integrity, or intensity of land use in crop production. However, any such improvements must balance scientific robustness with global applicability, consistency over time, and the feasibility of data collection and monitoring. Looking ahead, the scientific community is working to refine the **Land System Change** boundary, improve data sources, and evaluate the potential of alternative or additional control variables that reflect not just the quantity but the quality of land systems.

Data Sources

- Observed forest cover data Copernicus (2024),[261] accessed on 15 May 2024.
- Potential forest cover data from Ramankutty and Foley (1999).[260]
- CHELSA – 1km mean Annual Near-Surface Air Temperature (bio01).[262]

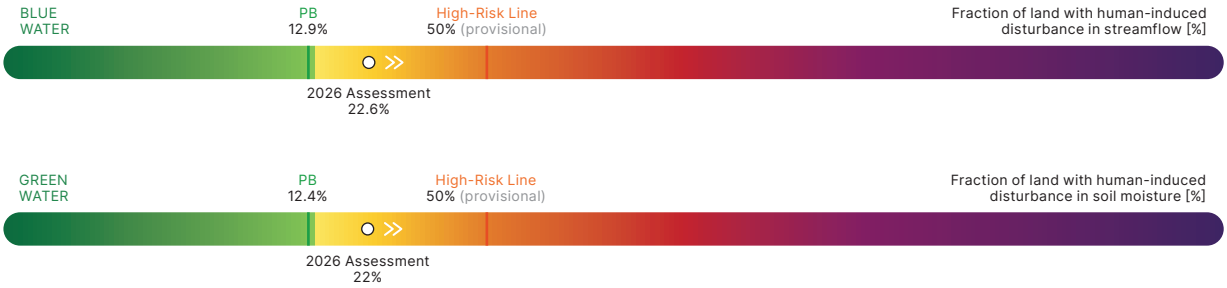
5.4 Freshwater Change

MAIN TAKEAWAY

Human actions change how freshwater flows and stocks are distributed on land and in the atmosphere. Specifically greenhouse gas emissions, irrigation and other water uses, water infrastructures, and the expansion of agricultural land have changed the global water cycle.

This has pervasive impacts throughout the water cycle; the occurrence of droughts and extreme precipitation has increased, while groundwater stocks are often declining and river flows to the ocean are widely interrupted. The Planetary Boundary for **Freshwater Change** measures how far streamflow (blue water) and soil moisture (green water) deviate from a quasi-stable state that is largely unaffected by human actions.

Anomalously dry or wet streamflow and soil moisture conditions now occur on approximately twice as much land as they did under pre-industrial-like conditions, due to direct and indirect human pressures on the water cycle. This surpasses the safe limit for human modification of the water cycle and places the **Freshwater Change** boundary in the increasing risk zone. Increasing freshwater anomalies may undermine terrestrial and aquatic ecosystem integrity, modify land carbon balance and affect hydro-climatic processes. They also change how water is available for human uses, which may compromise benefits that are gained by managing freshwater resources.



Definition

The alteration of the global hydrological cycle manifests through myriad shifts in flows and stocks of freshwater, including in rivers and water held in soil as well as altered precipitation patterns. Together, these changes impact critical functions on land, including carbon sequestration and biodiversity, which can undermine Earth's resilience. The Planetary Boundary for **Freshwater Change** covers these processes by representing changes in both streamflow (blue water) and soil moisture (green water) as key processes controlling this multitude of changes.[293]

2026 Status

Human-induced disturbances of **Freshwater Change** have exceeded the safe level.[293–295] According to the most recent estimate,[296] more than a fifth of the global land area experiences dry or wet deviations for both streamflow, i.e. blue water (22.6% of ice-free land area) and plant-available soil moisture, i.e. green water (22.0%). Both of these measures are **above their safe levels**, which are 12.9% (blue water) and 12.4% (green water). The hydrological model ensemble[297] used for analyzing this boundary[294] extends to year 2019, and the current status of the boundary reflects average conditions in streamflow and soil moisture over the period 2010–2019. Freshwater deviations are based on comparing current streamflow and soil moisture to a 119-year long pre-industrial-like baseline state that is largely unaffected by human-induced disturbances.[296]

CONTROL VARIABLE

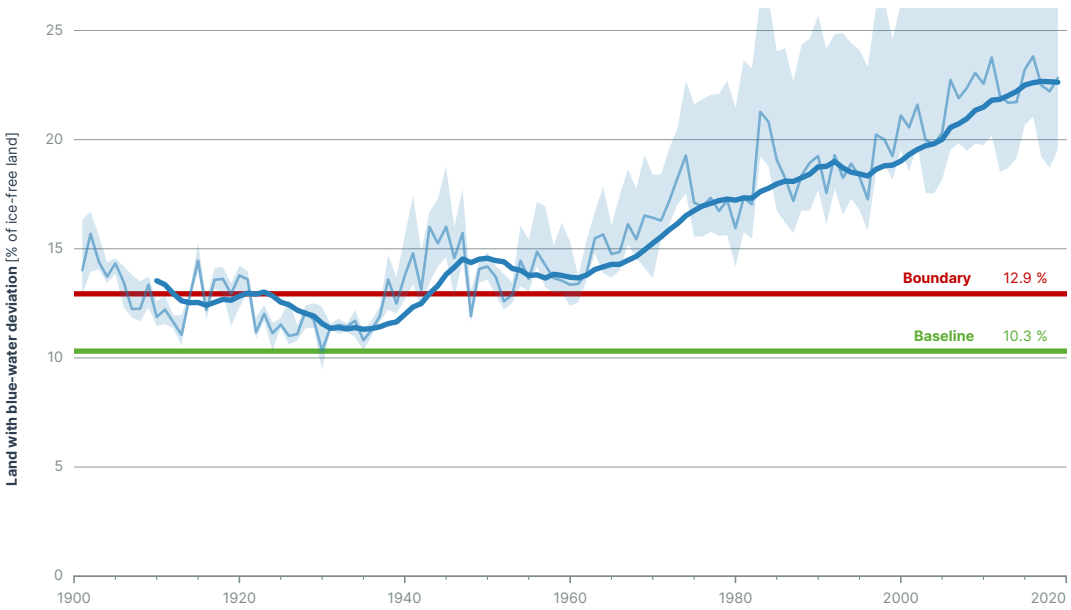
Blue Water

DEFINITION Human-induced disturbance of blue water, which refers to water in rivers, lakes, reservoirs, groundwater and wetlands, is approximated by the annual global area with significant deviations in streamflow from variability under the baseline (pre-industrial-like) state. The boundary reflects changes in blue water availability, which are crucial for the health of associated aquatic ecosystems and for water supply to human societies.

UNIT Percentage (%) of annual global ice-free land area.

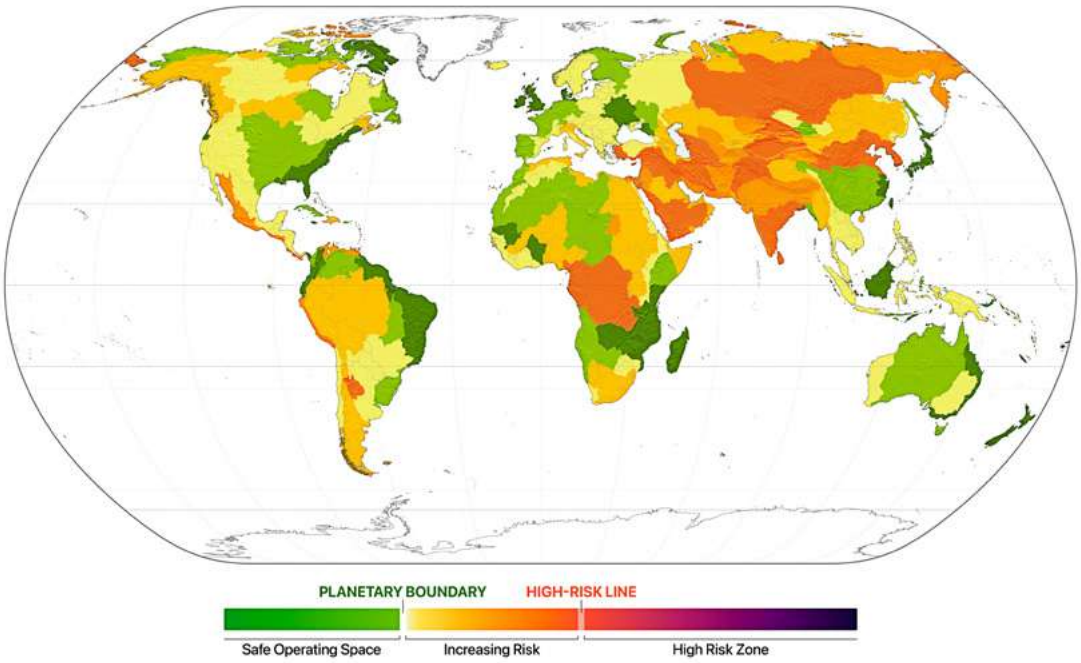
HISTORICAL RANGE The percentage of land area experiencing significant deviations in streamflow can range from 0% (no area affected) to 100% (all ice-free land area affected), with a baseline median value of about 10.3% representing natural variability. The baseline conditions approximate an Earth system state largely unaffected by humans, based on a 119-year long pre-industrial-like scenario with no anthropogenic climate change but with human forcing (land and water use) at year 1901 levels.

PLANETARY BOUNDARY (PB) The PB is set at 12.9% of the global ice-free land area experiencing significant dry or wet deviations in streamflow. This corresponds to the 95th percentile of the baseline state variability, during which anomalously dry or wet local conditions occurred annually with a likelihood of less than 5% on at least 12.9% of the global area.



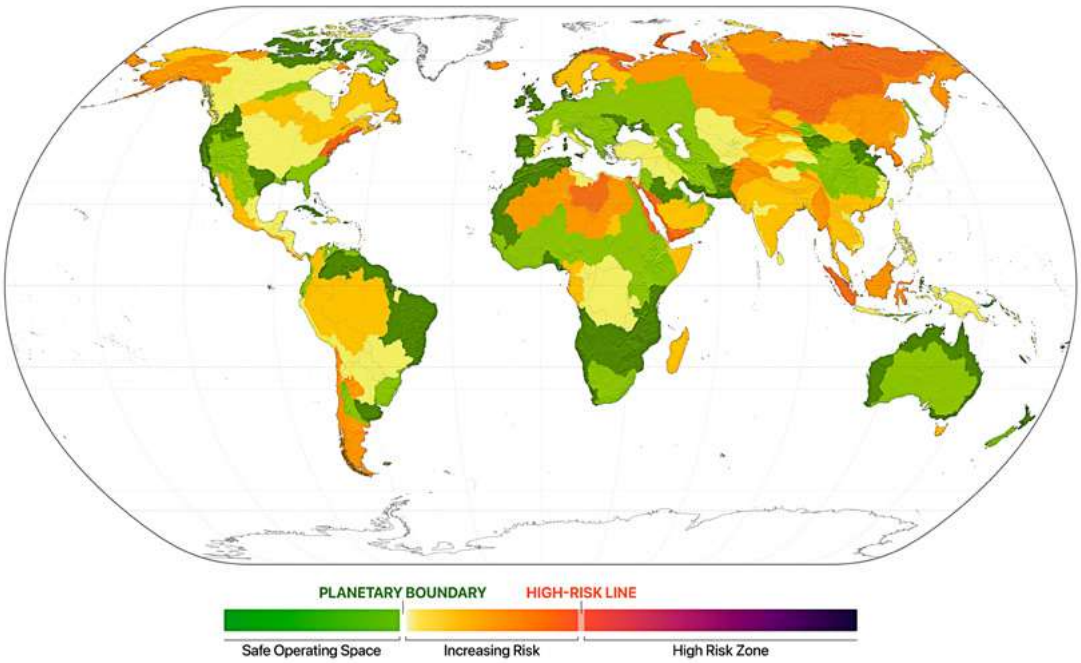
● **FIGURE 31:** Disturbance of Earth's freshwater systems (I) – Blue water. This figure shows the percentage of land area with significant alteration of blue water flows (streamflow) from 1901 to 2019 compared to the baseline state. The blue line shows the percentage of land area exhibiting local streamflow deviations (10-year moving average), with the shaded blue envelope representing the associated ensemble range.[294] The red line represents the Planetary Boundary of 12.9% land area affected, and the green line represents the baseline median of 10.3% land area affected. Data from Virkki et al. (2026).[294]

KEY TAKEAWAY: Streamflow deviations have significantly increased since the early 20th century, surpassing the Planetary Boundary around 1940 and continuing to rise since then.



● **FIGURE 32:** Global risk map of Earth's freshwater systems (I) – Blue water. This map shows boundary transgression at the river basin scale for major basins of the world (n = 268).[298] Transgression estimates are based on fractional basin land area with significant dry or wet streamflow deviations. For details on how the risk level is estimated for individual basins based on the streamflow change control variable, please see the Supplementary Materials. Based on data from Virkki et al. (2026).[296]

KEY TAKEAWAY: The increase in streamflow deviations across large parts of the world suggests increasing variability, drying or wetting trends, and instability in global freshwater systems.



● **FIGURE 33:** Global risk map of Earth's freshwater systems (II) – Green water. This map shows boundary transgression at river basin scale for major basins of the world (n = 268).[298] Transgression estimates are based on fractional basin land area with significant dry or wet soil moisture deviations. For details on how the risk level is estimated for individual basins based on the soil moisture change control variable, please see the Supplementary Materials. Based on data from Virkki et al. (2026).[296]

KEY TAKEAWAY: The increase in soil moisture deviations indicates growing variability and instability within global green water systems, which particularly affects water available for plants.

CONTROL VARIABLE

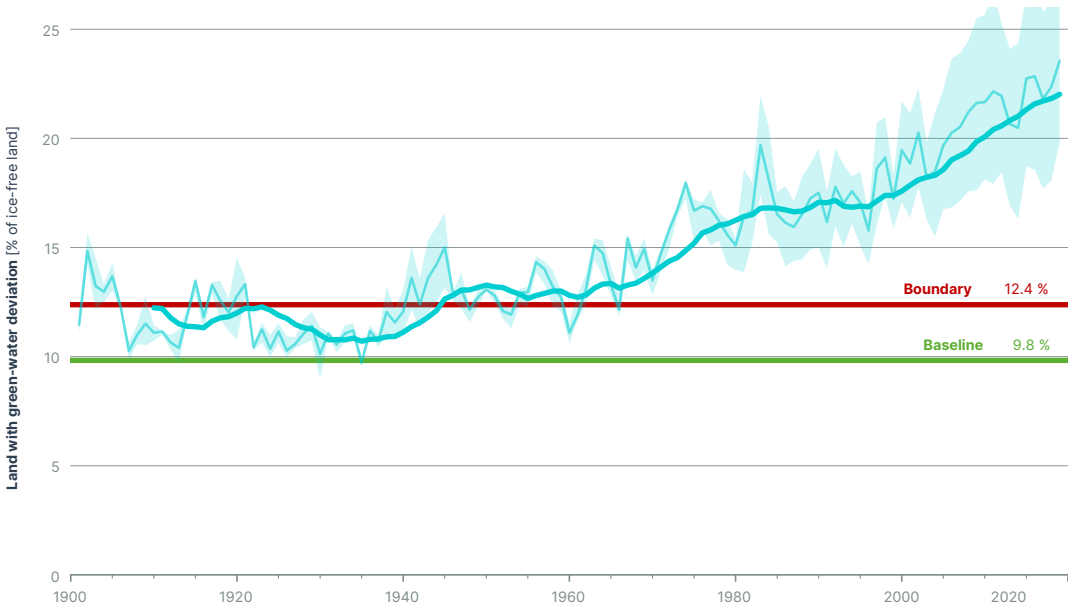
Green Water

DEFINITION Human-induced disturbance of green water, which broadly refers to water embedded in vegetation, soil, and the atmosphere, is approximated by the annual global area with significant deviations in root zone soil moisture (hereafter soil moisture) from variability under the baseline (pre-industrial-like) state. The boundary reflects changes in green water availability, impacting terrestrial ecosystems, climate regulation, and biogeochemical processes.

UNIT Percentage (%) of annual global ice-free land area.

HISTORICAL RANGE The percentage of land area experiencing significant deviations in soil moisture can range from 0% (no area affected) to 100% (all ice-free land area affected), with a baseline median value of about 9.8% representing natural variability. The baseline conditions approximate an Earth system state largely unaffected by humans, based on a 119-year long pre-industrial-like scenario with no anthropogenic climate change but with human forcing (land and water use) at year 1901 levels.

PLANETARY BOUNDARY (PB) The PB is set at 12.4% of the global ice-free land area experiencing significant dry or wet deviations in soil moisture. This corresponds to the 95th percentile of the baseline state variability, during which anomalously dry or wet local conditions occurred annually with a likelihood of less than 5% on at least 12.4% of the global area.



● **FIGURE 34:** Disturbance of Earth's freshwater systems (II) – Green water. This figure shows the percentage of land area with significant alteration of green water flows (soil moisture) from 1901 to 2019 compared to the baseline state. The turquoise line shows the percentage of land area exhibiting local soil moisture deviations (10-year moving average), with the shaded turquoise envelope representing the associated ensemble range.[294] The red line represents the Planetary Boundary of 12.4% land area affected, and the green line represents the baseline median of 9.8% land area affected. Data from Virkki et al. (2026).[294]

KEY TAKEAWAY: Soil moisture deviations have significantly increased since the early 20th century, surpassing the Planetary Boundary around 1940 and continuing to rise since then.

Key Drivers

Over the past century, **Climate Change** appears to have become the globally dominant driver of **Freshwater Change** boundary transgression.[296] Climate change intensifies and redistributes branches of the water cycle, which manifests as increasing deviations and novel hydrological regimes across the water cycle.[299–301] Additionally, direct human activities like freshwater withdrawals, river regulation or land use changes, intensify dry deviations in particular.[296]

The **Freshwater Change** boundary is closely intertwined with activities impacting other Planetary Boundaries. For instance, **Climate Change** affects variability and extreme events in the water cycle by altering atmospheric water-holding capacity, cloud formation, and circulation patterns.[295,302,303] Additionally, **Land-System Change** related to deforestation, agriculture, and urbanization affects soil water-holding capacity, runoff, streamflow, groundwater recharge, and evaporation rates. This can intensify droughts and alter large-scale precipitation patterns like monsoons, thereby creating feedback loops that further impact **Climate Change**.[295]

Impacts

Transgressing the **Freshwater Change** boundary has significant impacts on the functioning of the Earth system, as well as on human societies. Dry deviations in blue water flows can lead to loss of wetlands as well as depletion of lakes, reservoirs and in-stream environmental flows, resulting in aquatic ecosystem degradation and regional climate change impacts.[293] Dry deviations in green water stocks can lead to droughts, which – when combined with heatwaves that increase soil moisture evaporation – dry out landscapes, leading to forest fires, ecological collapses, and bursts of CO_2 emissions into the atmosphere.[304] Wet deviations in blue water can lead to diminished flow seasonality and extreme flooding events, which may have adverse impacts on ecosystems that are adapted to consistent freshwater availability and variability.[305] Wet deviations in green water can drive water logging in the soil and permafrost thawing, which may release vast quantities of CO_2 and CH_4 (methane) into the atmosphere, especially in the northern boreal zone.[306,307] In addition to local impacts, disrupting the water cycle may threaten biosphere integrity and ecosystem services across wide regions, such as the Amazon.[274]

For human societies, food security is especially threatened by reduced availability or overconsumption of blue and green water. Since human water demand peaks during droughts, water deficits resulting from withdrawals and meteorological conditions often compound, further exacerbating the impacts on ecosystems and human societies.[308,309]

Current and Future Research

The Freshwater Change boundary,[293,294] which was updated in the third Planetary Boundaries assessment[10] expands the former Freshwater Use boundary[11,310] by more comprehensively accounting for human-driven alterations across the water cycle. As such, it better captures Earth system impacts of both blue and green water change, but operationalizing its definition for applied use and policies remains challenging. Consequently, assessments may still partly or fully rely on volumetric freshwater use metrics,[311,312] even though some recent studies have applied the updated definition.[313,314]

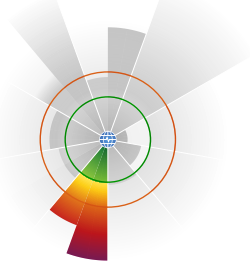
Two further scientific challenges with this boundary remain to be addressed. Most importantly, the consequences of **Freshwater Change** boundary transgressions should be more systematically evaluated by linking deviation patterns to independent empirical evidence of ecological and climatic impacts, which may possibly lead to an improved boundary definition. Moreover, future research should also seek to validate the transgression patterns by comparing how the modeled results, especially at the regional scale,[294] would be supported or contested by local and regional hydrological observations. Further research would thus help in addressing uncertainties that are inherent to the current model-based transgression estimates.[294]

Finally, a more systematic understanding and quantitative assessment of how the **Freshwater Change** boundary is interlinked with other boundaries is highly sought after.[315] For instance, incorporating analysis of moisture recycling (how atmospheric water flows related to evaporation and precipitation are changing) may be helpful to enhance this understanding since moisture recycling links multiple Earth system components. This is motivated by evidence that human activities destabilize and modify moisture recycling patterns, which strongly impacts ecosystem resilience,[316] water availability,[317–319] agricultural production,[320] and carbon sinks,[110] among others.

Data Sources

- Blue and green water deviations based on an analysis from Virkki et al. (2026) utilising the ISIMIP3a global hydrological model ensemble. Data available here.

5.5 Modification of Biogeochemical Flows



MAIN TAKEAWAY

In the 20th century, the invention of industrial nitrogen fixation made it possible to convert molecular nitrogen from the atmosphere into reactive forms, such as those used in inorganic fertilizers. Combined with the mining of phosphate rock, this led to a drastic increase in fertilizer application on agricultural land. Large quantities of both nutrients either remain directly on pastures and fields or enter the environment through animal manure and sewage.

Phosphorus attaches to soil and sediment, while nitrogen is released into the air and stored in groundwater and surface waters. Both nutrients are released into surface waters via soil erosion, surface runoff, and wastewater discharge. Excess nutrients can negatively affect biodiversity and the resilience of ecosystems on land, in freshwater, and in the ocean, environments which are adapted to specific nutrient levels. Currently, losses of both nutrients to the environment are disrupting ecosystems beyond the safe level.

Definition

Biogeochemical flows are the movement of the two key elements, nitrogen and phosphorus, through the environment and organisms. Both nitrogen and phosphorus are required for fundamental biological functions, and their availability in soils, freshwater and the ocean were once a major limiting factor for biological productivity on Earth.[321] Human activities are massively changing the magnitude of these nutrient cycles, with potentially severe consequences for the Earth system. The Planetary Boundary for **Modification of Biogeochemical Flows** is defined to keep these human changes at a safe level.

2026 Status

Both the application of mined phosphorus to cropland (18.2 Tg P/year)[322] and the anthropogenic fixation of nitrogen for agriculture (extracting nitrogen from the atmosphere; 165 Tg N/year)[52,323] are disrupting the corresponding nutrient cycles **beyond the safe levels** of 6.2 Tg P/year and 62 Tg N/year, respectively.

CONTROL VARIABLE

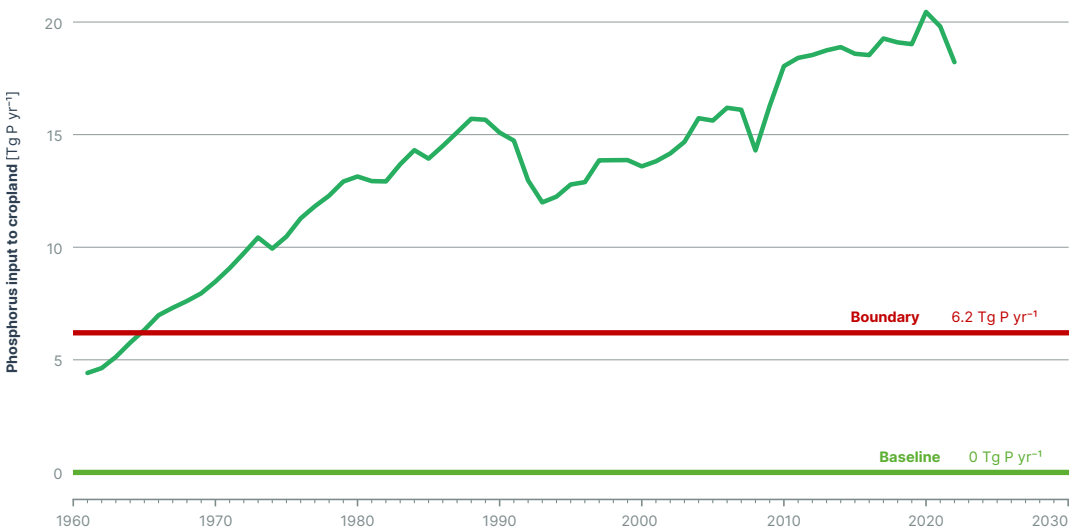
Phosphorus (P) Flows

DEFINITION The phosphorus boundary consists of a regional component, aiming to prevent eutrophication of freshwater systems, and a global component, aiming to prevent large-scale ocean anoxia over geological time scales. The regional boundary uses the application of mined phosphorus to erodible soils as an indicator of phosphorus flow into freshwater systems, while the global boundary is based on riverine transport of phosphorus to the ocean.

UNIT Teragrams of Phosphorus per Year (Tg of P/year). 1 teragram equals 1 million metric tons.

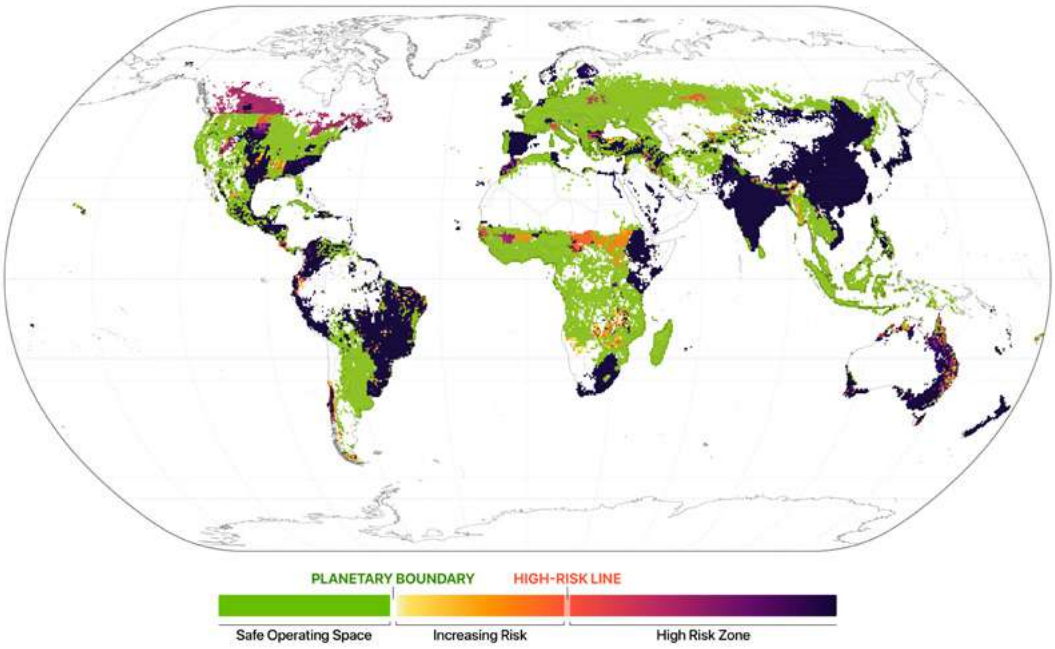
HISTORICAL RANGE Before human intervention, phosphorus flows were low (2.5 Tg P/year from land to freshwater and 1.3 Tg P/year of export to the ocean).[324] Human activities have increased flows from land to freshwater systems through a global application of mined phosphorus to cropland to around 18.2 Tg P/year (regional, aggregated) and have increased phosphorus flows to the ocean to around 4.4 Tg P/year (global), largely due to fertilizer use.[322,324]

PLANETARY BOUNDARY (PB) The regional boundary is set to an application of 6.2 Tg P per year,[11] while the global boundary is established at a flow of 11 Tg P per year, which is roughly ten times the natural flow rate.[9] Here, we focus on the regional boundary, as it sets a stricter threshold than the ocean boundary.



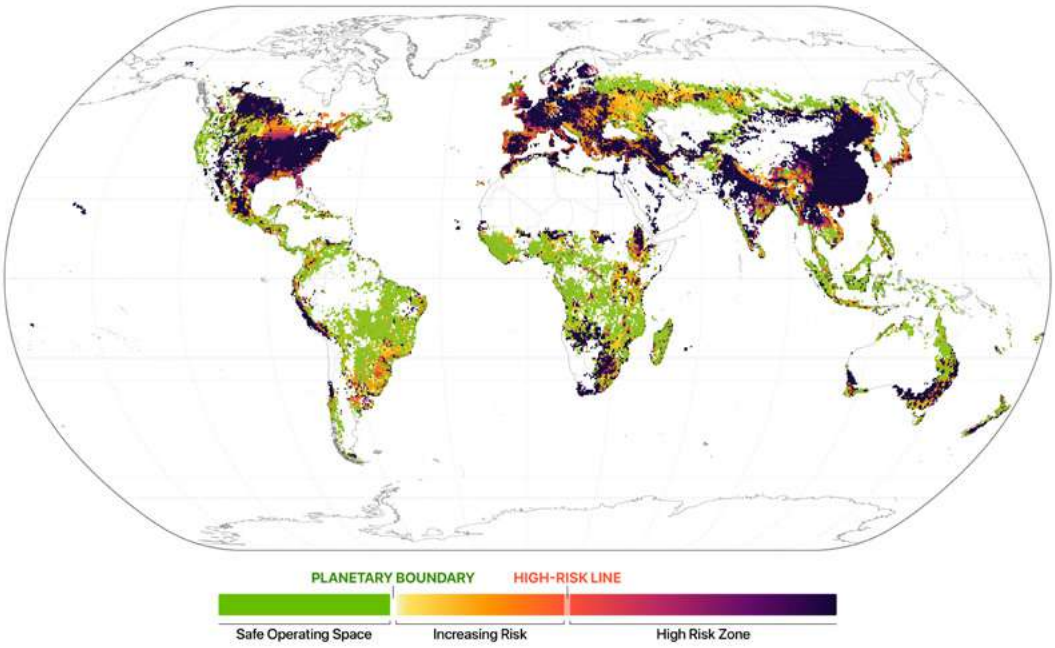
● **FIGURE 35:** Phosphorus inputs to global cropland. This graph shows the estimated global application of mineral phosphorus on all croplands (in Tg P/year, i.e., million tons per year) from 1961 until 2022. Data from Ludemann et al. (2024).[322]

KEY TAKEAWAY: The significant increase over time in phosphorus application highlights the growing reliance on phosphorus in agriculture over the decades.



● **FIGURE 36:** Global risk map for the transgression of the Modification of Biogeochemical Flows boundary – Phosphorus cycle. The regional boundary status is calculated based on agricultural phosphorus surplus in the year 2020. This graphic aligns with the suggestion for a control variable definition that is more closely related to phosphorus losses to the environment (phosphorus surplus instead of input).[52] The regional boundaries were preliminarily derived from the global boundaries, assuming a uniform sensitivity to fertilizer surplus. Regional pollution limits may deviate significantly from these boundaries.[11] Based on data from model runs with IMAGE-GNM, using the methodology of van Vuuren et al. (2025).[52]

KEY TAKEAWAY: The transgression of the phosphorus cycle boundary is particularly notable in parts of South America and Asia, where phosphorus use has exceeded safe ecological limits, indicating potential environmental threats.



● **FIGURE 37:** Global risk map for the transgression of the Modification of Biogeochemical Flows boundary – Nitrogen cycle. The regional boundary status is calculated based on agricultural nitrogen surplus in the year 2020 and estimates of regional surplus boundaries. The assessment aligns with the suggestion for a control variable definition[326] that is more closely related to nitrogen losses to the environment (nitrogen surplus instead of input). Values range from within the Safe Operating Space (green; no exceedance of regional surplus boundaries) to the Zone of Increasing Risk (orange), and extend to the High-Risk Zone (red/purple). The threshold between the Zone of Increasing Risk and the High-Risk Zone is calculated based on information from Schulte-Uebbing et al. (2022)[326] (see Supplementary Material). Based on data from model runs with IMAGE-GNM, using the methodology of Schulte-Uebbing et al. (2022).[326]

KEY TAKEAWAY: Nitrogen use in agriculture has exceeded safe ecological limits in several regions of the world, particularly in parts of Asia and Europe, indicating significant environmental risks.

CONTROL VARIABLE

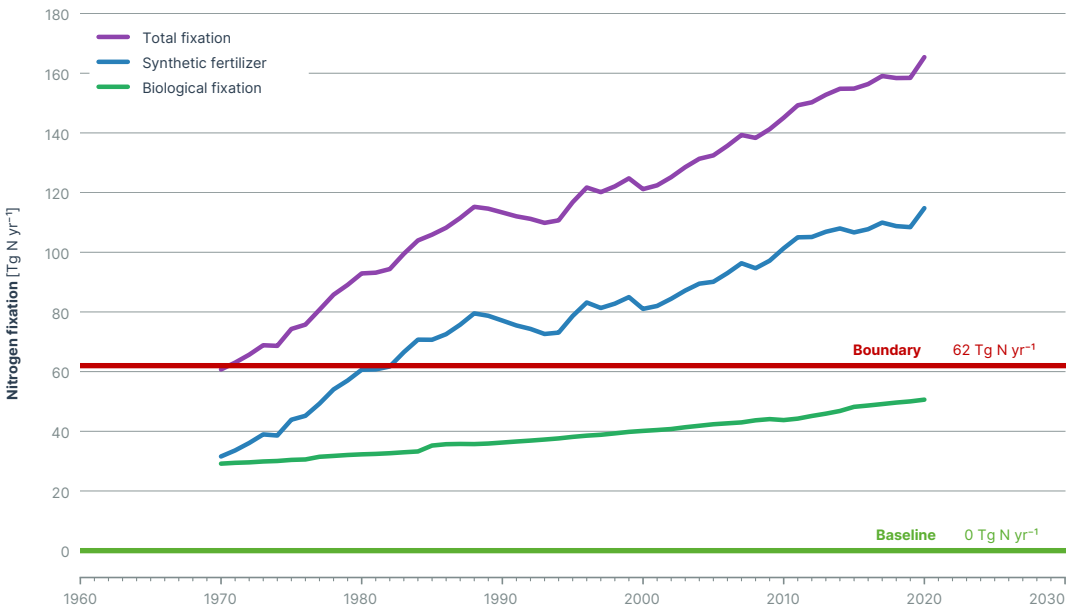
Nitrogen (N) Fixation

DEFINITION The nitrogen boundary sets a threshold for anthropogenic nitrogen fixation in agriculture. It is the sum of industrial nitrogen fixation through the Haber-Bosch process for fertilizer production and the intentional biological fixation through leguminous plants that host nitrogen-fixing bacteria in their roots.

UNIT Teragrams of Nitrogen per Year (Tg of N/year). 1 teragram equals 1 million metric tons.

HISTORICAL RANGE Human activities have increased anthropogenic nitrogen fixation rates from 0 to approximately 190 Tg of N/year globally, mainly through fertilizer use. As a result, human interference in the global nitrogen cycle now exceeds the total flux of fixed nitrogen from all natural sources, both on land and in the ocean.[325]

PLANETARY BOUNDARY (PB) The nitrogen PB targets industrial and intentional biological nitrogen fixation, setting a threshold at 62 Tg N/year. This boundary is established based on empirical data, environmental considerations, and the precautionary principle to uphold biogeochemical balance and safeguard ecosystem health.[11]



● **FIGURE 38:** Nitrogen inputs to agriculture. This graph shows the estimated global anthropogenic nitrogen fixation, through fertilizer application and biological fixation, on all agricultural land (in Tg N/year, i.e., million tons per year) from 1961 until 2022. Data from the IMAGE- GNM model[52] and FAO.[323]

KEY TAKEAWAY: The steady increase in nitrogen inputs over time is a result of both cropland expansion and higher nitrogen use rates, reflecting the growing demand for agricultural productivity.

Key Drivers

Human activities disrupt nitrogen and phosphorus cycles, similar to how they affect the global carbon cycle.[10,327] Key drivers include extensive fertilizer use and the cultivation of nitrogen-fixing crops in agriculture. Other major sources of nitrogen include nitrous oxides (NO_x) emissions from fossil fuel combustion and the release from long-term stocks such as the depletion of managed soils.

Today, the amount of human-generated nitrogen entering the biosphere exceeds all natural sources combined.[325] Similarly, agricultural activities have accelerated phosphorus inputs to the biosphere two to three times beyond natural rates.[283,328] The underlying driver of this development is the growing demand for food, in particular for livestock products that require the cultivation and fertilization of feed. The food system is responsible for about 70% of nitrogen and 75% of phosphorus inputs to surface waters.[311]

Besides the introduction of new nitrogen and phosphorus, other factors also contribute to the disruption of the respective nutrient cycles. These include low nutrient use efficiency within the agricultural system, the rates of food loss and waste, insufficient recycling of livestock and human excreta, as well as insufficient erosion control and wastewater treatment.[329] It is also important to note that the effects of accumulated soil phosphorus and groundwater nitrogen loadings can persist for several decades after initial inputs have been reduced.[327]

Anthropogenic nitrogen and phosphorus fluxes have varied significantly over time and across regions. While Europe and North America experienced strong initial growth since the mid-20th century, these have now stabilized. Currently, Asia is seeing substantial increases in nutrient fluxes, which are empirically linked to economic growth. In contrast, regions such as sub-Saharan Africa and Oceania are facing deficits in their nutrient budgets.[327,330]

Impacts

Transgressing the safe boundaries for phosphorus and nitrogen has profound and widespread impacts on aquatic and terrestrial ecosystems, human health, and economic sectors like agriculture, aquaculture, fisheries, and tourism. Nitrous oxide emissions contribute substantially to **Atmospheric Aerosol Loading**, **Stratospheric Ozone Depletion** and **Climate Change**.[331]

Excess nitrogen and phosphorus lead to the eutrophication of water bodies and can trigger dead zones in freshwater and marine systems, with geological evidence even for large-scale ocean anoxia.[332,333] Nitrogenous air pollution causes hundreds of thousands avoidable deaths every year.[334]

Besides the individual effects of nitrogen and phosphorus, shifts in their ratio itself can threaten ecosystem integrity and alter ecosystem composition by disrupting the nutrient balance across food webs.[335] Since the nutrient cycles have a central function in the Earth System, they also interact with other Planetary Boundaries, such as **Climate Change, Biosphere Integrity, and Land System Change**.

Current and Future Research

The nitrogen boundary currently considers only intentional nitrogen fixation for agriculture. Future assessments should also include reactive nitrogen from fossil fuel combustion and from the breakdown of long-accumulated soil nitrogen stocks. In addition, the emerging role of ammonia as a fuel and long-distance energy carrier may push nitrogen fixation to unprecedented levels in the coming decades, posing high pollution risks if not regulated effectively.[336]

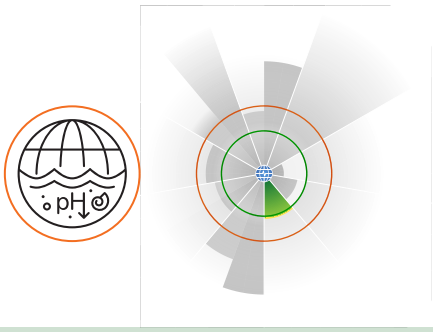
Several studies suggest using agricultural nitrogen surplus as a control variable, focusing on the amount of nitrogen remaining in the environment after harvest, and its resulting adverse effects.[55,326,337] A recent assessment of the regional boundary for phosphorus builds on the input of phosphorus to freshwater systems directly, considering phosphorus losses by soil erosion as well as non-agricultural sources of phosphorus.[311]

Future assessments of the nitrogen and phosphorus boundaries may benefit from more explicit incorporation of the role of both nutrients in the deoxygenation of freshwater systems, coastal waters, and the global ocean.[338]

Data Sources

- Synthetic nitrogen fertilizer application based on FAOStat (2026).[323]
- Phosphorus fertilizer input data from Ludemann et al. (2024).[322]
- Global Phosphorus flow into the ocean from model runs with IMAGE-GNM, based on the methodology of Beusen et al. (2022).[324]
- Exceedance of critical P surplus data from model runs with IMAGE-GNM, based on the methodology of van Vuuren et al. (2025).[52]
- Exceedance of critical N surplus data from model runs with IMAGE-GNM, based on the methodology of Schulte-Uebbing et al. (2022).[326]

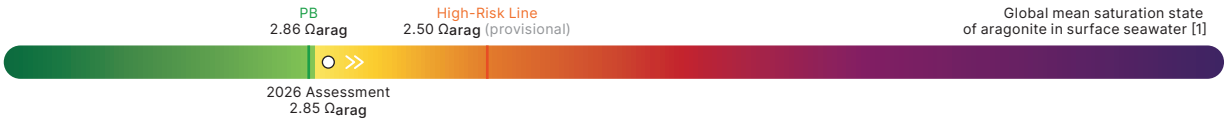
5.6 Ocean Acidification



MAIN TAKEAWAY

The ocean absorbs around 25% of the CO_2 released by human activities. This oceanic uptake slows climate change but causes the seawater to become more acidic – a process known as ocean acidification. Ocean acidification has now gone beyond what is considered safe for marine life. A key indicator of ocean acidification is the aragonite saturation state. Aragonite is a form of calcium carbonate that many marine organisms – like corals and shellfish – use to build their shells and skeletons.

As more CO_2 enters the ocean, it forms carbonic acid, which lowers the pH but also reduces the availability of carbonate ions. Increased acidity and reduced carbonate ion availability can make it more energetically costly for calcifying organisms to build and maintain their shells or skeletons. Also many non-calcifying organisms experience adverse effects on their physiology, growth and survival due to increasing acidity. In many regions, vulnerable species are already exposed to harmful conditions. Cold-water corals, tropical corals, Arctic calcifiers, and marine life in coastal upwelling systems are especially at risk as acidification continues to spread and intensify.



Definition

Ocean acidification refers to the increasing acidity (decreasing pH) of seawater caused by the absorption of anthropogenic CO_2 from the atmosphere. This process poses risks to many organisms, potentially disrupts marine ecosystems, and reduces the ocean's efficiency to absorb anthropogenic carbon.

2026 Status

The Planetary Boundary for **Ocean Acidification** is **transgressed**. This conclusion was first established in 2025[23,339] and is based on a high-quality global observation-based dataset of surface ocean acidification variables, combined with a revised estimate of pre-industrial conditions. The current best estimate of the preindustrial global mean surface aragonite saturation state (Ω) in the year 1750 is 3.57, according to the multi-model mean of observationally-adjusted CMIP6 simulations.[339,340] The Safe Operating Space of the Planetary Boundary for Ocean Acidification has been defined as 80% of the pre-industrial Ω value (i.e., a 20% decline).[9] Applying this threshold to the pre-industrial estimate of 3.57 yields a boundary value of 2.86. The observation-based global surface aragonite saturation state in 2024 was in between 2.85 ± 0.01,[341] which lies just below the revised Planetary Boundary threshold.

CONTROL VARIABLE

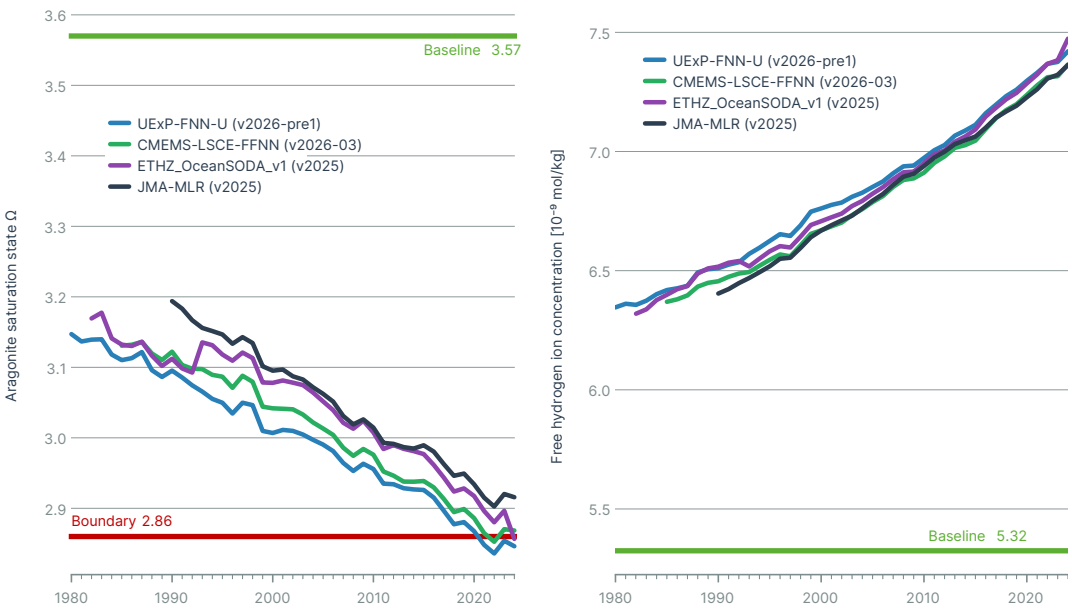
Aragonite Saturation State (Ω)

DEFINITION Aragonite is a form of calcium carbonate that many marine organisms – such as corals and shellfish – use to build their shells and skeletons. The aragonite saturation state (Ω) reflects the availability of carbonate ions in seawater relative to the amount needed for saturation with aragonite, with values below 1 indicating corrosive conditions. Ω is closely tied to CO_2 levels in the atmosphere, making it a useful indicator of the impact of rising CO_2 on both ocean chemistry and marine organisms.

UNIT Dimensionless.

HISTORICAL RANGE Ω varies by region, predominantly ranging from 3.3 to 4 in tropical regions to 1 to 2 in polar regions.

PLANETARY BOUNDARY (PB) The PB is set at the global mean surface Ω value of 2.86, which is 80% of the pre-industrial value of 3.57. The 80% threshold was selected with the aim of preventing large-scale aragonite undersaturation in high-latitude waters, while maintaining well-oversaturated conditions in low-latitude regions, and thereby limiting harmful impacts on marine calcifiers.



● **FIGURE 39:** Timeseries of the global surface aragonite saturation state (left panel) and the increase in global hydrogen ion concentration, the direct measure of acidity (right panel). For both variables, observation-based reconstructions are shown from UExP-FNN-U,[341] CMEMS-LSCE-FFNN,[342–344] ETHZ_OceanSODA_v1,[345] and JMA-MLR (v2025).[346,347] Global means are calculated on each product's native grid; differences between products largely reflect differences in spatial coverage. The aragonite saturation state has declined significantly in recent decades and has recently breached the Planetary Boundary (set at 80% of the pre-industrial state; red line). The baseline (green line) is the pre-industrial aragonite saturation state around the year 1750, based on Jiang et al. (2023).[340]

KEY TAKEAWAY: Ocean acidification has gone beyond safe limits, increasingly endangering marine ecosystems.

Key Drivers

While the term "acidification" refers specifically to a decrease in pH (i.e., an increase in hydrogen ion concentration and acidity), ocean acidification involves a broader set of chemical changes in seawater driven by CO_2 uptake,[348] including a reduction in the saturation state of aragonite, a form of calcium carbonate that many marine organisms use to build shells and skeletons.

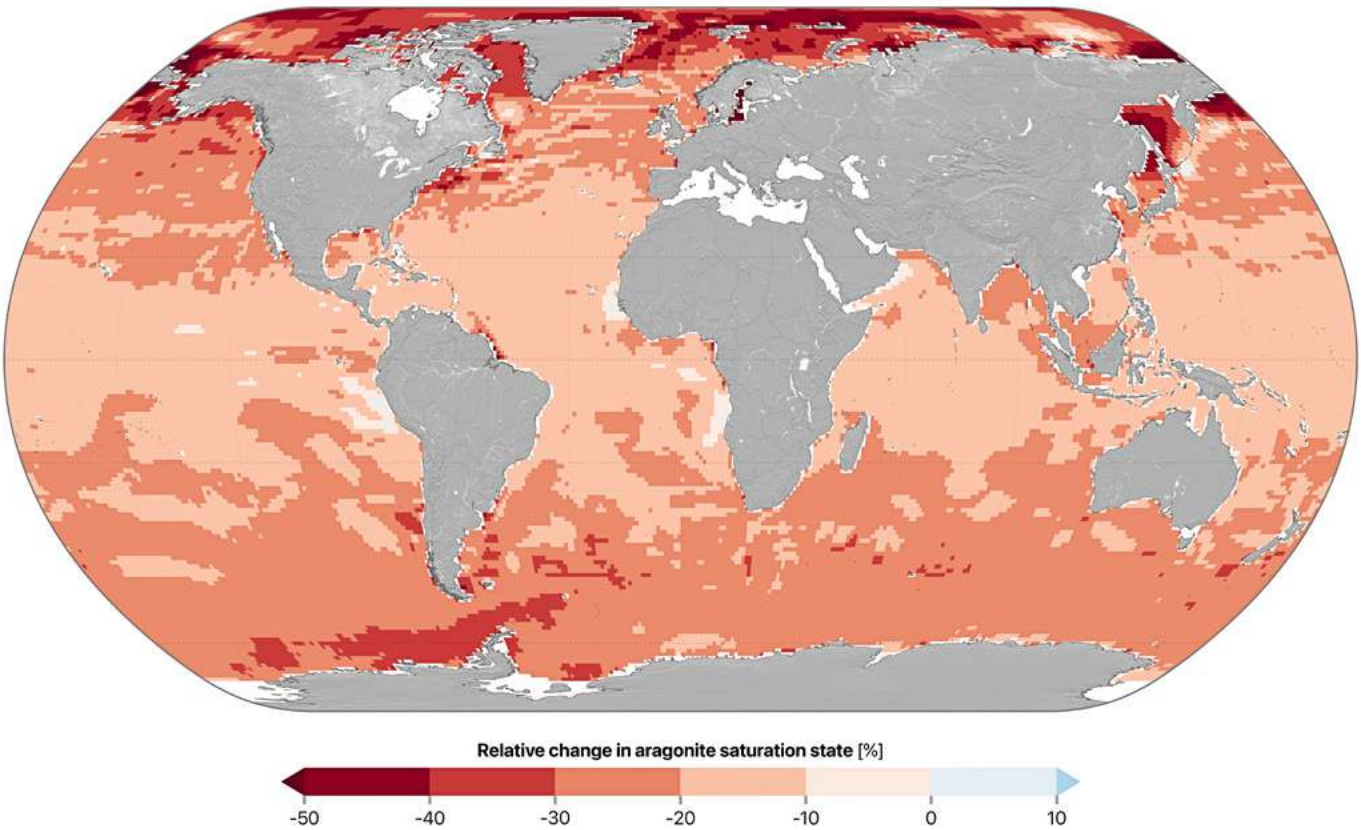
The ocean takes up approximately a quarter of human-caused CO_2 emissions.[348–350] As more CO_2 is absorbed in seawater, it forms carbonic acid, which breaks apart and releases hydrogen ions. These hydrogen ions bind with carbonate ions, reducing their availability and thereby lowering the aragonite saturation state, which can make it harder for shell-building organisms to maintain their shells and skeletons. Therefore, the aragonite saturation state indicates changes in ocean chemistry as well as the increasing pressure on marine life.

Human-caused CO_2 emissions are the dominant driver of ocean acidification at the global scale,[348,349] while coastal acidification is also influenced by additional processes such as excess nutrient runoff.

Impacts

Biological impacts of ocean acidification

Ocean acidification affects marine life in multiple ways. Calcifying organisms like corals, shelled mollusks, and some crustaceans require more energy to build and maintain their calcium carbonate structures. The increased energetic cost of calcification can lead to thinner, weaker shells and skeletons while also impairing growth, reproduction, and survival, as organisms are left with less energy for other crucial biological processes. Especially in polar regions, where acidification is progressing rapidly, signs of shell damage and dissolution have already



● **FIGURE 40:** Global map of surface aragonite saturation state, a key indicator of ocean acidification. This map shows relative anomalies in surface aragonite saturation state for the year 2024 (based on the observation-based data product UExP-FNN-U[341]) with respect to year 1750 (based on observationally-adjusted CMIP6 model results.[340]) Nearly all regions exhibit a significant decrease in aragonite saturation state. Declines are generally below 20% at low latitudes, progressively breach the 20% threshold through the mid-latitudes, and substantially exceed 20% at high latitudes, with the most pronounced reductions occurring in the Arctic.

KEY TAKEAWAY: The ocean has significantly acidified globally, particularly in the Arctic and Southern Ocean.

been observed in pteropods, tiny calcifying zooplankton commonly known as sea butterflies and recognized as some of the most vulnerable organisms to ocean acidification.[351,352] They are a sentinel group with well-researched and quantified thresholds for shell dissolution under a declining aragonite saturation state (Ω). Since pteropods play an important role in the marine food web, their decline could cause ripple effects that impact other species and potentially harm the wider marine ecosystem.

Tropical coral reefs are facing increased loss of suitable environmental conditions, including favorable pH levels.[10] While increasingly frequent marine heatwaves are the main cause of shallow-water coral reef bleaching in tropical regions, ocean acidification adds further pressure by impairing the recovery of bleached reefs. The degradation of tropical coral reefs, biodiversity hotspots that also serve as critical habitat for early life stages, leads to the loss of essential shelter and resources for many marine species.

Deep-water corals are particularly vulnerable to ocean acidification because they live near the aragonite saturation horizon, i.e. the depth where aragonite begins to dissolve. As anthropogenic CO_2 accumulates in the ocean interior, the aragonite saturation horizon rises closer to the surface.[349] As a result, deep-water corals face increasing difficulty building and maintaining their aragonite skeletons, making acidification one of their greatest threats.

Calcifying and non-calcifying organisms alike can be impacted by ocean acidification through another pathway, as internal physiology and neurology can be impacted by changes in seawater chemistry. Actively maintaining a stable internal pH as surrounding seawater acidifies can require more energy, leaving less energy for processes like growth and reproduction.[353] The co-occurrence of acidification, deoxygenation, and warming can intensify physiological stress and reduce habitat suitability for a wide range of species.[354,355]

Changes in ocean chemistry and CO_2 uptake

In addition to harming marine life, ocean acidification also influences the ocean's ability to absorb further CO_2 from the atmosphere. This effect is linked to the reduction in the carbonate ion concentration in seawater. Carbonate ions are crucial to the ocean's buffering capacity, which helps neutralize acidity by converting dissolved CO_2 into bicarbonate. As carbonate ions decline, less dissolved CO_2 is converted into bicarbonate than it would be under preindustrial conditions. A relatively higher CO_2 concentration in seawater reduces the CO_2 partial pressure difference between atmosphere and ocean – the very driver of CO_2 uptake – which ultimately slows down further CO_2 uptake compared to a less acidified state. Recent observations indicate that the CO_2 uptake efficiency has slightly declined, likely due to a combination of reduced buffer capacity and changes in ocean circulation linked to climate change.[350] Nevertheless, the ocean still absorbs about 25% of human-caused CO_2 emissions[280] and is expected to continue playing a major role in removing human-caused CO_2 from the atmosphere and moderating Climate Change.[356]

Any impacts on the biological functioning of the ocean from acidification could also feed back to surface ocean CO_2 concentration and CO_2 uptake, because marine organisms influence the carbon cycle in multiple ways. While the process of calcification actively releases CO_2 into surface waters, the biological carbon pump simultaneously transports organic carbon to the deep ocean. Consequently, shifts in such biological processes can alter the ocean's net uptake of atmospheric CO_2.[247,357–359]

Regional difference in ocean acidification

The Arctic Ocean has experienced the most severe acidification to date (● FIG. 40), driven by its naturally low buffer capacity, cold temperatures (which increase CO_2 solubility), and rising freshwater input. Some Arctic surface waters are already undersaturated with respect to aragonite, posing serious risks to calcifying organisms. At lower latitudes, tropical and subtropical waters currently maintain relatively high aragonite saturation states. However, the absolute rate of decline in aragonite saturation state is highest in these low latitude regions.[339] Coastal areas around the world often face additional acidification pressures from local factors such as upwelling, nutrient runoff from agriculture, high biological productivity, and freshwater input, but also acidification relief for example due to locally increasing alkalinity.[360] These processes contribute to strong regional and seasonal variability in acidification levels.

Current and Future Research

Further research is required to determine how regional differences, including sub-surface ocean acidification, along with a wider suite of sentinel species responses to acidification (e.g., coastal shellfish, pteropods, deep-water corals, and others) could be used to refine the boundary.[361] Initial research on these aspects suggests that a safe

boundary of 90% of the pre-industrial value (i.e., 10% decline) would better align with the precautionary principle, as this more conservative boundary would limit aragonite undersaturation to less than 10% of the area of the Arctic surface ocean, leaving only 3% of polar pteropod habitat exposed to conditions that result in severe shell dissolution.[339] Recently updated biological thresholds of acidification impacts on vulnerable species further suggest that the safe zone might be closer to a decline of 10% than 20%.[362]

Seawater pH has been proposed as an alternative control variable for the Planetary Boundary of Ocean Acidification[361] because pH reflects biological impacts of ocean acidification more broadly, far beyond the effects of reduced aragonite saturation state. Many marine species must actively regulate internal acid-base balance to keep cellular processes functioning, which becomes more energy-demanding as seawater pH decreases.[353] Lower pH also increases the energetic costs of building and maintaining calcium carbonate structures, even when the organism does not depend on carbonate ion availability. Experimental studies and meta-analyses consistently show that deviations from natural pH variability are linked to negative biological and ecosystem-level effects across diverse marine species.[363–367]

Declining ocean integrity beyond ocean acidification

While ocean acidification is well established within the PB framework, other equally critical marine processes are not yet included. Ocean warming and ocean deoxygenation are currently being evaluated as potential components of the PB framework, as they reflect additional dimensions of global ocean change.

Ocean warming

Incorporating ocean warming would add a critical dimension of ocean integrity by capturing cumulative heat storage and its role in driving physical, biogeochemical and ecological changes that are not fully reflected in the current framework.

Within the PB framework, **climate change** is represented through the atmospheric CO_2 concentration and radiative forcing. However, these metrics do not explicitly capture the accumulation, storage, and distribution of energy within the Earth system. As the dominant heat and carbon reservoir, the ocean plays a central role in climate regulation, cryosphere stability, and ecosystem changes. Sustained increases in ocean heat content reduce the ocean's ability to buffer climate change and increase the likelihood of long-term warming and non-linear Earth system change.

Since at least the 1970s, a persistent positive Earth energy imbalance has led to continuous energy uptake by the Earth system.[368,369] The ocean dominates this response, accounting for around 90% of the excess heat stored since that time. Recent studies show that ocean warming is accelerating, with a sustained increase in the rate of heat uptake over recent decades (0.15 ± 0.05 W/m^2 per decade)[370–372] and record-high ocean heat content in 2025.[373,374]

Ocean warming is also a major stressor on marine ecosystems and interacts with other human-induced pressures, including acidification and deoxygenation.[355,375]

Potential control variable candidates for ocean warming include upper ocean heat content (e.g., over 0–2000 m). It reflects the integrated response of the Earth system to radiative forcing and provides complementary information to atmospheric CO_2 or energy imbalance. Ocean heat content is derived from measured ocean temperatures, with good observational coverage of the upper 2000 m over the past several decades.

Ocean deoxygenation

Approximately 0.5–3% of the global ocean dissolved oxygen content has been lost over the past five decades.[59,376] Ocean deoxygenation influences Earth system stability through several interconnected pathways, for example by influencing how organic matter is decomposed as it sinks through the water column. Under oxygen-rich conditions, aerobic microbes rapidly decompose sinking organic matter, recycling it into dissolved inorganic carbon that can return to the atmosphere as CO_2. Under low-oxygen conditions, microbial decomposition occurs through slower anaerobic pathways, allowing a significantly larger fraction of organic carbon to become buried in seafloor sediments. These processes can affect atmospheric CO_2 and thereby influence Earth's climate over long timescales.[377] Ocean deoxygenation also plays an important role in regulating how efficiently nitrogen is cycled in the ocean. Low-oxygen conditions drive nitrogen-depleting microbial processes (denitrification and anammox) that transform biologically available nitrogen mainly into inert N_2 gas, and a smaller fraction into the potent greenhouse gas N_2O. Ocean deoxygenation increases the volume of water masses that are critically low in oxygen (hypoxic) or completely oxygen-depleted (anoxic). One consequence is the expansion of oxygen minimum zones –

massive hypoxic water layers that can shoal upward from the mid-depth ocean. Most marine animals cannot survive in hypoxic waters for long, so they either suffocate or flee to oxygen-rich areas, resulting in altered species distribution and impaired ecosystem functioning.[332] Ocean acidification and deoxygenation are increasingly recognized as important co-stressors, with evidence that their co-occurrence can intensify physiological stress, particularly in calcifying and metabolically sensitive organisms.[378,379] Geological evidence further indicates that past mass extinction events coincided with periods of expanded ocean anoxia, highlighting the potential for profound changes at planetary scale under reduced oxygen conditions.[380]

Hypoxic water volume could serve as a control variable for ocean deoxygenation, integrating the effects of warming, stratification, and circulation change. There is substantial evidence for ecological and physiological thresholds beyond which impacts on marine ecosystems are likely to be exacerbated, providing a basis for defining a safe operating space.[338,381]

Data Sources

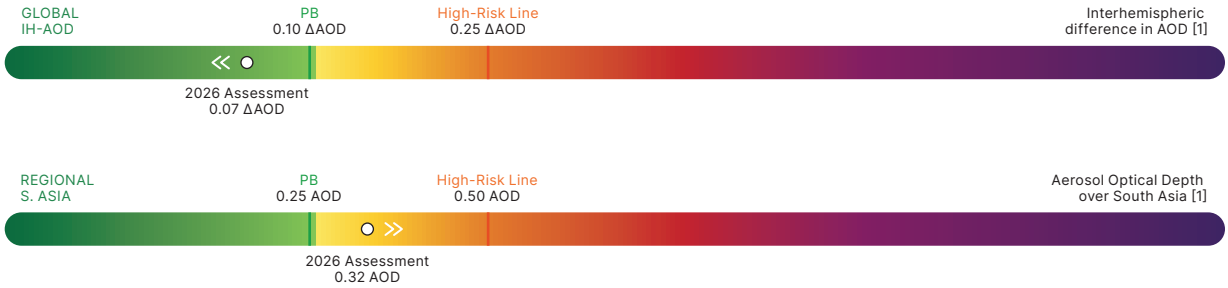
- The observation-based data product UExP-FNN-U (v2026-pre1)[341] is used for the current value, map **(FIG. 40)**, and timeseries **(FIG. 39)**.
- Observationally-adjusted CMIP6 model data from Jiang et al. (2023)[340] is used for the preindustrial baseline and boundary value **(ALSO IN FIG. 39)**, and as preindustrial reference distribution for the map **(FIG. 40)**.
- The following observation-based data products are also used in the timeseries **(FIG. 39)**: CMEMS-LSCE-FFNN (v2026-03),[342–344] ETHZ_OceanSODA_v1 (v2025),[345] and JMA-MLR (v2025).[346,347]
- We thank Luke Gregor (OceanSODA-ETHZ), Marion Gehlen and Frederic Chevallier (CMEMS-LSCE-FFNN), and Yosuke Iida (JMA-MLR) for their advice and assistance with their datasets. DJF and JDS were supported by the European Space Agency projects Ocean Carbon for Climate (OC4C; 3-18399/24/I-NB) and Satellite-based observations of Carbon in the Ocean: Pools, Fluxes and Exchanges (SCOPE; 4000142532/23/I-DT). HSF received funding from a Natural Environment Research Council grant NE/X006271/1.
- For additional information on data and methodology, please see Supplementary Materials.

5.7 Increase in Atmospheric Aerosol Loading

MAIN TAKEAWAY

Atmospheric Aerosol Loading refers to the concentration of small particles suspended in the atmosphere, which originate from both natural processes like dust storms and volcanic eruptions, and human activities such as burning fossil fuels, industrial processes, and agriculture. These particles influence the Earth's climate by interacting with sunlight and clouds. Some reflect sunlight and cool the planet (such as sulfates), while others absorb heat and contribute to warming (such as black carbon). Aerosols also affect cloud formation and precipitation patterns, making their climate effects complex and regionally varied.

In recent decades, efforts to improve air quality have led to declining aerosol emissions in many higher-income regions, while emission levels remain high or are increasing in parts of Asia and Africa due to rapid industrial growth and biomass burning. Overall, global anthropogenic aerosol loading is decreasing, which helps to reduce air pollution and health risks but may accelerate global warming by removing the cooling effect that some aerosols provide. Managing aerosol emissions presents a trade-off: While their reduction benefits human health and ecosystems, it also reveals more of the warming caused by greenhouse gases.



Definition

Atmospheric Aerosol Loading refers to the concentration and spatial distribution of fine particulate matter in the atmosphere that can influence Earth's energy balance, cloud formation, and hydrological cycles. Human-driven transgression of this Planetary Boundary is primarily caused by emissions of aerosols such as black carbon, sulfates, and organic particles, which can alter regional climate systems, affect monsoon patterns, and pose risks to both ecosystems and human health.[9,382,383]

2026 Status

The difference in **Atmospheric Aerosol Loading** (0.07) between the two hemispheres (interhemispheric difference) is below the Planetary Boundary of 0.1, and thus **within the Safe Operating Space**, trending towards safer values.[9,84] A proposed regional control variable, the aerosol optical depth over South Asia (0.32), is now assessed as transgressed (see section on Current and Future Research).[9,84]

CONTROL VARIABLE

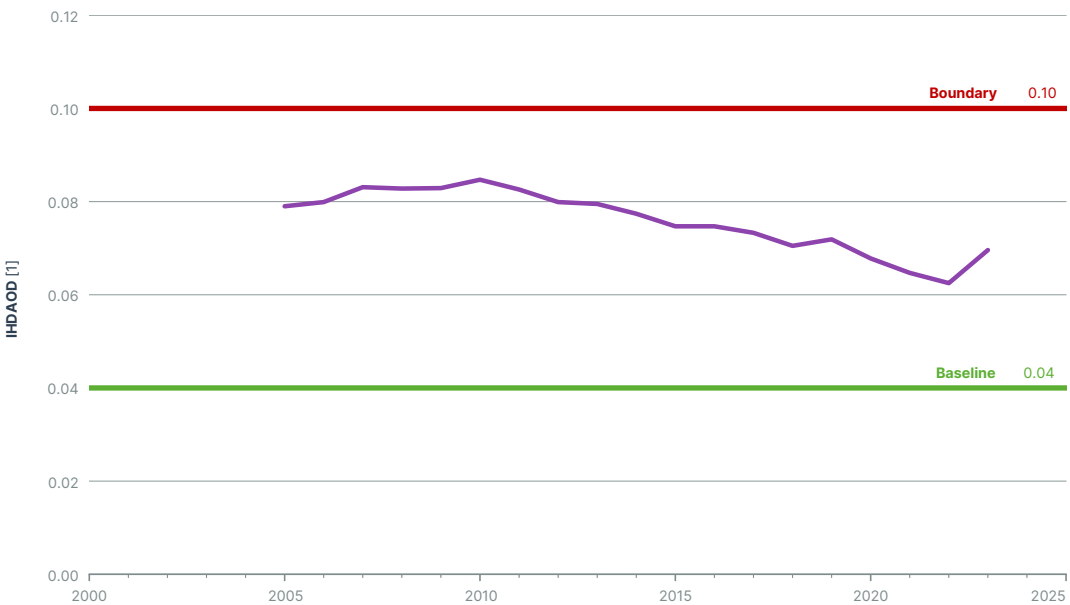
Interhemispheric Difference in Aerosol Optical Depth (AOD)

DEFINITION AOD measures how many aerosols (small particles suspended in the air) block the transmission of light in the atmosphere, without distinguishing whether the particles absorb or reflect light. The interhemispheric difference refers to how much higher AOD tends to be in the Northern Hemisphere – where most human activity and emissions occur – compared to the Southern Hemisphere. Globally, this control variable measures the interhemispheric difference in aerosol concentrations between the Northern and Southern Hemispheres.

UNIT Dimensionless.

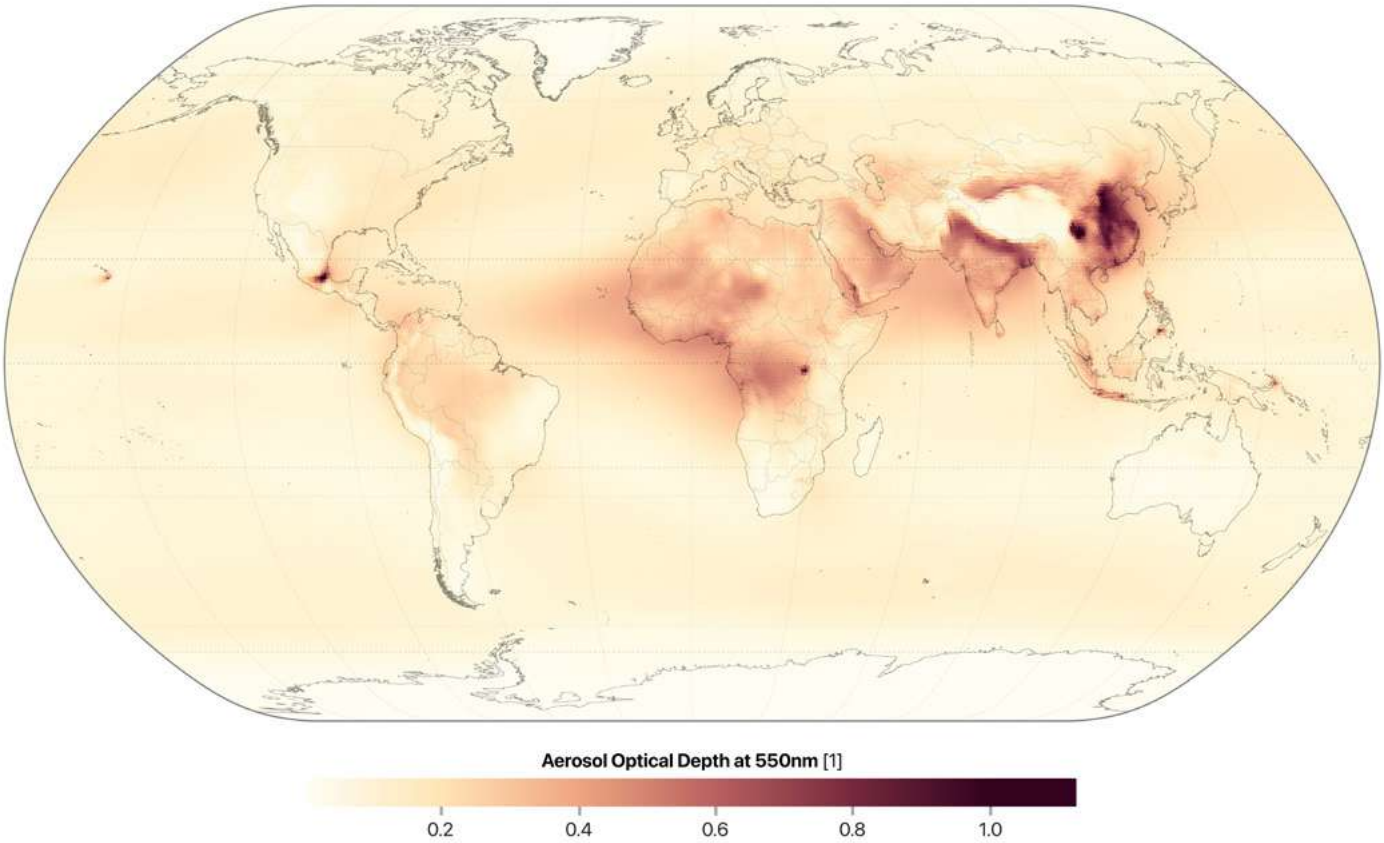
HISTORICAL RANGE AOD values range from 0 (no aerosols) to 1 or higher (very dense aerosol layer). The difference in AOD between the Northern and Southern Hemispheres has been decreasing from 2010 to 2025 and ranging between 0.08 and 0.06.

PLANETARY BOUNDARY (PB) The PB is defined by an interhemispheric difference in AOD of 0.1. This threshold is based on observational evidence from volcanic eruptions and on modeling studies, which suggest that a rising interhemispheric difference in AOD can trigger regional-scale tipping points, potentially leading to shifts in monsoonal patterns. Such changes can significantly affect weather cycles, increasing the risk of floods and droughts. This threshold is also relevant in the context of justice considerations related to human health.[55]



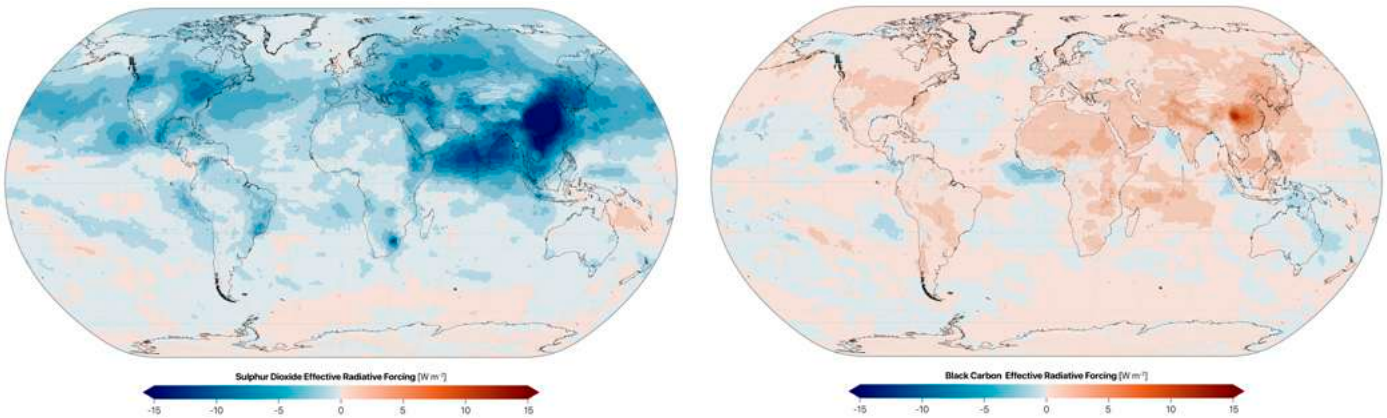
● **FIGURE 41:** Bridging the divide: Declining interhemispheric difference in aerosol loading. This chart shows the 5-year running mean of the difference in the aerosol optical depth (AOD) between the Northern and Southern Hemispheres, calculated by averaging data from 60° north to 60° south for the period from 2003–2025. Horizontal lines indicate the Planetary Boundary of 0.1 and the pre-industrial baseline of 0.04. Despite a slight uptick in the most recent data point, we consider the post-2010 trend towards safer values to continue. Data from CAMS EAC4.[384]

KEY TAKEAWAY: The difference in aerosol optical depth between the Northern and Southern Hemispheres has been decreasing from 2010 to 2025, indicating that we are moving further into the Safe Operating Space.



● **FIGURE 42:** Global total aerosol optical depth (AOD) at 550 nm, time-averaged over 2010–2020. The Copernicus Atmosphere Monitoring Service (CAMS) global reanalysis (EAC4) integrates satellite retrievals and model simulations to produce consistent, spatially and temporally resolved fields of atmospheric composition. Total AOD represents the aerosol optical depth due to all aerosol species, including sulfates, black carbon, organic matter, sea salt, and dust.

KEY TAKEAWAY: High AOD values occur over major dust source regions (such as the Sahara and Arabian Peninsula), biomass-burning zones (such as Central Africa and the Amazon), and industrially polluted areas (such as India and Eastern China). Low AOD is found over remote oceans and the polar regions.



● **FIGURE 43:** Effective radiative forcing (W/m²) of sulfur dioxide and black carbon, averaged annually over 2010–2020. Effective radiative forcing (ERF) estimates for sulfur dioxide (SO_2, left) and black carbon (BC, right) are shown, based on simulations from CMIP6 models participating in the Aerosols and Chemistry Model Intercomparison Project (AerChemMIP). ERF represents the net change in Earth's energy balance due to these aerosol emissions, including both direct radiative effects and interactions with clouds. SO_2 generally exerts a cooling effect by increasing reflective sulfate aerosols, while BC leads to warming by absorbing sunlight in the atmosphere.

KEY TAKEAWAY: Different kinds of aerosols have both significant warming and cooling effects on the climate system.

Key Drivers

The main anthropogenic drivers of changes in Aerosol Optical Depth (AOD), and thus of potential transgression of the global control variable, are emissions from fossil fuel and biomass burning.[385,386] Sulfur dioxide (SO_2) and black carbon are among the most important aerosol precursors (substances that react in the atmosphere to form aerosol particles) and are primarily emitted through industrial activity, power generation and transportation.[369,387] Agricultural activities, particularly open burning of crop residues and traditional biomass use, are notable contributors to black carbon emissions, although they play a minimal role in sulfur dioxide release.[369,387] The CAMS reanalysis, averaged over 2010–2020 **(● FIG. 42)**, highlights substantial differences in AOD between the Northern and Southern Hemispheres.

While the global control variable remains within the Safe Operating Space of the Planetary Boundary **(● FIG. 41)**, it does not fully capture regional risks. In some areas, such as South Asia, aerosol emissions and thus AOD levels exceed safe thresholds **(● FIG. 44)**, contributing to significant climate and societal impacts such as altered rainfall patterns and increased respiratory diseases. More research is needed to understand past natural conditions, consolidate observations and modeling, and grasp both local causes and effects as well as global-scale consequences.

Impacts

Aerosols influence the Earth system in complex and far-reaching ways.[388] One of the most important global-scale effects is their impact on atmospheric circulation, particularly through the interhemispheric difference in AOD. This imbalance, driven by higher emissions in the Northern Hemisphere, alters the distribution of absorbed solar energy across the hemispheres, which in turn affects large-scale wind patterns and the position of the Intertropical Convergence Zone.[389] These changes can alter global monsoon systems, including the South Asian, West African, and East Asian monsoons, potentially producing less rainfall or delayed onset.[390]

Aerosols also modify Earth's energy balance through effective radiative forcing.[391] Scattering aerosols (like sulfate, formed from sulfur dioxide) tend to cool the atmosphere by reflecting incoming sunlight, while absorbing aerosols (like black carbon) warm the atmosphere by trapping solar radiation **(● FIG. 43)**.[391] These opposing effects complicate the overall climate response and can lead to regionally contrasting impacts on temperature, precipitation, and cloud formation.

While interhemispheric difference in AOD is a globally averaged indicator, many significant aerosol-related effects are regional. The regional aerosol boundary of 0.25–0.5 AOD over South Asia is more relevant for capturing such local effects **(● FIG. 44)**. Elevated aerosol concentrations over South Asia have been linked to a weakening of the South Asian monsoon, increasing the risk of prolonged droughts and reduced agricultural productivity.[11]

Current and Future Research

Current research on the **Increase in Atmospheric Aerosol Loading** has shifted from measuring direct radiative forcing to understanding complex interactions across the Earth system. Future research priorities include quantifying aerosol-monsoon interactions, aerosol-cryosphere feedbacks in the Arctic, understanding interactions between warming-induced biogenic emissions and secondary aerosol formation, and moving towards regional aerosol boundaries that target hydroclimate tipping points such as monsoon collapse or accelerated ice melt. This Planetary Boundary is now seen as deeply entangled with **Climate Change**, **Land System Change**, **Freshwater Change**, and **Change in Biosphere Integrity**, with upcoming assessments likely to define a Safe Operating Space based on preventing abrupt Earth system regime shifts rather than radiative forcing alone.

Data Sources

- AOD data (total AOD for light at 550 nm wavelength) is the ECMWF Atmospheric Composition Reanalysis 4 (EAC4) product from the Copernicus Atmosphere Monitoring Service (CAMS).[384,395]
- Effective radiative forcing estimates are derived from simulations conducted by climate models participating in CMIP6 (the sixth phase of the Coupled Model Intercomparison Project) which provides a coordinated framework for comparing global climate models.[396]
- Specifically, data sets come from models involved in AerChemMIP, a CMIP6 sub-project focused on understanding the role of atmospheric aerosols and chemistry in the climate system.[397]

CONTROL VARIABLE

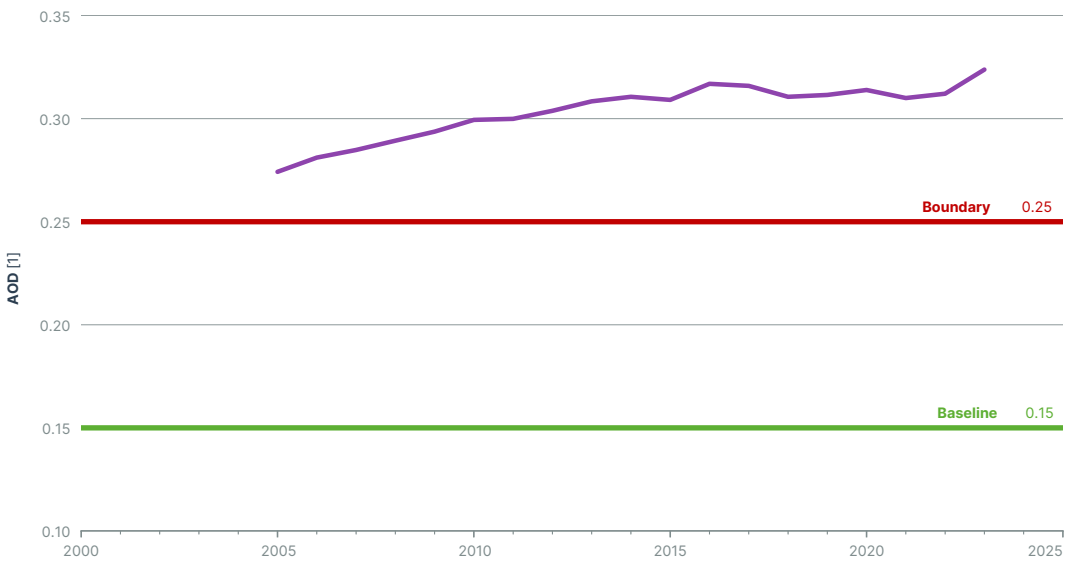
Proposed regional control variable: Aerosol Optical Depth over South Asia

DEFINITION No globally uniform AOD threshold can currently be defined for climate impacts because the interactions of aerosol loading with climate effects vary strongly across regions. Instead, the global control variable is the interhemispheric aerosol optical depth difference. A **regional boundary** has, however, been identified for South Asia, where aerosol loading affects the South Asian summer monsoon, a key component of the global hydrological cycle. The regional aerosol boundary for South Asia is defined using AOD as the control variable, representing the column aerosol loading over the South Asian region. Regional AOD correlates with PM2.5 (fine particulate matter with diameters 2.5 micrometers, a health-hazardous air pollutant, which is also particularly important in the context of justice considerations regarding human health.[55,392]) concentration.[393] However, this regional correlation is not yet fully integrated into the Planetary Boundaries framework.

UNIT Dimensionless.

HISTORICAL RANGE AOD values range from 0 (no aerosols) to 1 or higher (very dense aerosol layer); 0.32 at present over South Asia.

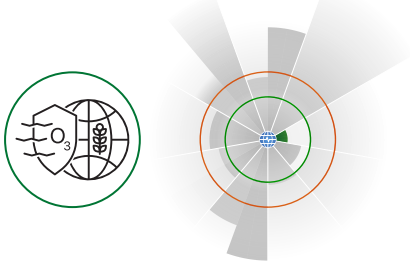
PLANETARY BOUNDARY (PB) Following[11], a safe boundary of AOD 0.25 (Range 0.25–0.5) is proposed, with a zone of uncertainty extending to AOD 0.5, beyond which substantial disruption to the regional hydrological cycle is expected. This boundary has been recently confirmed using climate model simulations,[394] which show that increasing AOD to 0.25 leads to a 10% reduction in South Asian monsoon precipitation (drought conditions), while AOD 0.5 results in 15–20% reductions in the rainfall, indicating severe monsoon weakening.



● **FIGURE 44:** Regional control variable: aerosol optical depth (AOD) over South Asia. This chart shows the 5-year running mean of the annual mean aerosol optical depth (AOD at 550 nm; unitless) averaged over the South Asian region (5°N-40°N, 65°E-100°E) for the period 2003–2025, from CAMS reanalysis data. The red line shows the Planetary Boundary of 0.25, while the green line represents the baseline of 0.15. Data from CAMS EAC4.[384]

KEY TAKEAWAY: Aerosol optical depth (AOD) over South Asia indicates that this regional PB has been transgressed, and the trend over the last year shows that it is moving further outside the Safe Operating Space.

5.8 Stratospheric Ozone Depletion



MAIN TAKEAWAY

The ozone layer in the upper atmosphere protects the Earth from harmful solar ultraviolet radiation. Additionally, ozone plays an important role in atmospheric energy balance. Because of the release of ozone depleting substances (ODS), the ozone layer has substantially declined over the second half of the 20th century.

Since the mid-1990s, thanks to the international agreements limiting ODS release, the ozone layer has largely recovered, and it is expected to stay within the safe limits. The ozone layer depletion and its subsequent recovery had measurable effects on atmospheric circulation, particularly in the Southern Hemisphere.

Definition

The Planetary Boundary for **Stratospheric Ozone Depletion** is defined to ensure sufficient ozone concentrations in the stratosphere to prevent harmful levels of ultraviolet radiation at Earth's surface. Depletion is driven primarily by the emission of ozone-depleting substances, such as chlorofluorocarbons, which catalyze the breakdown of ozone molecules, particularly under polar stratospheric conditions.

2026 Status

The current total amount of stratospheric ozone (286 DU) is above the Planetary Boundary of 277.4 DU, and thus **within safe levels**. Recovery is ongoing, although it may have plateaued in recent years, with values still below mid-20th century levels.

CONTROL VARIABLE

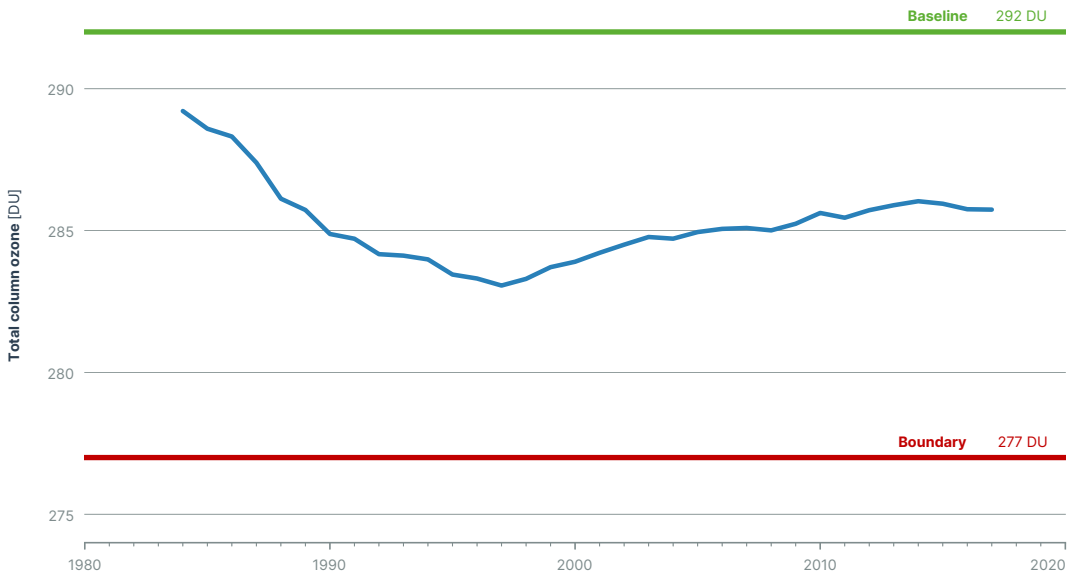
Stratospheric Ozone Concentration

DEFINITION Average stratospheric ozone concentration in the extra-polar zone – the region of the Earth's atmosphere outside the polar areas, spanning from 60°N to 60°S. While the polar 'ozone hole' is widely known, the impacts on humans and ecosystems are more severe when it comes to the extra-polar ozone layer. Additionally, the ozone hole phenomenon involves complex factors beyond just anthropogenic ozone-depleting substances, making extra-polar ozone a more relevant measure for a Planetary Boundary.[9]

UNIT Dobson Unit (DU). One DU represents a layer of ozone that would be 0.01 millimeters thick under standard temperature and pressure.

HISTORICAL RANGE Typical local values range from about 100 to 500 DU.

PLANETARY BOUNDARY (PB) There is no clear threshold for defining a boundary for global extra-polar stratospheric ozone. As a preliminary estimate, the PB is set as a maximum reduction of 5% from the reference level (mean of the years 1964–1980). With the reference level estimated at 292 DU, the Planetary Boundary is set at 277.4 DU.



● **FIGURE 45:** Ozone layer revival: A success story. This chart displays the 11-year running mean of the control variable "global mean stratospheric ozone concentration" measured in Dobson Units (DU) for the data from 1979–2022. The red line shows the Planetary Boundary of about 277, while the green line represents the baseline of 292 (values updated[10]) Data from Copernicus (2020).[398]

KEY TAKEAWAY: While the global stratospheric ozone layer has recovered since the mid-1990s, this recovery may have plateaued in recent years.

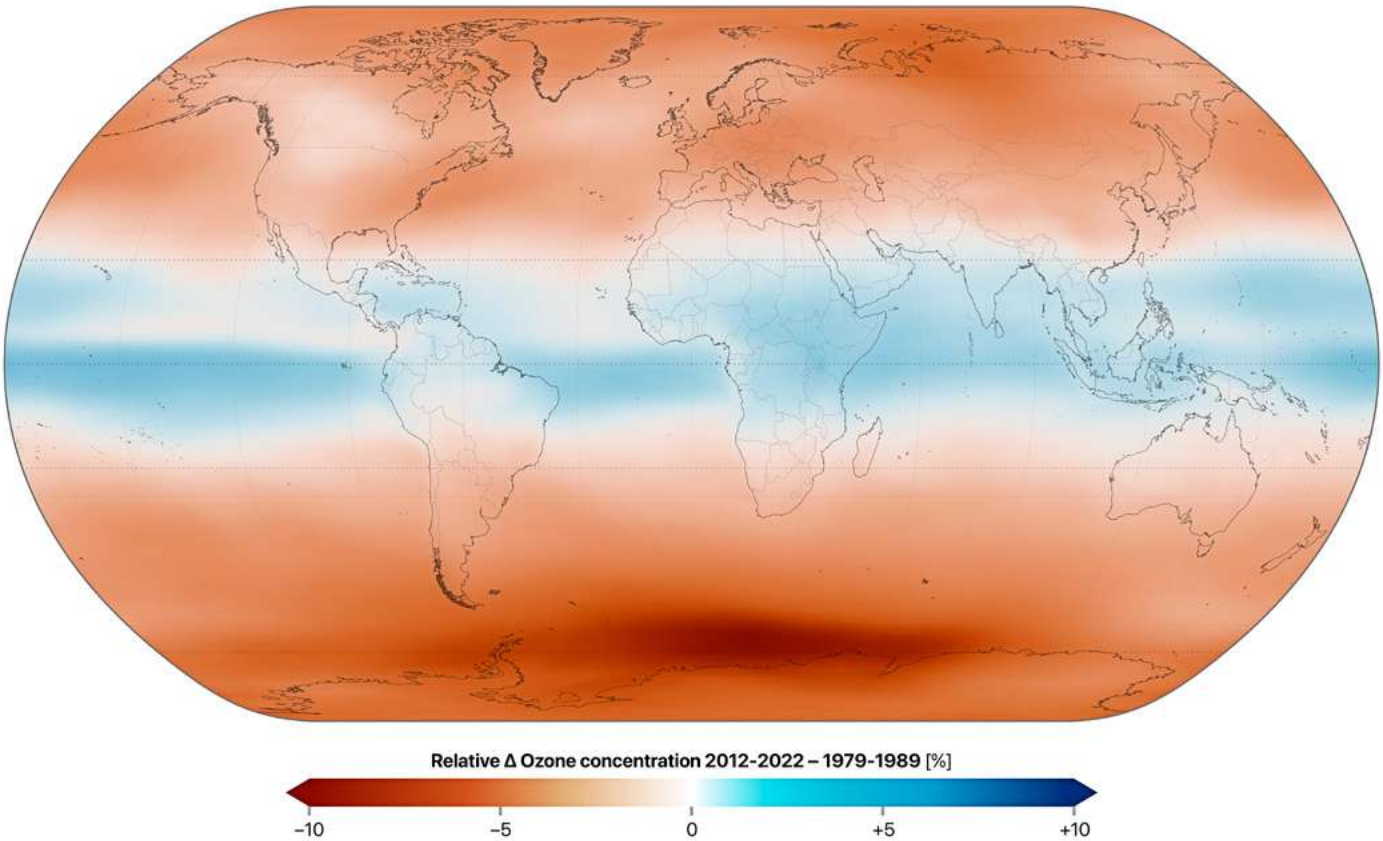
Key Drivers

Ultraviolet (UV) radiation reaching Earth's surface poses a threat to life, but an intact ozone layer in the stratosphere absorbs much of this harmful radiation. Therefore, the concentration of O_3 (ozone) in the atmosphere is a critical control variable that must not exceed the established Planetary Boundary level.

The primary driver of ozone destruction in the stratosphere are highly reactant atoms, mostly chlorine. This chlorine is produced in the stratosphere through the breakdown of stable chlorofluorocarbons (CFCs) by UV radiation. CFCs are a class of chemicals that have been used as refrigerants, aerosol propellants, fire suppression systems, and solvents. These stable molecules can persist in the atmosphere for up to a century after being emitted at the Earth's surface – all the while continuing to break down ozone (O_3) into regular oxygen (O_2).[400] The Montreal Protocol has successfully controlled CFC emissions; today, the most significant remaining source of ozone-depleting substances is nitrous oxide (N_2O).[401] Agricultural activities contribute a major share of global N_2O emissions through various pathways.[402]

Impacts

Depletion of stratospheric ozone allows more harmful UV radiation to reach the Earth's surface, significantly increasing the risk of skin cancer, cataracts, and other health problems in humans. This increased UV radiation also adversely affects terrestrial and aquatic ecosystems. In the ocean, it can damage phytoplankton populations, which are crucial for marine food webs. On land, elevated UV levels can impact crop yields and the health of forest ecosystems.[403] Additionally, changes in stratospheric ozone levels influence climate dynamics, as alterations in ozone concentrations affect atmospheric temperatures and circulation patterns, impacting both regional and global climate systems.



● **FIGURE 46:** Global map of recent ozone layer changes. This map shows the relative change of the control variable "global mean stratospheric ozone concentration" between 1979–1989 (first 11-year cycle of this data set) and 2012–2022 (last 11-year cycle of this data set, e.g., a change from 260 DU to 273 DU would be indicated by a value of +5%). Areas where total ozone has increased are shown in shades of blue, and areas where it decreased are shown in shades of red. Data from Copernicus (2020).[398]

KEY TAKEAWAY: Global changes in stratospheric ozone concentration between the periods 1979–1989 and 2012–2022 show mixed trends, with increases in some regions and decreases in others, while the persistent Antarctic ozone hole highlights ongoing recovery challenges.[399]

The depletion of Antarctic stratospheric ozone in the period from 1960 to 2000 resulted in the cooling of the lower stratosphere over the Antarctic, which led to a strengthening of the Antarctic polar vortex during austral spring and a delay in the polar vortex breakup dates.[404] This led to changes in the Southern Hemisphere tropospheric circulation, including the poleward shift of the mid-latitude tropospheric wind jet, a positive trend in the Southern Annular Mode and the poleward expansion of the equatorial tropospheric convection cell, which also had an impact on rain precipitation and ocean salinity in the Southern Hemisphere.[405] After the year 2000, the Antarctic ozone recovery led to a weakening of the Antarctic polar vortex and to earlier polar vortex breakup dates.[404] Recent studies[406] reported that the Southern Hemisphere tropospheric circulation changes paused, or slightly reversed, after the year 2000 due to the Antarctic ozone recovery. While there is evidence that tropospheric circulation and surface climate in the Southern Hemisphere were influenced by Antarctic ozone depletion- and recovery-related changes, no robust evidence of such linkage was found in the Northern Hemisphere.[404]

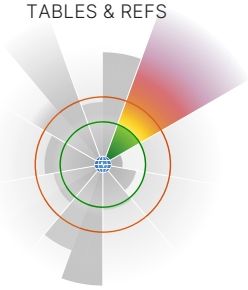
Current and Future Research

The increasing amount of space debris in low-Earth orbit ultimately leads to ozone depletion, due to the production of nitrogen monoxide in the middle atmosphere by re-entering space debris. Additionally, a growing amount of rocket launches and re-entering space debris introduce new aerosols in the middle atmosphere. The impacts of these aerosols on ozone concentration and on radiative balance in the middle atmosphere remain poorly understood. Changes in the vertical distribution of ozone concentration also play a crucial role in radiative balance.[404]

Data Sources

- Ozone data from Copernicus (2020),[398] accessed on 18 Mar 2026.

5.9 Introduction of Novel Entities



MAIN TAKEAWAY

Novel entities comprise human-made chemicals and materials and naturally occurring substances that are mobilized by humans. Produced and released in myriad forms and huge quantities, they can interact, accumulate and elicit impacts in ways that can threaten the Earth system. For example, many novel entities (certain pollutants and plastics) are widespread globally with poor reversibility. They accumulate along the food chain and cause adverse effects, by themselves or in combination with other stressors (e.g., heat or drought), ultimately with the potential to threaten biosphere integrity.

However, our understanding of planetary-scale exposure and impacts is still fragmented due to the tremendous, ever-increasing number and diversity of novel entities. To assess the potential planetary risk arising from our ignorance, we use a practical proxy: the proportion of novel entities that does not undergo adequate safety testing before widespread production and use. That share is currently very high, and on this basis the Planetary Boundary for Novel Entities is considered transgressed – the creation of novel entities far outpaces our capacity to evaluate them. Future assessments may incorporate additional metrics, such as production, release to the environment, transport to and accumulation in remote sinks, and impacts.

Definition

Novel entities are novel anthropogenic introductions or mobilizations to the Earth system. These include human-made and -mobilized chemicals and materials (e.g., organic pollutants, (micro)plastics and (radioactive) elements). They can disrupt Earth system processes, mainly by impacting other boundaries, for example through impacts on biosphere integrity, or the depletion of the ozone layer via the release of chlorofluorocarbons (CFCs). Since the Planetary Boundaries framework focuses on Earth system stability rather than human or ecosystem health, a key scientific challenge is to determine how much novel entity loading the Earth system can tolerate before it shifts irreversibly into a less habitable state.

2026 Status

Following the precautionary principle, Richardson et al. (2023)[10] defined the Planetary Boundary of Novel Entities at 0 % release of inadequately tested novel entities to the environment. According to this definition, the number and diversity of human-made chemicals and materials without adequate testing, as well as human-mobilized elements introduced into infrastructure, technology, and the environment, are currently beyond safe levels. The increasing production, use, emissions, and impacts of different subsets of novel entities are illustrated in ● **FIG. 47**. As it is impossible to test all novel entities before their release, the current control variable is not actionable. Furthermore, it is inconsistent with other boundaries, whose control variables are based on risk rather than precaution. Therefore, alternative control variables for the **Introduction of Novel Entities** boundary are under development.

CONTROL VARIABLE

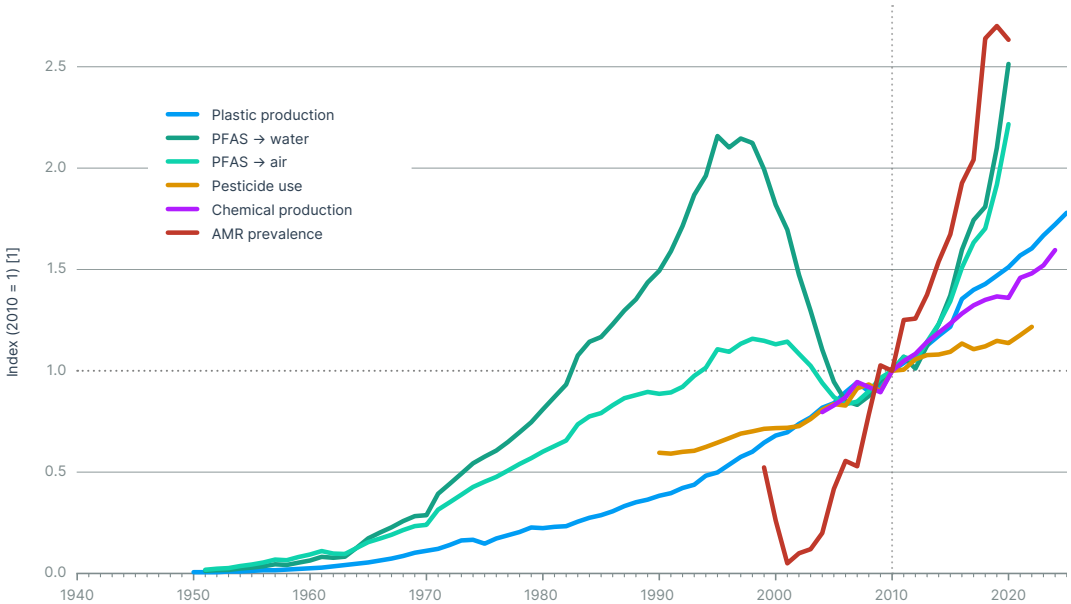
Percentage of novel entities released to the environment without adequate safety testing

DEFINITION The share of human-made or -mobilized chemicals and materials released into or mobilized in the environment without adequate safety testing. This control variable reflects our level of understanding of the risks of novel entities and how effective regulations are. Monitoring this share is essential for managing the potential impacts these substances may have on the Earth system.

UNIT Percentage, i.e. the fraction of synthetic chemicals and materials released without adequate safety testing.

HISTORICAL RANGE This percentage can vary from 0% (all chemicals and materials undergo sufficient testing before release) to 100% (none are tested).

PLANETARY BOUNDARY (PB) Following the precautionary principle, the Planetary Boundary of Novel Entities is set at 0 % – no human-made or -mobilized chemicals and materials should be released or mobilized without adequate safety testing.[10] Examples of novel entities include polychlorinated biphenyls (PCBs), which, even decades after their ban in the Stockholm Convention, are still present in the Earth system and partly exceed effect thresholds in marine mammals;[407] or the global spread of highly persistent per- and polyfluoroalkyl substances (PFASs). Such examples underscore the need for strict testing before large-volume production and use. Other aspects that require consideration are the environmental transport and transformation of novel entities which may result in transformation products that are more toxic than the original chemicals. An example is a tire wear-derived oxidation product of the additive 6PPD-quinone, which was found to induce acute mortality in coho salmon[408] and other fish species of commercial, cultural and ecological importance.[409]



● **FIGURE 47:** Novel entities on the rise. Illustration of trends across the life cycle of different subsets of novel entities, including production of plastics and chemicals, use of pesticides, emissions of per- and polyfluoroalkyl substances (PFASs), and impacts such as antimicrobial resistance (AMR).

KEY TAKEAWAY: Production, use, release and impacts of many novel entities such as plastics, pesticides, PFASs and others are increasing, posing threats to the Earth system as well as to environmental and human health.

Key Drivers

The control variable for the **Novel Entities** Planetary Boundary measures the percentage of human-made and -mobilized chemicals and materials without adequate safety testing, and is directly driven by human activities. It has been transgressed since the onset of large-scale chemical production, use and associated environmental releases. In recent decades, the rate and degree of this transgression have increased due to the rapid growth in chemical production, both in volume and diversity. At the same time, institutional capacity to test, regulate and monitor these chemicals has not kept pace. Contributing factors include insufficient research on toxicological pathways, in particular covering complex interactions of chemical mixtures and multiple stressor settings, and insufficient monitoring covering all components of novel entities, including transformation products.

Impacts

Novel entities are constantly being released as a result of human activities and accumulate in the environment in poorly reversible ways, with the potential of disrupting Earth system processes.[410] The global accumulation and persistence of certain subsets of novel entities and their transformation products can lead to long-term, possibly irreversible changes in the environment, including the contamination of soil and sediments, air, water bodies and wildlife as well as the alteration of natural habitats. Some impacts caused by novel entities have already severely affected the status of other PBs. One example is **Stratospheric Ozone Depletion** caused by chlorofluorocarbons, which has consequently been defined as a separate PB. The global application of pesticides has contributed to substantial declines in insects, including pollinators,[411] with potential negative consequences for the delivery of ecosystem services such as crop production, and food-web stability, linked to **Change in Biosphere Integrity**.

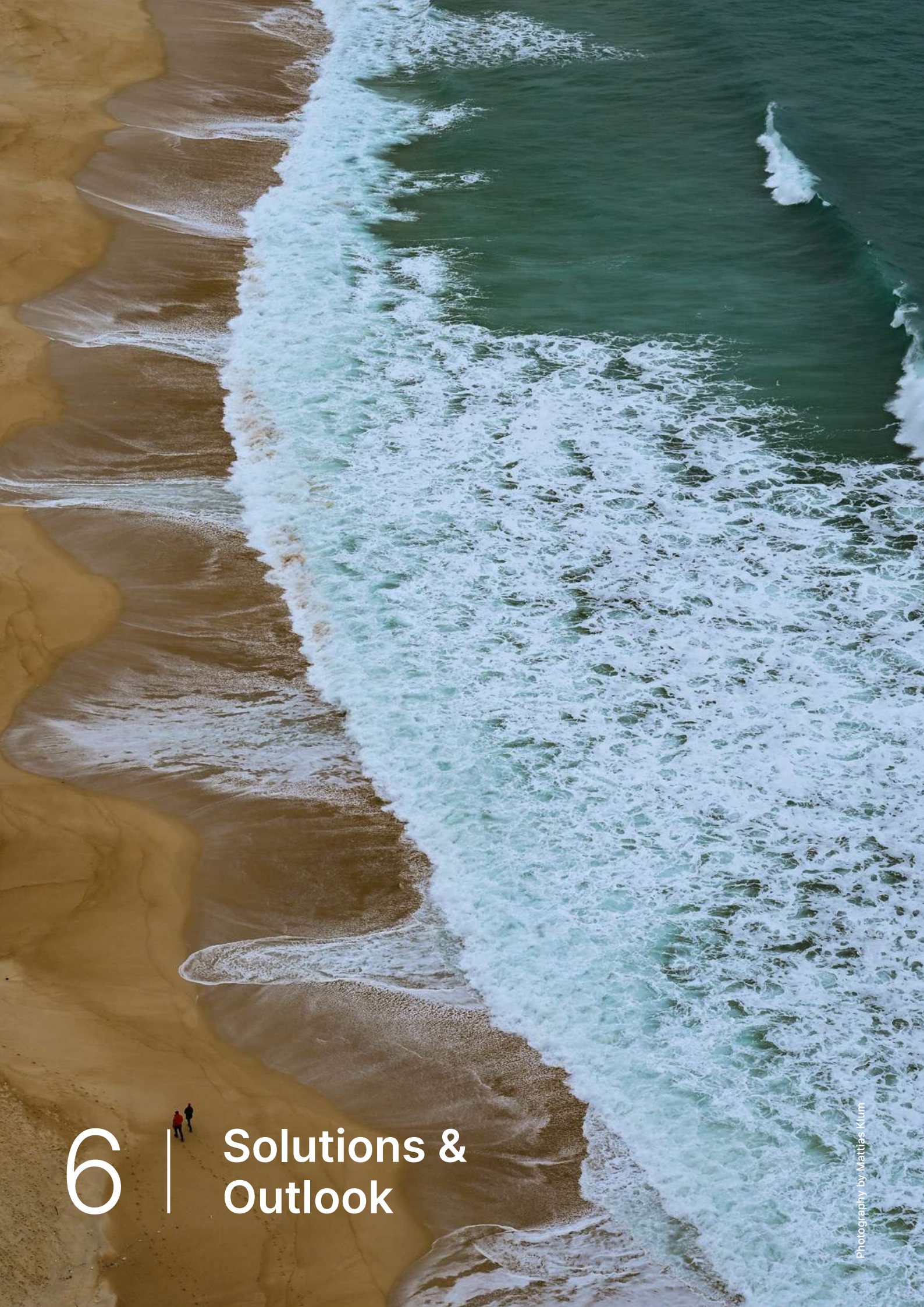
Persistent organic pollutants like PCBs, PFASs and anthropogenic materials including (micro)plastics and their associated chemicals pose risks of irreversible environmental effects with potential Earth system relevance because they are globally distributed and cannot readily be removed from the Earth system.[176] Impacts may also emerge through biological and evolutionary responses. For example, the overuse of antimicrobial agents can promote antimicrobial resistance (AMR), which can spread among microbial communities through horizontal gene transfer. These resistance traits can persist and propagate, creating long-term and potentially irreversible risks for human, animal, and environmental health.

Current and Future Research

The currently used control variable for **Introduction of Novel Entities** is the percentage of inadequately tested chemicals and materials released into the environment, which so far is challenging to assess accurately and comprehensively. Large-scale safety testing of novel entities is important, but highly challenging to implement. However, even high-quality safety tests cannot assess all possible combinations and environmental interactions, nor can they cover long-term, low-probability, high-impacts of novel entities. An effective control variable should meet three criteria: it must (1) refer to measurable indicators, (2) be robust and directly linked to effects on the Earth system, and (3) be able to capture the global scope of the problem. Persson et al. (2022)[154] propose to employ a set of control variables for novel entities that comprise the main stages of the impact pathway. The impact pathway includes production and use, release, accumulation and impacts of novel entities. Accordingly, trends in the production volume and use, in the release to the environment, and in impacts of novel entities on other PBs (e.g. **Biosphere Integrity**, **Climate Change**, **Biogeochemical Flows**) can be used as alternative control variables.

Data Sources

- Data for plastic production from fossil resources excluding additives compiled from Plastics Europe Market Data.[412]
- Data on chemical production from European Chemical Industry Council (Cefic).[413]
- Data on global antimicrobial resistance from Naghavi et al. (2024).[414]
- Data on pesticide use in agriculture from FAOSTAT (2024).[322]
- Data on per- and polyfluoroalkyl substances (PFASs) emissions from Simon et al. (2024).[415]



6 Solutions & Outlook

Photography by Mattias Klum

The Planetary Health Check is designed as a diagnostic tool. It identifies where human pressure on the planet is already too high, where risks are increasing, and where continued transgression could undermine Earth's stability and resilience. Such a diagnosis does not define a single policy program, but it does set a clear benchmark for action: Societies need to return to, and remain within, the Safe Operating Space. This call has consequences far beyond the realm of "environmental protection" or "saving nature". If taken seriously, adhering to this benchmark would mean a complete overhaul of how economies, and therefore societies, function. Biophysical Earth system limits must be translated into binding material caps and circular production models. Economic goals should be re-focused on maintaining the stability of Earth's life support systems, as well as human well-being, rather than GDP growth.

The **Paris Agreement** is a foundational step towards this effort. Limiting warming, and returning from any temporary overshoot to below 1.5°C, is essential for avoiding dangerous and potentially irreversible impacts. Yet climate stabilization depends on more than emissions reductions alone. Given the interconnected nature of the Earth system, respecting the other Planetary Boundaries is a necessary condition for any credible climate pathway. Besides storing carbon, forests, soils, oceans, freshwater systems, and living ecosystems recycle moisture, buffer heat, and sustain the processes that help keep the climate stable. If these systems are degraded, the chances of returning from climate overshoot decline.

At the national level, countries need stronger institutional capacity to interpret and respond to the increasing risks caused by the ongoing transgressions of multiple Planetary Boundaries. Several landmark governmental assessments published in 2025 and 2026 explicitly frame environmental degradation, biodiversity loss, and climate change as interconnected, systemic national and financial security risks.[415–417] Additionally, there are already a number of studies aiming to quantify how individual countries contribute to the transgression of the Planetary Boundaries.[418] To ensure this scientific knowledge can be put into practice, we recommend establishing a **Chief Planetary Scientist**, or an equivalent independent advisory role, in every country. Such a position would translate complex global Earth system science into budgetary decisions, relevant policies, and national security planning. The establishment of national Chief Planetary Scientists addresses a critical gap, as most governments lack the capabilities and systems needed to integrate the nine interconnected life-support systems that define humanity's Safe Operating Space into national policy across all the relevant ministries.

The Planetary Boundaries should also inform **macroeconomic thinking** more broadly. While climate policy has already introduced the idea of a remaining carbon budget, comparable limit and budget approaches are needed for other boundaries. Such strategies translate and help integrate biophysical constraints into economic models. They reveal where risks are underpriced, and clarify the value of intact forests, clean water, stable soils, and functioning oceans. This represents a powerful driver of innovation, which could be leveraged to direct investment and technological development towards solutions that reduce pressure on the Earth system while supporting long-term prosperity. This perspective also points to the importance of Planetary Commons[419]: elements of the Earth system that are of planet-wide significance, irrespective of whether they lie within or beyond national jurisdictions. Biophysical systems such as rainforests, Monsoon systems or ice sheets may be located within or outside of national borders, but the functions they perform are critical to Earth system stability as a whole. Recognizing such systems as Planetary Commons underscores the need for economic frameworks to account for their transboundary and global value. This, in turn, raises important questions about how their stewardship can be supported through appropriate incentives, investment, and international cooperation.

International efforts are slowly moving in this direction. The implementation of the Kunming-Montreal Global Biodiversity Framework is underway and progress is indicative of the strong international commitment to halt and reverse the world's biodiversity loss. The High Seas Treaty marks progress for the governing of marine biodiversity beyond national jurisdiction, while debates over deep-sea mining show that seafloor integrity remains an unresolved frontier. Negotiations of the UN Global Plastics Treaty show growing recognition that novel entities pose a major systemic risk to global public health and food systems, and require international control across their life cycle. The United Nations Convention to Combat Desertification, adopted in 1994, is an important global policy mechanism for restoring the Land-System Change and Freshwater Change Planetary Boundaries, preventing land degradation and drought from scaling into systemic geopolitical and food security risks. The Montreal protocol's success in controlling Stratospheric Ozone Depletion has demonstrated that such efforts can reverse the trend of Planetary Boundary transgression.

The **Sustainable Development Goals**, which set out global aspirations to be achieved by the year 2030, have provided an important shared language for development, poverty reduction, and environmental protection. A post-2030 agenda will need to build on this foundation while placing greater emphasis on the biophysical guardrails that make long-term development possible. Planetary Boundaries offer a scientific basis for linking human well-being with the stability of the Earth system, as adopted in the "Safe and Just Earth System Boundaries"[55] and the "Doughnut Economics" frameworks,[420] as well as the Planetary Health Diet.[240] They can help ensure that future development goals are not only socially ambitious, but also physically achievable on a finite planet.

The science is clear:
We have pushed the planet far beyond its Safe Operating Space. Despite some positive developments, our current efforts are far from sufficient. The window of opportunity to act and avoid irreversible change is narrowing, but it is still open. Through urgent and decisive action, we can change our trajectory towards sustainability. Returning to the Safe Operating Space is the defining task for a stable and livable future.

An open invitation

To advance the Planetary Boundaries framework and coordinate the annual Planetary Health Check, the Potsdam Institute for Climate Impact Research established the Planetary Boundaries Science Lab (PBScience Lab) in 2025. We are now co-creating the Planetary Boundaries Initiative (PBI) to scale our efforts globally, turn cutting-edge science into real-world impact, and support other global efforts such as the Sustainable Development Goals. The PBI is a multi-institutional effort to catalyze systemic shifts in how societies produce, consume, and govern, bringing human activity back within the Safe Operating Space on Earth. It is envisioned as cross-disciplinary, cross-institutional clusters that integrate science, solutions and communication:

Science for Diagnostics: monitors PBs in high spatial and temporal resolution, advances the PB framework, enhances the precision of boundary settings, assesses PB interactions, analyzes tipping risks and Earth resilience.

Science for Solutions: translates diagnostics into transformation pathways and targets, tracks real-world responses, identifies best practices and solutions to accelerate systemic change.

Communication and Community for Action: translates PB research into credible, compelling, accessible and emotionally engaging content that makes the risks and opportunities of our planetary situation understandable, urgent, and actionable, building a global action community.

A central part of the PBI is the Planetary Boundaries Analyzer (PBAnalyzer), which is currently under development. This modular tool and workflow integrates Earth observation, models, socioeconomic data, and scientific literature to accelerate assessments, enable continuous updates, and identify causal relationships and high-leverage intervention points. These data and analysis capabilities will be made available through a free, intelligent decision-support platform for scientists, policymakers, civil society, and other stakeholders. Users will be able to access the most up-to-date science and explore strategies for remaining within or returning to Earth's Safe Operating Space. The platform will enable faster responses to scientific insights and more informed decisions in support of far-reaching political, developmental, and societal ambitions.

As a growing effort, the PBI welcomes engagement with similar initiatives that have operationalized the Planetary Boundaries through concrete policies, toolkits, or targets. We invite researchers, institutions, students, Indigenous knowledge holders, practitioners, and other stakeholders to help turn planetary knowledge into coordinated action. If you are actively using the Planetary Boundaries, we would be pleased to learn from your experience and work together to change the current trajectory.

Contact: pbscience@pik-potsdam.de
Website: planetaryhealthcheck.org

7 | Tables & References

Photography by Mattias Klum

7.1 Latest Planetary Boundaries assessments in numbers

This table lists the Earth system processes, descriptions of the control variables, the current values of those control variables (as of 2026 or the latest documented year), and their reference values (Holocene-like, pre-industrial, or alternative baseline; see PB Info Sheets **(CH. 5)** for the specific period used). The table also includes the value of the respective Planetary Boundary (PB), indicated as a dark green circle in ● **FIG. 3**, which delineates the Safe Operating Space, as well as the High-Risk Threshold, marked by an orange circle in ● **FIG. 3**, indicating the zone with a high probability of destabilizing the Earth system. For a more detailed explanation of PB processes, their control variables, and the current state, please refer to the PB Info Sheets **(CH. 5)**. For comparison, we present the results of the latest PB assessment within the 2026 Planetary Health Check (PHC) alongside the most recent PB assessment from Richardson et al. (2023).[10]

ASSESSMENT		CURRENT VALUE OF CV		REFERENCE VALUE		PB VALUE		HIGH-RISK VALUE	
Boundary	**Control Variable**	**PHC 2026**	**Richardson et al. (2023)**	**PHC 2026**	**Richardson et al. (2023)**	**PHC 2026**	**Richardson et al. (2023)**	**PHC 2026**	**Richardson et al. (2023)**
Climate Change	Atmospheric CO_2 concentration (ppm CO_2)	426 ppm	417 ppm	280 ppm	280 ppm	350 ppm	350 ppm	450 ppm	450 ppm
	Total anthropogenic radiative forcing at top-of-atmosphere (W/m^2)	3.10 W/m^2	+2.91 W/m^2	0 W/m^2	0 W/m^2	+1 W/m^2	+1 W/m^2	+1.5 W/m^2	+1.5 W/m^2
Change in Biosphere Integrity	Extinctions per million species years (E/MSY)	100–1000 E/MSY	>100 E/MSY	1 E/MSY	1 E/MSY	<10 E/MSY	<10 E/MSY	100 E/MSY	100 E/MSY
	Energy removed from ecosystems (HANPP as % of pre-industrial NPP)	21–30% HANPP	30% HANPP	0% HANPP	1.9% HANPP	<10% HANPP	<10% HANPP	20% HANPP	20% HANPP
Land System Change	Area of forested land as % of original forest cover	64%	60%	100%	100%	78%	75%	54%	54%
Freshwater Change	Blue water: human-induced disturbance of river discharge	22.6%	18.20%	10.3%	9.4%	12.9%	10.2%	50.0%	50.0%
	Green water: human-induced disturbance of soil moisture	22.0%	15.8%	9.8%	9.8%	12.4%	11.1%	50.0%	50.0%
Modification in Biogeochemical Flows	Global: P flow from freshwater systems into the ocean	4.4 Tg/year	22.6 Tg/year	0 Tg/year	0 Tg/year	11 Tg/year	11 Tg/year	100 Tg/year	100 Tg/year
	Regional: Application of mined P to cropland	18.2 Tg/year	17.5 Tg/year	0 Tg/year	0 Tg/year	6.2 Tg/year	6.2 Tg/year	11.2 Tg/year	11.2 Tg/year
	Intentional N fixation in agriculture	165 Tg/year	190 Tg/year	0 Tg/year	0 Tg/year	62 Tg/year	62 Tg/year	82 Tg/year	82 Tg/year
Ocean Acidification	Global mean saturation state of aragonite in surface seawater (Ω)	2.85	2.81	3.57	3.44	2.86	2.75	2.50	2.41
Increase in Atmospheric Aerosol Loading	Interhemispheric difference in Aerosol Optical Depth	0.07	0.076	0.04	0.03	0.1	0.1	0.25	0.25
Stratospheric Ozone Depletion	Stratospheric O_3 concentration (global average) (DU)	285.7	284.6	292	290	277	276	263	261
Introduction of Novel Entities	Percentage of synthetic chemicals released without adequate safety testing	>0	>0	0	0	0	0	—	—
Proposed new boundary:									
Increase in Atmospheric Aerosol Loading	Regional: Aerosol Optical Depth over South Asia	0.32				0.25		0.5	

7.2 Planetary Boundaries control variable information

This table lists the global control variables of the PB processes, their observation and modeling periods, as well as temporal resolutions.

Earth system process	Control variable	Data sources	Temporal coverage	Temporal resolution
Climate Change	Atmospheric CO_2 concentration	In-situ observations	1979–2025	Monthly
	Total anthropogenic radiative forcing at top-of-atmosphere	In-situ observations & Earth system modeling	1750–2025	Annual
Change in Biosphere Integrity	Genetic Diversity: E/MSY	In-situ observations	≈1500–2000	Centennial
	Functional integrity: HANPP	In-situ observations & Earth system modeling	1910–2010	Decadal
Land System Change	Forest Area	Remote sensing	1992–2022	Annual
Freshwater Change	Human induced disturbance of blue water flow	Earth system modeling	1901–2019	Annual
	Human induced disturbance of water available to plants	Earth system modeling	1901–2019	Annual
Modification of Biogeochemical Flows	Phosphorus flow from freshwater systems into the ocean	Earth system modeling	1961–2023	Annual
	Industrial and intentional fixation of Nitrogen	Earth system modeling	1961–2023	Annual
Ocean Acidification	Global mean saturation state of aragonite in surface seawater (Ω)	In-situ observations & remote sensing	1980–2024	Monthly
Increase in Aerosol Loading	Interhemispheric-difference in AOD	Reanalysis	2003–2025	Monthly
Stratospheric Ozone Depletion	Stratospheric O_3 concentration	Remote sensing	1970–2025	Monthly
Introduction of Novel Entities	Percentage of synthetic chemicals released to the environment without adequate safety testing	In-situ observations & Earth system modeling	1950–2024	Annual

7.3 Author contributions and affiliations

Chapters which are not listed were updated or written by the Editors / PBScience core team. Lead authors printed in bold.

Chapter	Name	Affiliation
Editors	**Niklas H. Kitzmann**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany** **University of Potsdam, Potsdam, Germany**
	Boris Sakschewski	Potsdam Institute for Climate Impact Research, Potsdam, Germany
	Levke Caesar	Potsdam Institute for Climate Impact Research, Potsdam, Germany
	Johan Rockström	Potsdam Institute for Climate Impact Research, Potsdam, Germany University of Potsdam, Potsdam, Germany
2.1 Assessing Planetary Boundaries	**Kasra Rafiezadeh Shahi**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany**
	Xinyu Dou	International Research Center of Big Data for Sustainable Development Goals, Beijing, China Department of Earth Sciences, The University of Hong Kong, Hong Kong SAR, China
	Nicholas J. Murray	College of Science and Engineering, James Cook University, Townsville, Queensland, Australia
	Zhu Liu	Department of Earth System Science, Tsinghua University, Beijing, China
2.2 One Earth System: Why Planetary Boundaries Are Connected	**Levke Caesar**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany**
3.1 Extreme Weather Events of 2025 and 2026	**Friederike Otto**	**Centre for Environmental Policy, Imperial College London, UK**
	Emmanuel Raju	Dept. of Public Health, Copenhagen Centre for Disaster Research, University of Copenhagen, Denmark African Centre for Disaster Studies, North-West University, South Africa
3.2 Tipping Points	**Donovan P. Dennis**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany** **Max Planck Institute of Geoanthropology, Jena, Germany**
	Shivani Ehrenfeucht	Potsdam Institute for Climate Impact Research, Potsdam, Germany
	Axel E. Eriksson	Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden Instituto Dom Luiz and Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal
	Nicole C. Laureanti	Potsdam Institute for Climate Impact Research, Potsdam, Germany
	Sina Loriani	Potsdam Institute for Climate Impact Research, Potsdam, Germany Max Planck Institute of Geoanthropology, Jena, Germany
	Karoline Ramin	Potsdam Institute for Climate Impact Research, Potsdam, Germany
	Lukas Röhrich	Potsdam Institute for Climate Impact Research, Potsdam, Germany
	Norman J. Steinert	CICERO Center for International Climate Research, Oslo, Norway Potsdam Institute for Climate Impact Research, Potsdam, Germany
4.1 Earth Resilience: When Land Stops Buffering Climate Change	**Boris Sakschewski**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany**
	Jonathan F. Donges	Potsdam Institute for Climate Impact Research, Potsdam, Germany Stockholm Resilience Centre, Stockholm University, Sweden Max Planck Institute of Geoanthropology, Jena, Germany
4.2 Seafloor Integrity: Why the Bottom of the Ocean Matters	**Jacob Geersen**	**Leibniz Institute for Baltic Sea Research Warnemünde**
	Nele Matz-Lück	Walther Schücking Institute for International Law at Kiel University, Germany
	Levke Caesar	Potsdam Institute for Climate Impact Research, Potsdam, Germany
4.3 Novel Entities: Known Impacts and Unknown Planetary Threats	**Miriam L. Diamond**	**Department of Earth Sciences, University of Toronto, Toronto, Canada**
	Anna Shalin	School of the Environment, University of Toronto, Toronto, Canada
	Zhanyun Wang	Department of Green Technology and Danish Institute for Advanced Study, University of Southern Denmark, Odense, Denmark

7.3 Author contributions and affiliations

Chapters which are not listed were updated or written by the Editors / PBScience core team. Lead authors printed in bold.

Chapter	Name	Affiliation
PB Information Sheets		
Climate Change	**Josef Ludescher**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany**
	Masoud Rostami	Potsdam Institute for Climate Impact Research, Potsdam, Germany Laboratoire de Météorologie Dynamique / IPSL, ENS-PSL Université, Ecole Polytechnique-Institut Polytechnique de Paris, Sorbonne Université, CNRS, Paris, France School of Geosciences, China University of Petroleum (East China), Qingdao, China
	Tim Beringer	Potsdam Institute for Climate Impact Research, Potsdam, Germany
Change in Biosphere Integrity	**Maik Billing**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany**
	Heicko Stuckas	Senckenberg Naturhistorische Sammlungen Dresden, Dresden, Germany
	Liad Ben Uri	Department of Plant and Environmental Sciences, Weizmann Institute of Science, Rehovot, Israel
	Fabrice DeClerck	Alliance of Bioversity and CIAT, CGIAR, Montpellier, France Bioversity International, CGIAR, Montpellier, France
	Samantha Joye	Department of Marine Sciences, University of Georgia, Athens, GA, USA
Land System Change	**Fabian Stenzel**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany Stockholm Resilience Centre, Stockholm, Sweden**
	Axel E. Eriksson	Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden Instituto Dom Luiz and Centre for Ecology, Evolution and Environmental Changes, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal
	Ingo Fetzer	Stockholm Resilience Centre, Stockholm, Sweden Bolin Centre for Climate Research, Stockholm, Sweden
	Chaohui Li	Potsdam Institute for Climate Impact Research, Potsdam, Germany Laboratory of Systems Ecology and Sustainability Science, Peking University, China
	Alex Pielaet	Post Growth Institute, OR, USA Wellbeing Economy Alliance, The Netherlands
	Johanna Braun	Potsdam Institute for Climate Impact Research, Potsdam, Germany
Freshwater Change	**Heindriken Dahlmann**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany Integrative Research Institute on Transformations of Human-Environment Systems and Department of Geography, Humboldt-Universität zu Berlin, Berlin, Germany**
	Dieter Gerten	Potsdam Institute for Climate Impact Research, Potsdam, Germany Integrative Research Institute on Transformations of Human-Environment Systems and Department of Geography, Humboldt-Universität zu Berlin, Berlin, Germany
	Simon Fahrländer	Potsdam Institute for Climate Impact Research, Potsdam, Germany Institute for Environmental Science and Geography, University of Potsdam, Potsdam, Germany
	Vili Virkki	Department of Environmental and Biological Sciences, University of Eastern Finland, Joensuu, Finland
	Lauren Seaby Andersen	Potsdam Institute for Climate Impact Research, Potsdam, Germany
Modification in Biogeochemical Flows	**Tim Heckmann**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany**
	Arthur Beusen	PBL Netherlands Environmental Assessment Agency, the Hague, Netherlands Utrecht University, Utrecht, Netherlands
	Benjamin Leon Bodirsky	Potsdam Institute for Climate Impact Research, Potsdam, Germany
	Denise Breitburg	Smithsonian Environmental Research Center, Edgewater, MD, USA

Chapter	Name	Affiliation
Ocean acidification	**Sabine Mathesius**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany**
	Véronique Garçon	Centre National de la Recherche Scientifique, Institut de Physique du Globe de Paris, Paris, France
	Thomas Frölicher	Climate and Environmental Physics, Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, Switzerland
	Nicolas P. Gruber	Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich, Zürich, Switzerland
	Willem Huiskamp	Potsdam Institute for Climate Impact Research, Potsdam, Germany Climate Change Research Centre, UNSW Sydney, Australia
	Jonas Kaiser	Potsdam Institute for Climate Impact Research, Potsdam, Germany
	Jens Daniel Müller	Carbon to Sea Initiative, Washington D.C., USA Climate and Environmental Physics, Physics Institute and Oeschger Centre for Climate Change Research, University of Bern, Switzerland
	Helen S. Findlay	Plymouth Marine Laboratory, Plymouth, UK
	Sam Dupont	University of Gothenburg, Fiskebäckskil, Sweden
	Daniel J. Ford	University of Exeter, Penryn, UK
	Jamie D. Shutler	University of Exeter, Penryn, UK
	Nina Bednaršek	Institute Jožef Stefan, Ljubljana, Slovenia Cooperative Institute for Marine Resources Studies, Hatfield Marine Science Center, Newport, OR, USA
Increase in Atmospheric Aerosol Loading	**Svetlana Botsyun**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany**
	Govindaswamy Bala	Center for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bengaluru, India
	Thejna Tharammal	Interdisciplinary Centre for Water Research, Indian Institute of Science, Bengaluru, India
Stratospheric Ozone Depletion	**Dimitry Pokhotelov**	**Potsdam Institute for Climate Impact Research, Potsdam, Germany**
Introduction of Novel Entities	Christian Schmidt	Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany
	Dana Kühnel	Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany
	Annika Jahnke	Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany Institute for Environmental Research, RWTH Aachen University, Aachen, Germany
	Katrin Wendt-Potthoff	Helmholtz Centre for Environmental Research – UFZ, Magdeburg, Germany
	Yuge Bai	Potsdam Institute for Climate Impact Research, Potsdam, Germany

7.4 References

1 Jouzel, J. *et al.* Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years. *Science* **317**, 793–796 (2007).
2 Masson-Delmotte, V. *et al.* EPICA Dome C record of glacial and interglacial intensities. *Quaternary Science Reviews. Climate of the Last Million Years: New Insights from EPICA and Other Records* **29**, 113–128 (2010).
3 Osman, M. B. *et al.* Globally resolved surface temperatures since the Last Glacial Maximum. *Nature* **599**, 239–244 (2021).
4 Neukom, R. *et al.* Consistent multidecadal variability in global temperature reconstructions and simulations over the Common Era. *Nature Geoscience* **12**, 643–649 (2019).
5 Morice, C. P. *et al.* An Updated Assessment of Near-Surface Temperature Change From 1850: The HadCRUT5 Data Set. *Journal of Geophysical Research: Atmospheres* **126**, e2019JD032361 (2021).
6 Met Office, Climatic Research Unit (University of East Anglia). HadCRUT Temperature Data. 2026.
7 Summary for Policymakers. in *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (ed Intergovernmental Panel on Climate Change (IPCC)) 3–32 (Cambridge University Press, Cambridge, 2021).
8 Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O. & Ludwig, C. The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review* **2**, 81–98 (2015).
9 Rockström, J. *et al.* A safe operating space for humanity. *Nature* **461**. Number: 7263, 472–475 (2009).
10 Richardson, K. *et al.* Earth beyond six of nine planetary boundaries. *Science Advances* **9**, eadh2458 (2023).
11 Steffen, W. *et al.* Planetary boundaries: Guiding human development on a changing planet. *Science* **347**, 1259855 (2015).
12 Braidwood, R. J. The Agricultural Revolution. *Scientific American* **203**, 130–152 (1960).
13 Larsen, C. S. The agricultural revolution as environmental catastrophe: Implications for health and lifestyle in the Holocene. *Quaternary International. Impact of rapid environmental changes on humans and ecosystems* **150**, 12–20 (2006).
14 Rehfeld, K., Münch, T., Ho, S. L. & Laepple, T. Global patterns of declining temperature variability from the Last Glacial Maximum to the Holocene. *Nature* **554**, 356–359 (2018).
15 Messori, G., Gaetani, M., Zhang, Q., Zhang, Q. & Pausata, F. S. R. The water cycle of the mid-Holocene West African monsoon: The role of vegetation and dust emission changes. *International Journal of Climatology* **39**, 1927–1939 (2019).
16 Palmer, H. M., Vriesman, V. P., Livsey, C. M., Fish, C. R. & Hill, T. M. Holocene climate and oceanography of the coastal Western United States and California Current System. *Climate of the Past* **19**, 199–232 (2023).
17 Birks, H., Felde, V. A. & Seddon, A. W. Biodiversity trends within the Holocene. *The Holocene* **26**, 994–1001 (2016).
18 Fritz, S. C. The climate of the Holocene and its landscape and biotic impacts. *Tellus B: Chemical and Physical Meteorology* **65**, 20602 (2013).
19 United Nations Department of Economic and Social Affairs, P. D. Probabilistic Population Projections based on the World Population Prospects 2022. 2022.
20 Foster, G. & Rahmstorf, S. Global Warming Has Accelerated Significantly. *Geophysical Research Letters* **53**, e2025GL118804 (2026).
21 Forster, P. M. *et al.* Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data* **17**, 2641–2680 (2025).
22 The Global Tipping Points Report 2025 (eds Lenton, T. *et al.*) (2025).
23 Sakschewski, B. *et al.* Planetary Health Check 2025: A Scientific Assessment of the State of the Planet. Tech. rep. (Potsdam Institute for Climate Impact Research (PIK), 2025), 144 pages, 22 MB.
24 Balsamo, G. *et al.* Satellite and In Situ Observations for Advancing Global Earth Surface Modelling: A Review. *Remote Sensing* **10**. Number: 12, 2038 (2018).
25 Kulmala, M. Build a global Earth observatory. *Nature* **553**. Bandiera_abtest: a Cg_type: Comment Subject_term: Climate change, Atmospheric science, Environmental sciences, 21–23 (2018).
26 Sitch, S. *et al.* Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology* **9**, 161–185 (2003).
27 Shahi, K. R., Ghamisi, P., Rasti, B., Scheunders, P. & Gloaguen, R. Unsupervised Data Fusion With Deeper Perspective: A Novel Multi-sensor Deep Clustering Algorithm. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* **15**, 284–296 (2022).
28 Fu, Y. *et al.* Remote Sensing Time Series Analysis: A Review of Data and Applications. *Journal of Remote Sensing* **4**, 0285 (2024).
29 Hersbach, H. *et al.* The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* **146**, 1999–2049 (2020).
30 Reichstein, M. *et al.* Deep learning and process understanding for data-driven Earth system science. *Nature* **566**, 195–204 (2019).
31 Brown, C. F. *et al.* AlphaEarth Foundations: An embedding field model for accurate and efficient global mapping from sparse label data. arXiv:2507.22291. 2025.
32 Herzog, H. *et al.* OlmoEarth: Stable Latent Image Modeling for Multimodal Earth Observation. arXiv:2511.13655. 2025.
33 Dou, X. *et al.* Near-real-time global gridded daily CO2 emissions 2021. *Scientific Data* **10**, 69 (2023).
34 Shendryk, Y. Fusing GEDI with earth observation data for large area aboveground biomass mapping. *International Journal of Applied Earth Observation and Geoinformation* **115**, 103108 (2022).
35 Shahi, K. R. *et al.* Governing Generative AI in Disaster Risk Management (2026).
36 Rafiezadeh Shahi, K., Caesar, L., Persello, C., Rockström, J. & Sakschewski, B. Toward Actionable Planetary Boundary Intelligence. *One Earth* (2026).
37 Lopez, A. Carbon dioxide data from 2002 to present derived from satellite observations. updated 2026. 2018.
38 Group on Earth Observations. Global Ecosystems Atlas. 2026.
39 Lade, S. J. *et al.* Human impacts on planetary boundaries amplified by Earth system interactions. *Nature Sustainability* **3**. Number: 2, 119–128 (2020).
40 Ellison, D. *et al.* Trees, forests and water: Cool insights for a hot world. *Global Environmental Change* **43**, 51–61 (2017).
41 Smith, C., Baker, J. C. A. & Spracklen, D. V. Tropical deforestation causes large reductions in observed precipitation. *Nature* **615**, 270–275 (2023).
42 Zhou, S. *et al.* Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. *Proceedings of the National Academy of Sciences* **116**, 18848–18853 (2019).
43 Tobian, A. *et al.* Climate change critically affects the status of the land-system change planetary boundary. *Environmental Research Letters* **19**, 054060 (2024).
44 Drüke, M. *et al.* The long-term impact of transgressing planetary boundaries on biophysical atmosphere–land interactions. *Earth System Dynamics* **15**, 467–483 (2024).
45 Sakschewski, B. *et al.* Resilience of Amazon forests emerges from plant trait diversity. *Nature Climate Change* **6**, 1032–1036 (2016).
46 Flores, B. M. *et al.* Critical transitions in the Amazon forest system. *Nature* **626**, 555–564 (2024).
47 Rocha, J. C., Peterson, G., Bodin, Ö. & Levin, S. Cascading regime shifts within and across scales. *Science* **362**, 1379–1383 (2018).
48 Rocha, J. C. Ecosystems are showing symptoms of resilience loss. *Environmental Research Letters* **17**, 065013 (2022).
49 Wunderling, N. *et al.* Climate tipping point interactions and cascades: a review. *Earth System Dynamics* **15**, 41–74 (2024).
50 Sala, E. *et al.* Protecting the global ocean for biodiversity, food and climate. *Nature* **592**, 397–402 (2021).
51 Tilman, D. & Clark, M. Global diets link environmental sustainability and human health. *Nature* **515**, 518–522 (2014).
52 Van Vuuren, D. P. *et al.* Exploring pathways for world development within planetary boundaries. *Nature* **641**, 910–916 (2025).
53 Beier, F. D. *et al.* Planetary boundaries under a land-based climate change mitigation scenario with a food demand transformation: a modelling study. *The Lancet Planetary Health* **9** (2025).
54 Egorova, T. *et al.* Montreal Protocol's impact on the ozone layer and climate. *Atmospheric Chemistry and Physics* **23**, 5135–5147 (2023).

55 Rockström, J. *et al.* Safe and just Earth system boundaries. *Nature* **619**. Number: 7968, 102–111 (2023).
56 Otto, F. E. Attribution of Extreme Events to Climate Change. *Annual Review of Environment and Resources* **48**, 813–828 (2023).
57 Philip, S. *et al.* A protocol for probabilistic extreme event attribution analyses. *Advances in Statistical Climatology, Meteorology and Oceanography* **6**, 177–203 (2020).
58 Jézéquel, A. *et al.* Behind the veil of extreme event attribution. *Climatic Change* **149**, 367–383 (2018).
59 Lee, H. *et al.* IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. Tech. rep. Edition: First (Intergovernmental Panel on Climate Change (IPCC), 2023).
60 Otto, F. E. L. & Raju, E. Harbingers of decades of unnatural disasters. *Communications Earth & Environment* **4** (2023).
61 CRED / UCLouvain. EM-DAT. Brussels, Belgium, 2025.
62 Delforge, D. *et al.* EM-DAT: the Emergency Events Database. *International Journal of Disaster Risk Reduction* **124**, 105509 (2025).
63 Harrington, L. J. & Otto, F. E. L. Reconciling theory with the reality of African heatwaves. *Nature Climate Change* **10**, 796–798 (2020).
64 Mahecha, M. D., Guha-Sapir, D., Smits, J., Gans, F. & Kraemer, G. Data challenges limit our global understanding of humanitarian disasters triggered by climate extremes. in *Climate Extremes and Their Implications for Impact and Risk Assessment* 243–256 (Elsevier, 2020).
65 Otto, F. E. L. *et al.* Challenges to Understanding Extreme Weather Changes in Lower Income Countries. *Bulletin of the American Meteorological Society* **101**, E1851–E1860 (2020).
66 Raju, E., Boyd, E. & Otto, F. Stop blaming the climate for disasters. *Communications Earth & Environment* **3** (2022).
67 Otto, F. E. L. *et al.* Climate change increased extreme monsoon rainfall, flooding highly vulnerable communities in Pakistan. *Environmental Research: Climate* **2**, 025001 (2023).
68 Zachariah, M. *et al.* Climate change intensified heavy monsoon rain in Pakistan, exacerbating urban floods that impacted highly exposed communities (2025).
69 FAO, WFP & GNAFC. 2026 Global Report on Food Crises – Joint analysis for better decisions. Tech. rep. (FAO & WFP, Rome, 2026).
70 Lenton, T. M. *et al.* Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences* **105**, 1786–1793 (2008).
71 Armstrong McKay, D. I. *et al.* Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* **377**, eabn7950 (2022).
72 Lochte, A. A. *et al.* Labrador Sea freshening at 8.5 ka BP caused by Hudson Bay Ice Saddle collapse. *Nature Communications* **10**, 586 (2019).
73 Nian, D. *et al.* A potential collapse of the Atlantic Meridional Overturning Circulation may stabilise eastern Amazonian rainforests. *Communications Earth & Environment* **4**, 470 (2023).
74 Högner, A. *et al.* Causal pathway from AMOC to Southern Amazon rainforest indicates stabilising interaction between two climate tipping elements. *Environmental Research Letters* **20**, 074026 (2025).
75 Akabane, T. K. *et al.* Weaker Atlantic overturning circulation increases the vulnerability of northern Amazon forests. *Nature Geoscience* **17**, 1284–1290 (2024).
76 Mu, Y., Biggs, T. W. & Jones, C. Importance in Shifting Circulation Patterns for Dry Season Moisture Sources in the Brazilian Amazon. *Geophysical Research Letters* **50**, e2023GL103167 (2023).
77 Ben-Yami, M. *et al.* Robust and irreversible impacts of an AMOC collapse on tropical monsoon systems: a multi-model comparison. 2023.
78 DiNezio, P. N. *et al.* Tropical response to ocean circulation slowdown raises future drought risk. *Nature* **644**, 676–683 (2025).
79 Thoma, M., Jenkins, A., Holland, D. & Jacobs, S. Modelling Circumpolar Deep Water intrusions on the Amundsen Sea continental shelf, Antarctica. *Geophysical Research Letters* **35** (2008).
80 Kusahara, K. & Hasumi, H. Modeling Antarctic ice shelf responses to future climate changes and impacts on the ocean. *J ournal of Geophysical Research: Oceans* **118**, 2454–2475 (2013).
81 Sinet, S., von der Heydt, A. S. & Dijkstra, H. A. Meltwater from West Antarctic ice sheet tipping affects AMOC resilience. *Science Advances* **11**, eadw3852 (2025).
82 Laureanti, N. C., Chou, S. C., Nobre, P. & Curchitser, E. On the relationship between the South Atlantic Convergence Zone and sea surface temperature during Central-East Brazil extreme precipitation events. *Dynamics of Atmospheres and Oceans* **105**, 101422 (2024).
83 Jackson, L. *et al.* Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. *Climate dynamics* **45**, 3299–3316 (2015).
84 Steffen, W. *et al.* Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences* **115**, 8252–8259 (2018).
85 Friedlingstein, P. *et al.* Global Carbon Budget 2025. *Earth System Science Data Discussions,* 1 – 139 (2025).
86 Sixth Assessment Report – IPCC. Tech. rep. (2021).
87 Ke, P. *et al.* Low latency carbon budget analysis reveals a large decline of the land carbon sink in 2023. *National Science Review* **11**, nwae367 (2024).
88 Yuan, X. *et al.* Weakening of global terrestrial carbon sequestration capacity under increasing intensity of warm extremes. *Nature Ecology & Evolution* **9**, 124–133 (2025).
89 Ruehr, S. *et al.* Evidence and attribution of the enhanced land carbon sink. *Nature Reviews Earth & Environment* **4**, 518–534 (2023).
90 Pan, Y. *et al.* The enduring world forest carbon sink. *Nature* **631**, 563–569 (2024).
91 Keenan, T. F. *et al.* Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature* **499**, 324–327 (2013).
92 Terrer, C. *et al.* Nitrogen and phosphorus constrain the CO2 fertilization of global plant biomass. *Nature Climate Change* **9**, 684–689 (2019).
93 Du, E. *et al.* Global patterns of terrestrial nitrogen and phosphorus limitation. *Nature Geoscience* **13**, 221–226 (2020).
94 Humphrey, V. *et al.* Soil moisture–atmosphere feedback dominates land carbon uptake variability. *Nature* **592**, 65–69 (2021).
95 Reichstein, M. *et al.* Climate extremes and the carbon cycle. *Nature* **500**, 287–295 (2013).
96 Schwalm, C. R. *et al.* Global patterns of drought recovery. *Nature* **548**, 202–205 (2017).
97 Brienen, R. J. W. *et al.* Forest carbon sink neutralized by pervasive growth-lifespan trade-offs. *Nature Communications* **11**, 4241 (2020).
98 Terrer, C. *et al.* A trade-off between plant and soil carbon storage under elevated CO2. *Nature* **591**, 599–603 (2021).
99 Yi, C., Hendrey, G., Niu, S., McDowell, N. & Allen, C. D. Tree mortality in a warming world: causes, patterns, and implications. *Environmental Research Letters* **17**, 030201 (2022).
100 Bowman, D. M. J. S. *et al.* Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment* **1**, 500–515 (2020).
101 Anderegg, W. R. L. *et al.* Climate-driven risks to the climate mitigation potential of forests. *Science* **368**, eaaz7005 (2020).
102 Burton, C. A. *et al.* Fire weakens land carbon sinks before 1.5 °C. *Nature Geoscience* **17**, 1108–1114 (2024).
103 McDowell, N. G. *et al.* Mechanisms of woody-plant mortality under rising drought, CO2 and vapour pressure deficit. *Nature Reviews Earth & Environment* **3**, 294–308 (2022).
104 Paudel, S., Ovando-Montejo, G. A. & Lant, C. L. Human Appropriation of Net Primary Production: From a Planet to a Pixel. *Sustainability* **13**, 8606 (2021).
105 Kastner, T. *et al.* Land use intensification increasingly drives the spatiotemporal patterns of the global human appropriation of net primary production in the last century. *Global Change Biology* **28**, 307–322 (2022).
106 IPBES. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Tech. rep. (Zenodo, 2019).
107 Lade, S. J. *et al.* Potential feedbacks between loss of biosphere integrity and climate change. *Global Sustainability* **2**, e21 (2019).
108 Stenzel, F. *et al.* Breaching planetary boundaries: Over half of global land area suffers critical losses in functional biosphere integrity. *One Earth* **8**, 101393 (2025).

109 Isbell, F. *et al.* Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* **526**, 574–577 (2015).
110 Gentine, P. *et al.* Coupling between the terrestrial carbon and water cycles—a review. *Environmental Research Letters* **14**, 083003 (2019).
111 Wang, S. *et al.* Recent global decline of CO2 fertilization effects on vegetation photosynthesis. *Science* **370**, 1295–1300 (2020).
112 Fischer, E. M., Sippel, S. & Knutti, R. Increasing probability of record-shattering climate extremes. *Nature Climate Change* **11**, 689–695 (2021).
113 Gatti, L. V. *et al.* Amazonia as a carbon source linked to deforestation and climate change. *Nature* **595**, 388–393 (2021).
114 Miner, K. R. *et al.* Permafrost carbon emissions in a changing Arctic. *Nature Reviews Earth & Environment* **3**, 55–67 (2022).
115 Möller, T. *et al.* Achieving net zero greenhouse gas emissions critical to limit climate tipping risks. *Nature Communications* **15**, 6192 (2024).
116 Gier, B. K. *et al.* Representation of the Terrestrial Carbon Cycle in CMIP6. arXiv:2402.05671 [physics]. 2024.
117 Yuan, W., Xia, J., Song, C. & Wang, Y.-P. Simulating the land carbon sink: Progresses and challenges of terrestrial ecosystem models. *Agricultural and Forest Meteorology* **358**, 110264 (2024).
118 Dallmeyer, A., Claussen, M. & Brovkin, V. Harmonising plant functional type distributions for evaluating Earth system models. *Climate of the Past* **15**, 335–366 (2019).
119 Loarie, S. R. *et al.* The velocity of climate change. *Nature* **462**, 1052–1055 (2009).
120 Valladares, F. *et al.* The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. *Ecology Letters* **17**, 1351–1364 (2014).
121 Grant, N., Hawkes, A., Mittal, S. & Gambhir, A. The policy implications of an uncertain carbon dioxide removal potential. *Joule* **5**, 2593–2605 (2021).
122 Special Report on Climate Change and Land. Tech. rep. (IPCC).
123 Spracklen, D. V., Arnold, S. R. & Taylor, C. Observations of increased tropical rainfall preceded by air passage over forests. *Nature* **489**, 282–285 (2012).
124 Clarke, J. *et al.* Conditions for instability in the climate–carbon cycle system. *Earth System Dynamics* **16**, 2087–2100 (2025).
125 Gibbs, D. A. *et al.* Revised and updated geospatial monitoring of 21st century forest carbon fluxes. *Earth System Science Data* **17**, 1217–1243 (2025).
126 McKie, R. Bottom trawling: how to empty the seas in just 150 years. *The Guardian* (2014).
127 Singh, P. & Jaeckel, A. Undermining by Mining? Deep Seabed Mining in Light of International Marine Environmental Law. **118**, 72–77 (2024).
128 Amoroso, R. O. *et al.* Bottom trawl fishing footprints on the world's continental shelves. *Proceedings of the National Academy of Sciences* **115**, E10275–E10282 (2018).
129 Weaver, P. P. E. *et al.* Assessing plume impacts caused by polymetallic nodule mining vehicles. *Marine Policy* **139**, 105011 (2022).
130 Puig, P. *et al.* Ploughing the deep sea floor. *Nature* **489**, 286–289 (2012).
131 Clark, M. R. *et al.* The impacts of deep-sea fisheries on benthic communities: a review. *ICES Journal of Marine Science* **73**, i51–i69 (2016).
132 Vonnahme, T. R. *et al.* Effects of a deep-sea mining experiment on seafloor microbial communities and functions after 26 years. *Science Advances* **6**, eaaz5922 (2020).
133 Boetius, A. & Haeckel, M. Mind the seafloor. *Science* **359**, 34–36 (2018).
134 Epstein, G., Middelburg, J. J., Hawkins, J. P., Norris, C. R. & Roberts, C. M. The impact of mobile demersal fishing on carbon storage in seabed sediments. *Global Change Biology* **28**, 2875–2894 (2022).
135 Watson, S. J. *et al.* The footprint of ship anchoring on the seafloor. *Scientific Reports* **12**, 7500 (2022).
136 Geersen, J. *et al.* Ship wake-induced water column mixing and meter-scale seabed erosion in the Baltic Sea. *Nature Communications* **17**, 1350 (2026).
137 Atwood, T. B. *et al.* Atmospheric CO2 emissions and ocean acidification from bottom-trawling. *Frontiers in Marine Science* **10** (2024).
138 Zhang, W. *et al.* Long-term carbon storage in shelf sea sediments reduced by intensive bottom trawling. *Nature Geoscience* **17**, 1268–1276 (2024).
139 Reusch, T. B. H. *et al.* The Baltic Sea as a time machine for the future coastal ocean. *Science Advances* **4**, eaar8195 (2018).
140 Voss, M. *et al.* Coastal zones of the Baltic Sea in the Anthropocene: Current state and the impact of climate change. *Estuarine, Coastal and Shelf Science* **326**, 109504 (2025).
141 Group, G. C. The GEBCO 2026 Grid – a continuous terrain model of the global oceans and land. 2026.
142 TeleGeography. Submarine Cable Map. accessed 5 June 2026. 2026.
143 National Geospatial-Intelligence Agency. World Port Index. accessed 5 May 2026. 2026.
144 Paolo, F. S. *et al.* Satellite mapping reveals extensive industrial activity at sea. *Nature* **625**, 85–91 (2024).
145 Satlas / Allen Institute for Artificial Intelligence. Global marine infrastructure detections. accessed 5 May 2026. 2026.
146 Kroodsma, D. A. *et al.* Tracking the global footprint of fisheries. *Science* **359**, 904–908 (2018).
147 Global Maritime Traffic Density Service (GMTDS). Data of Global Maritime Traffic Density Service. AIS-derived global vessel density data. accessed 5 May 2026.
148 World Bank. Global Shipping Traffic Density - World Bank Data Catalog. 2020.
149 Petersen, S. *et al.* News from the seabed – Geological characteristics and resource potential of deep-sea mineral resources. *Marine Policy* **70**, 175–187 (2016).
150 Hein, J. R., Koschinsky, A. & Kuhn, T. Deep-ocean polymetallic nodules as a resource for critical materials. *Nature Reviews Earth & Environment* **1**, 158–169 (2020).
151 International Seabed Authority. DeepData – Maps of exploration contract areas. 2026.
152 Global Energy Monitor. Global Oil Infrastructure Tracker. 2026.
153 Zhou, C. *et al.* Global Marine LNG Terminals, Tankers & Trade: A High-Resolution AIS-Based Dataset of LNG Trade (2020–2024). *Scientific Data* (2026).
154 Persson, L. *et al.* Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. *Environmental Science & Technology* **56**, 1510–1521 (2022).
155 Jahnke, A. *et al.* Planetary Boundary for Novel Entities: Time for a Reboot. *Environmental Science & Technology* (2026).
156 Jaureguiberry, P. *et al.* The direct drivers of recent global anthropogenic biodiversity loss. *Science Advances* **8**, eabm9982 (2022).
157 The IUCN Red List of Threatened Species. 2022.
158 Janousek, W. M. *et al.* Recent and future declines of a historically widespread pollinator linked to climate, land cover, and pesticides. *Proceedings of the National Academy of Sciences* **120**, e2211223120 (2023).
159 Rigal, S. *et al.* Farmland practices are driving bird population decline across Europe. *Proceedings of the National Academy of Sciences* **120**, e2216573120 (2023).
160 Hallmann, C. A., Foppen, R. P. B., van Turnhout, C. A. M., de Kroon, H. & Jongejans, E. Declines in insectivorous birds are associated with high neonicotinoid concentrations. *Nature* **511**, 341–343 (2014).
161 Baker, N. J., Bancroft, B. A. & Garcia, T. S. A meta-analysis of the effects of pesticides and fertilizers on survival and growth of amphibians. *Science of The Total Environment* **449**, 150–156 (2013).
162 Desforges, J.-P. *et al.* Predicting global killer whale population collapse from PCB pollution. *Science* **361**, 1373–1376 (2018).
163 Rosi-Marshall, E. J., Bernhardt, E. S., Buso, D. C., Driscoll, C. T. & Likens, G. E. Acid rain mitigation experiment shifts a forested watershed from a net sink to a net source of nitrogen. *Proceedings of the National Academy of Sciences* **113**, 7580–7583 (2016).
164 UNEP - UN Environment Programme. Plastic pollution. accessed 7 July 2026. 2024.
165 Chamas, A. *et al.* Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering* **8**, 3494–3511 (2020).
166 Sidik, S. 'A double-whammy problem': how plastic dust is altering natural processes. *Nature*. Bandiera_abtest: a Cg_type: Spotlight Subject_term: Climate change, Industry, Research data, Ocean sciences, Atmospheric science (2025).
167 Kesic, R. *et al.* Continuing Persistence and Biomagnification of DDT and Metabolites in Northern Temperate Fruit Orchard Avian Food Chains. *Environmental Toxicology and Chemistry* **40**, 3379–3391 (2021).
168 Pain, D. J., Mateo, R. & Green, R. E. Effects of lead from ammunition on birds and other wildlife: A review and update. *Ambio* **48**, 935–953 (2019).

169 Chételat, J., Ackerman, J. T., Eagles-Smith, C. A. & Hebert, C. E. Methylmercury exposure in wildlife: A review of the ecological and physiological processes affecting contaminant concentrations and their interpretation. *Science of The Total Environment* **711**, 135117 (2020).
170 Athey, S. N. *et al.* The Widespread Environmental Footprint of Indigo Denim Microfibers from Blue Jeans. *Environmental Science & Technology Letters* **7**, 840–847 (2020).
171 Athey, S. N. *et al.* Unraveling Physical and Chemical Effects of Textile Microfibers. *Water* **14**, 3797 (2022).
172 Ehalt Macedo, H., Lehner, B., Nicell, J. A., Khan, U. & Klein, E. Y. Antibiotics in the global river system arising from human consumption. *PNAS Nexus* **4**, pgaf096 (2025).
173 Blumenthal, J., Diamond, M. L., Hoffmann, M. & Wang, Z. Time to Break the 'Lock-In' Impediments to Chemicals Management. *Environmental Science & Technology* **56**, 3863–3870 (2022).
174 Shalin, A., Diamond, M. L. & Wang, Z. Breaking Lock-ins to Enable a Green Pharmacy. *Environmental Science & Technology* **60**, 5960–5969 (2026).
175 Cousins, I. T., Johansson, J. H., Salter, M. E., Sha, B. & Scheringer, M. Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS). *Environmental Science & Technology* **56**, 11172–11179 (2022).
176 Arp, H. P. H. *et al.* Weathering Plastics as a Planetary Boundary Threat: Exposure, Fate, and Hazards. *Environmental Science & Technology* **55**, 7246–7255 (2021).
177 UNEP - UN Environment Programme. Global Chemicals Outlook II. Report 978-92-807-3745-5 (United Nations Environment Programme, Nairobi, Kenya, 2019).
178 Ezekoye, O., Rompen, F. & Periwal, S. Chemicals 2025: A new reality for the global chemical industry | McKinsey. 2025.
179 United Nations Environment Programme & International Resource Panel. Global Resources Outlook 2024 – Bend the trend: Pathways to a Liveable Planet as Resource Use Spikes. Trans. by Bruyninckx, H. et al. (2024).
180 Wiedmann, T. Role of Shared Responsibility in Defining Novel Entity Boundaries. *Environmental Science & Technology* **59**, 26316–26319 (2025).
181 Zhou, H., Mo, X., Yi, M., Li, Y. & Liang, S. Transmission centers of global embodied mercury emissions are moving from developed to developing regions. *Journal of Cleaner Production* **477**, 143881 (2024).
182 Wang, Z., Walker, G. W., Muir, D. C. G. & Nagatani-Yoshida, K. Toward a Global Understanding of Chemical Pollution: A First Comprehensive Analysis of National and Regional Chemical Inventories. *Environmental Science & Technology* **54**, 2575–2584 (2020).
183 Van Dijk, J., Sharma, A., Nowack, B., Wang, Z. & Scheringer, M. From Ambition to Action: Navigating Obstacles and Opportunities of 'Safe and Sustainable by Design'. *Environmental Science & Technology* **59**, 14832–14841 (2025).
184 Zhang, X. *et al.* Exploring global oceanic persistence and ecological effects of legacy persistent organic pollutants across five decades. *Science Advances* **10**, eado5534 (2024).
185 Cousins, I. T. *et al.* Finding essentiality feasible: common questions and misinterpretations concerning the 'essential-use' concept. *Environmental Science: Processes & Impacts* **23**, 1079–1087 (2021).
186 Muir, D. C. G., Getzinger, G. J., McBride, M. & Ferguson, P. L. How Many Chemicals in Commerce Have Been Analyzed in Environmental Media? A 50 Year Bibliometric Analysis. *Environmental Science & Technology* **57**, 9119–9129 (2023).
187 Maggi, F., Tang, F. H. M. & Tubiello, F. N. Agricultural pesticide land budget and river discharge to oceans. *Nature* **620**, 1013–1017 (2023).
188 Wilkinson, J. L. *et al.* Pharmaceutical pollution of the world's rivers. *Proceedings of the National Academy of Sciences* **119**, e2113947119 (2022).
189 Maggi, F., Tang, F. H. M., Black, A. J., Marks, G. B. & McBratney, A. The pesticide health risk index - An application to the world's countries. *Science of The Total Environment* **801**, 149731 (2021).
190 Hou, D. *et al.* Global soil pollution by toxic metals threatens agriculture and human health. *Science* **388**, 316–321 (2025).
191 Shekhar, C. *et al.* A systematic review of pesticide exposure, associated risks, and long-term human health impacts. *Toxicology Reports* **13**, 101840 (2024).
192 Sung, H. *et al.* Differences in cancer rates among adults born between 1920 and 1990 in the USA: an analysis of population-based cancer registry data. *The Lancet Public Health* **9**, e583–e593 (2024).
193 Larsen, B. & Sánchez-Triana, E. Global health burden and cost of lead exposure in children and adults: a health impact and economic modelling analysis. *Lancet Planet Health,* e831–e840 (2023).
194 Martin, J. H. Glacial-interglacial CO2 change: The Iron Hypothesis. *Paleoceanography* **5**, 1–13 (1990).
195 Garbe, J., Albrecht, T., Levermann, A., Donges, J. F. & Winkelmann, R. The hysteresis of the Antarctic Ice Sheet. *Nature* **585**. Number: 7826, 538–544 (2020).
196 Hansen, J. *et al.* Target atmospheric CO2: Where should humanity aim? *The Open Atmospheric Science Journal* **2**. arXiv:0804.1126 [physics], 217–231 (2008).
197 Höning, D. *et al.* Multistability and Transient Response of the Greenland Ice Sheet to Anthropogenic CO 2 Emissions. *Geophysical Research Letters* **50**, e2022GL101827 (2023).
198 Lan, X., Tans, P. & Thoning, K. Trends in globally-averaged CO2 determined from NOAA Global Monitoring Laboratory measurements.
199 Pongratz, J., Raddatz, T., Reick, C. H., Esch, M. & Claussen, M. Radiative forcing from anthropogenic land cover change since A.D. 800. *Geophysical Research Letters* **36** (2009).
200 Ward, D. S. *et al.* The changing radiative forcing of fires: global model estimates for past, present and future. *Atmospheric Chemistry and Physics* **12**, 10857–10886 (2012).
201 Skeie, R. B. *et al.* Anthropogenic radiative forcing time series from pre-industrial times until 2010. *Atmospheric Chemistry and Physics* **11**, 11827–11857 (2011).
202 Smith, C. *et al.* Indicators of Global Climate Change 2025. 2026.
203 Fahey, D. *et al.* Ch. 2: Physical Drivers of Climate Change. Climate Science Special Report: Fourth National Climate Assessment, Volume I. Tech. rep. (U.S. Global Change Research Program, 2017).
204 Chataut, G., Bhatta, B., Joshi, D., Subedi, K. & Kafle, K. Greenhouse gases emission from agricultural soil: A review. *Journal of Agriculture and Food Research* **11**, 100533 (2023).
205 Kweku, D. W. *et al.* Greenhouse Effect: Greenhouse Gases and Their Impact on Global Warming. *Journal of Scientific Research and Reports,* 1–9 (2017).
206 Archer, D. *et al.* Atmospheric Lifetime of Fossil Fuel Carbon Dioxide. *Annual Review of Earth and Planetary Sciences* **37**, 117–134 (2009).
207 Held, I. M. & Soden, B. J. Water Vapor Feedback and Global Warming. *Annual Review of Environment and Resources* **25**, 441–475 (2000).
208 Ramanathan, V., Crutzen, P. J., Kiehl, J. T. & Rosenfeld, D. Aerosols, Climate, and the Hydrological Cycle. *Science* **294**, 2119–2124 (2001).
209 Unger, N. *et al.* Attribution of climate forcing to economic sectors. *Proceedings of the National Academy of Sciences* **107**, 3382–3387 (2010).
210 Climate TRACE. Climate TRACE Emissions Inventory v4.0.
211 Otto, F. E. L. *et al.* Toward an Inventory of the Impacts of Human-Induced Climate Change. *Bulletin of the American Meteorological Society* **101**, E1972–E1979 (2020).
212 Karl, T. R. & Trenberth, K. E. Modern Global Climate Change. *Science* **302**, 1719–1723 (2003).
213 Hoegh-Guldberg, O. & Bruno, J. F. The Impact of Climate Change on the World's Marine Ecosystems. *Science* **328**, 1523–1528 (2010).
214 Ondiko, J. H., Karanja, A. M. & Ombogo, O. A Review of the Anthropogenic Effects of Climate Change on the Physical and Social Environment. *Open Access Library Journal* **9**. Number: 2, 1–14 (2022).
215 Hare, W. Assessment of Knowledge on Impacts of Climate Change-Contribution to the Specification of Art. in (2003).
216 Kurukulasuriya, P. & Rosenthal, S. Climate Change and Agriculture: A Review of Impacts and Adaptations. Tech. rep. (World Bank, Washington, DC, 2013).
217 Little, M. A., Garruto, R. M., Bhasin, V. & Bhasin, M. K. Global Impacts of Anthropogenic Climate Change on Human Health and Adaptability. in (2007).
218 Berkely Earth. Global Monthly Land + Ocean, 1° × 1° Latitude-Longitude Grid (1850–Recent).
219 Jones, M. W. *et al.* National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Scientific Data* **10**, 155 (2023).
220 Jones, M. W. *et al.* National contributions to climate change due to historical emissions of carbon dioxide, methane and nitrous oxide. 2025.

221 Loeb, N. G. *et al.* Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Top-of-Atmosphere (TOA) Edition-4.0 Data Product. *Journal of Climate* **31**, 895–918 (2018).
222 CERES Ordering Tool.
223 Zwieten, L. V. *et al.* Biochar and Emissions of Non-CO2 Greenhouse Gases from Soil. in *Biochar for Environmental Management* Num Pages: 24 (Routledge, 2009).
224 Rohde, R. A. & Hausfather, Z. The Berkeley Earth Land/Ocean Temperature Record. *Earth System Science Data* **12**, 3469–3479 (2020).
225 Stenzel, F. *et al.* Breaching planetary boundaries: Over half of global land area suffers critical losses in functional biosphere integrity: One Earth. *One Earth* **8**, 101393 (2025).
226 Krausmann, F. *et al.* Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the National Academy of Sciences* **110**, 10324–10329 (2013).
227 Matej, S. *et al.* A global land-use data cube 1992–2020 based on the Human Appropriation of Net Primary Production. *Scientific Data* **12**, 511 (2025).
228 Barnosky, A. D. *et al.* Has the Earth's sixth mass extinction already arrived? *Nature* **471**, 51–57 (2011).
229 Ceballos, G. & Ehrlich, P. R. Mutilation of the tree of life via mass extinction of animal genera. *Proceedings of the National Academy of Sciences* **120**, e2306987120 (2023).
230 Ceballos, G. *et al.* Accelerated modern human-induced species losses: Entering the sixth mass extinction. *Science Advances* **1**, e1400253 (2015).
231 Rounsevell, M. D. A. *et al.* A biodiversity target based on species extinctions. *Science* **368**, 1193–1195 (2020).
232 Cowie, R. H., Bouchet, P. & Fontaine, B. The Sixth Mass Extinction: fact, fiction or speculation? *Biological Reviews* **97**, 640–663 (2022).
233 Kleidon, A. Sustaining the Terrestrial Biosphere in the Anthropocene: A Thermodynamic Earth System Perspective. *Ecology, Economy and Society–the INSEE Journal* **6**, 53–80 (2023).
234 The global assessment report of the intergovernmental science-policy platform on biodiversity and ecosystem services (eds Brondízio, E. S., Settele, J., Díaz, S. & Ngo, H. T.) OCLC: 1336011247 (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), Bonn, 2019).
235 Mazor, T. *et al.* Global mismatch of policy and research on drivers of biodiversity loss. *Nature Ecology & Evolution* **2**, 1071–1074 (2018).
236 Sala, O. E. *et al.* Global Biodiversity Scenarios for the Year 2100. *Science* **287**, 1770–1774 (2000).
237 Haberl, H., Erb, K.-H. & Krausmann, F. Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries. *Annual Review of Environment and Resources* **39**, 363–391 (2014).
238 Longhurst, A. R. Role of the marine biosphere in the global carbon cycle. *Limnology and Oceanography* **36**, 1507–1526 (1991).
239 Mohamed, A. *et al.* Securing Nature's Contributions to People requires at least 20%–25%(semi-) natural habitat in human-modified landscapes. *One Earth* **7**, 59–71 (2024).
240 Klein, A.-M. *et al.* Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences* **274**, 303–313 (2007).
241 Rockström, J. *et al.* The EAT–Lancet Commission on healthy, sustainable, and just food systems. *The Lancet* **406**, 1625–1700 (2025).
242 Stenzel, F. *et al.* biospheremetrics v1.0.2: an R package to calculate two complementary terrestrial biosphere integrity indicators – human colonization of the biosphere (BioCol) and risk of ecosystem destabilization (EcoRisk). *Geoscientific Model Development* **17**, 3235–3258 (2024).
243 Pereira, H. M. *et al.* Essential Biodiversity Variables. *Science* **339**, 277–278 (2013).
244 Purvis, A. *et al.* Chapter 2.2 Status and Trends – Nature. Tech. rep. (Zenodo, 2019).
245 IPBES. Decision IPBES-11/1: Implementation of the rolling work programme of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services up to 2030. 2024.
246 Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G. B. & Worm, B. How Many Species Are There on Earth and in the Ocean? *PLoS Biology* **9** (ed Mace, G. M.) e1001127 (2011).
247 Siegel, D. A., DeVries, T., Cetinić, I. & Bisson, K. M. Quantifying the Ocean's Biological Pump and Its Carbon Cycle Impacts on Global Scales. *Annual Review of Marine Science* **15**, 329–356 (2023).
248 Iversen, M. H. Carbon Export in the Ocean: A Biologist's Perspective. *Annual Review of Marine Science* **15**, 357–381 (2023).
249 Duarte, C. M., Middelburg, J. J. & Caraco, N. Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences* **2**, 1–8 (2005).
250 Howard, J. *et al.* Coastal blue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrasses (International Union for Conservation of Nature (IUCN), Arlington, VA, USA, 2014).
251 Alongi, D. M. Current status and emerging perspectives of coastal blue carbon ecosystems. *Carbon Footprints* **2** (2023).
252 Duarte, C. M. Reviews and syntheses: Hidden forests, the role of vegetated coastal habitats in the ocean carbon budget. *Biogeosciences* **14**, 301–310 (2017).
253 Bianchi, D., Carozza, D. A., Galbraith, E. D., Guiet, J. & DeVries, T. Estimating global biomass and biogeochemical cycling of marine fish with and without fishing. *Science Advances* **7**, eabd7554 (2021).
254 Hatton, I. A., Heneghan, R. F., Bar-On, Y. M. & Galbraith, E. D. The global ocean size spectrum from bacteria to whales. *Science Advances* **7**, eabh3732 (2021).
255 Saba, G. K. *et al.* Toward a better understanding of fish-based contribution to ocean carbon flux. *Limnology and Oceanography* **66**, 1639–1664 (2021).
256 Pinti, J. *et al.* Model estimates of metazoans' contributions to the biological carbon pump. *Biogeosciences* **20**, 997–1009 (2023).
257 Mariani, G. *et al.* The combined impact of fisheries and climate change on future carbon sequestration by oceanic macrofauna. *Nature Communications* **16**, 8845 (2025).
258 Snyder, P. K., Delire, C. & Foley, J. A. Evaluating the influence of different vegetation biomes on the global climate. *Climate Dynamics* **23**, 279–302 (2004).
259 West, P. C., Narisma, G. T., Barford, C. C., Kucharik, C. J. & Foley, J. A. An alternative approach for quantifying climate regulation by ecosystems. *Frontiers in Ecology and the Environment* **9**, 126–133 (2011).
260 Ramankutty, N. & Foley, J. A. Estimating historical changes in global land cover: Croplands from 1700 to 1992. *Global Biogeochemical Cycles* **13**, 997–1027 (1999).
261 Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Land cover classification gridded maps from 1992 to present derived from satellite observation. 2024.
262 Brun, P., Zimmermann, N. E., Hari, C., Pellissier, L. & Karger, D. N. CHELSA-BIOCLIM+ A novel set of global climate-related predictors at kilometre-resolution (2022).
263 Bullock, E. L., Woodcock, C. E., Souza Jr., C. & Olofsson, P. Satellite-based estimates reveal widespread forest degradation in the Amazon. *Global Change Biology* **26**, 2956–2969 (2020).
264 Wunderling, N. *et al.* Deforestation-induced drying lowers Amazon climate threshold. *Nature,* 1–7 (2026).
265 Goldewijk, K. K. & Ramankutty, N. Land use changes during the past 300 years. *Land-Use, Land Cover and Soil Sciences* **1**, 147–168 (2009).
266 Harris, W. V. Defining and detecting Mediterranean deforestation, 800 BCE to 700 CE. in *The Ancient Mediterranean Environment between Science and History* 173–194 (Brill, 2013).
267 Pongratz, J., Reick, C., Raddatz, T. & Claussen, M. A reconstruction of global agricultural areas and land cover for the last millennium. *Global Biogeochemical Cycles* **22** (2008).
268 FAO. The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies (Food and Agriculture Organization of the United Nations, Rome, 2022).
269 Thompson, S. T. & Magrath, W. B. Preventing illegal logging. *Forest Policy and Economics* **128**, 102479 (2021).
270 Sims, M. J. *et al.* Global drivers of forest loss at 1 km resolution. *Environmental Research Letters* (2025).
271 Bousfield, C. G., Morton, O. & Edwards, D. P. Climate change will exacerbate land conflict between agriculture and timber production. *Nature Climate Change* **14**, 1071–1077 (2024).
272 Scullion, J. J., Vogt, K. A., Drahota, B., Winkler-Schor, S. & Lyons, M. Conserving the Last Great Forests: A Meta-Analysis Review of the Drivers of Intact Forest Loss and the Strategies and Policies to Save Them. *Frontiers in Forests and Global Change* **2** (2019).
273 Worku, A. Review on drivers of deforestation and associated socio-economic and ecological impacts. *Advances in Agriculture, Food Science and Forestry* **11**, 1–11 (2023).

274 Xu, X. *et al.* Deforestation triggering irreversible transition in Amazon hydrological cycle. *Environmental Research Letters* **17**, 034037 (2022).
275 Jaime, L., Batllori, E. & Lloret, F. Bark beetle outbreaks in coniferous forests: a review of climate change effects. *European Journal of Forest Research* **143**, 1–17 (2024).
276 Seidl, R. & Rammer, W. Climate change amplifies the interactions between wind and bark beetle disturbances in forest landscapes. *Landscape Ecology* **32**, 1485–1498 (2017).
277 Global Forest Resources Assessment 2025 (FAO, 2025).
278 Foley, J. A. *et al.* Global Consequences of Land Use. *Science* **309**, 570–574 (2005).
279 Newbold, T. *et al.* Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science* **353**, 288–291 (2016).
280 Friedlingstein, P. *et al.* Global Carbon Budget 2024. *Earth System Science Data* **17**, 965–1039 (2025).
281 Alkama, R. & Cescatti, A. Biophysical climate impacts of recent changes in global forest cover. *Science* **351**, 600–604 (2016).
282 Zemp, D. C. *et al.* Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks. *Nature communications* **8**, 1–10 (2017).
283 Campbell, B. M. *et al.* Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecology and Society* **22** (2017).
284 Morris, R. J. Anthropogenic impacts on tropical forest biodiversity: a network structure and ecosystem functioning perspective. *Philosophical Transactions of the Royal Society B: Biological Sciences* **365**, 3709–3718 (2010).
285 MacDonald, A. J. & Mordecai, E. A. Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing. *Proceedings of the National Academy of Sciences* **116**, 22212–22218 (2019).
286 Berazneva, J. & Byker, T. S. Does Forest Loss Increase Human Disease? Evidence from Nigeria. *American Economic Review* **107**, 516–521 (2017).
287 Brandon, K. Ecosystem Services from Tropical Forests: Review of Current Science. in *SSRN Electronic Journal* Journal Abbreviation: SSRN Journal (Elsevier BV, 2014).
288 Dinerstein, E. *et al.* An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. *BioScience* **67**, 534–545 (2017).
289 Brockerhoff, E. G. *et al.* Forest biodiversity, ecosystem functioning and the provision of ecosystem services. *Biodiversity and Conservation* **26**, 3005–3035 (2017).
290 Barredo, J. *et al.* Mapping and assessment of primary and old-growth forests in Europe (Publications Office, 2021).
291 Rogers, B. *et al.* Using ecosystem integrity to maximize climate mitigation and minimize risk in international forest policy. *Frontiers in Forests and Global Change* **5** (2022).
292 Holdridge, L. R. *Life zone ecology*. (Tropical Science Center, San Jose, 1967).
293 Porkka, M. *et al.* Notable shifts beyond pre-industrial streamflow and soil moisture conditions transgress the planetary boundary for freshwater change. *Nature Water* **2**, 262–273 (2024).
294 Virkki, V., Andersen, L. S., Te Wierik, S., Gerten, D. & Porkka, M. Regionally divergent drivers behind transgressions of the freshwater change planetary boundary. *Nature Communications* **17**, 5132 (2026).
295 Wang-Erlandsson, L. *et al.* A planetary boundary for green water. *Nature Reviews Earth & Environment* **3**. Number: 6, 380–392 (2022).
296 Virkki, V., Andersen, L. S., te Wierik, S., Gerten, D. & Porkka, M. Regionally divergent drivers behind transgressions of the freshwater change planetary boundary. *EarthArXiv* (2025).
297 Gosling, S. N. *et al.* ISIMIP3a Simulation Data from the Global Water Sector. 2026.
298 Lehner, B. & Grill, G. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. *Hydrological Processes* **27**, 2171–2186 (2013).
299 Gudmundsson, L. *et al.* Globally observed trends in mean and extreme river flow attributed to climate change. *Science* **371**, 1159–1162 (2021).
300 IPCC AR6 WGI. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Tech. rep. Backup Publisher: IPCC (Cambridge University Press. In Press., 2021).
301 World Meteorological Organization. State of Global Water Resources 2024. Tech. rep. (World Meteorological Organization, 2025).
302 Bonfils, C. J. W. *et al.* Human influence on joint changes in temperature, rainfall and continental aridity. *Nature Climate Change* **10**, 726–731 (2020).
303 Samaniego, L. *et al.* Anthropogenic warming exacerbates European soil moisture droughts. *Nature Climate Change* **8**, 421–426 (2018).
304 Miralles, D. G., Gentine, P., Seneviratne, S. I. & Teuling, A. J. Land–atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges. *Annals of the New York Academy of Sciences* **1436**, 19–35 (2019).
305 Rolls, R. J. *et al.* Scaling biodiversity responses to hydrological regimes. *Biological Reviews* **93**, 971–995 (2018).
306 Natali, S. M. *et al.* Permafrost thaw and soil moisture driving CO2 and CH4 release from upland tundra. *Journal of Geophysical Research: Biogeosciences* **120**, 525–537 (2015).
307 Magnússon, R. Í. *et al.* Extremely wet summer events enhance permafrost thaw for multiple years in Siberian tundra. *Nature Communications* **13**, 1556 (2022).
308 Pastor, A. V. *et al.* Understanding the transgression of global and regional freshwater planetary boundaries. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **380**, 20210294 (2022).
309 Veldkamp, T. I. E. *et al.* Changing mechanism of global water scarcity events: Impacts of socioeconomic changes and inter-annual hydroclimatic variability. *Global Environmental Change* **32**, 18–29 (2015).
310 Rockström, J. *et al.* Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society* **14** (2009).
311 Te Wierik, S. *et al.* Identifying the safe operating space for food systems. *Nature Food* **6**, 1153–1163 (2025).
312 Hou, S. *et al.* Tracking grid-level freshwater boundary exceedance along global supply chains from consumption to impact. *Nature Water* **3**, 439–448 (2025).
313 Lai, E. N., Wang-Erlandsson, L., Virkki, V., Porkka, M. & Van Der Ent, R. J. Root zone soil moisture in over 25% of global land permanently beyond pre-industrial variability as early as 2050 without climate policy. *Hydrology and Earth System Sciences* **27**, 3999–4018 (2023).
314 Yang, D., Peng, S. & Xu, X. Green water will deviate the planetary boundary twice by the end of the 21st Century. *Global and Planetary Change* **262**, 105482 (2026).
315 Gerten, D., Almeida, B., Lade, S. J. & Norberg, A. Join the dots on planetary boundary interactions. 2025.
316 Keys, P. W. *et al.* Invisible water security: Moisture recycling and water resilience. *Water Security* **8**, 100046 (2019).
317 Wang-Erlandsson, L. *et al.* Remote land use impacts on river flows through atmospheric teleconnections. *Hydrology and Earth System Sciences* **22**, 4311–4328 (2018).
318 Asselin, O. *et al.* Blue in green: forestation turns blue water green, mitigating heat at the expense of water availability. *Environmental Research Letters* **19**, 114003 (2024).
319 Engel, F., Hoek Van Dijke, A. J., Roebroek, C. T. J. & Benedict, I. Can large-scale tree cover change negate climate change impacts on future water availability? *Hydrology and Earth System Sciences* **29**, 1895–1918 (2025).
320 Nyasulu, M. K. *et al.* African rainforest moisture contribution to continental agricultural water consumption. *Agricultural and Forest Meteorology* **346**, 109867 (2024).
321 Harpole, W. S. *et al.* Nutrient co-limitation of primary producer communities. *Ecology Letters* **14**, 852–862 (2011).
322 Ludemann, C. I. *et al.* A global FAOSTAT reference database of cropland nutrient budgets and nutrient use efficiency (1961–2020): nitrogen, phosphorus and potassium. *Earth System Science Data* **16**, 525–541 (2024).
323 FAO. Land, Inputs and Sustainability: Fertilizers by Nutrient. 2026.
324 Beusen, A. *et al.* Exploring river nitrogen and phosphorus loading and export to global coastal waters in the Shared Socio-economic pathways. *Global Environmental Change* **72**, 102426 (2022).
325 Battye, W., Aneja, V. P. & Schlesinger, W. H. Is nitrogen the next carbon? *Earth's Future* **5**, 894–904 (2017).
326 Schulte-Uebbing, L. F., Beusen, A. H. W., Bouwman, A. F. & de Vries, W. From planetary to regional boundaries for agricultural nitrogen pollution. *Nature* **610**, 507–512 (2022).
327 Sandström, V. *et al.* Disparate history of transgressing planetary boundaries for nutrients. *Global Environmental Change* **78**, 102628 (2023).

328 Smil, V. Phosphorus in the Environment: Natural Flows and Human Interferences. *Annual Review of Environment and Resources* **25**, 53–88 (2000).
329 Bodirsky, B. L. *et al.* Reactive nitrogen requirements to feed the world in 2050 and potential to mitigate nitrogen pollution. *Nature Communications* **5**, 3858 (2014).
330 Demay, J., Ringeval, B., Pellerin, S. & Nesme, T. Half of global agricultural soil phosphorus fertility derived from anthropogenic sources. *Nature Geoscience* **16**, 69–74 (2023).
331 De Vries, W. *et al.* Trends and geographic variation in adverse impacts of nitrogen use in Europe on human health, climate, and ecosystems: A review. *Earth-Science Reviews* **253**, 104789 (2024).
332 Breitburg, D. *et al.* Declining oxygen in the global ocean and coastal waters. *Science* **359**, eaam7240 (2018).
333 Watson, A. J., Lenton, T. M. & Mills, B. J. W. Ocean deoxygenation, the global phosphorus cycle and the possibility of human-caused large-scale ocean anoxia. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **375**, 20160318 (2017).
334 Giannadaki, D., Giannakis, E., Pozzer, A. & Lelieveld, J. Estimating health and economic benefits of reductions in air pollution from agriculture. *Science of The Total Environment* **622-623**, 1304–1316 (2018).
335 Sardans, J., Janssens, I. A., Ciais, P., Obersteiner, M. & Peñuelas, J. Recent advances and future research in ecological stoichiometry. *Perspectives in Plant Ecology, Evolution and Systematics* **50**, 125611 (2021).
336 Bertagni, M. B. *et al.* Minimizing the impacts of the ammonia economy on the nitrogen cycle and climate. *Proceedings of the National Academy of Sciences* **120**, e2311728120 (2023).
337 Springmann, M. *et al.* Options for keeping the food system within environmental limits. *Nature* **562**, 519–525 (2018).
338 Rose, K. C. *et al.* Aquatic deoxygenation as a planetary boundary and key regulator of Earth system stability. *Nature Ecology & Evolution* **8**, 1400–1406 (2024).
339 Findlay, H. S., Feely, R. A., Jiang, L.-Q., Pelletier, G. & Bednaršek, N. Ocean Acidification: Another Planetary Boundary Crossed. *Global Change Biology* **31** (2025).
340 Jiang, L.-Q. *et al.* Global Surface Ocean Acidification Indicators From 1750 to 2100. *Journal of Advances in Modeling Earth Systems* **15**, e2022MS003563 (2023).
341 Ford, D. J., Kulk, G., Watson, A. J., Sathyendranath, S. & Shutler, J. D. UExP-FNN-U full surface ocean carbonate system. 2026.
342 Chau, T.-T.-T., Chevallier, F. & Gehlen, M. Global Analysis of Surface Ocean CO2 Fugacity and Air-Sea Fluxes With Low Latency. *Geophysical Research Letters* **51**, e2023GL106670 (2024).
343 Chau, T.-T.-T., Gehlen, M., Metzl, N. & Chevallier, F. CMEMS-LSCE: a global, 0.25°, monthly reconstruction of the surface ocean carbonate system. *Earth System Science Data* **16**, 121–160 (2024).
344 European Union-Copernicus Marine Service. Surface ocean carbon fields. 2019.
345 Gregor, L. & Gruber, N. OceanSODA-ETHZ: a global gridded data set of the surface ocean carbonate system for seasonal to decadal studies of ocean acidification. *Earth System Science Data* **13**, 777–808 (2021).
346 Iida, Y., Takatani, Y., Kojima, A. & Ishii, M. Global trends of ocean CO2 sink and ocean acidification: an observation-based reconstruction of surface ocean inorganic carbon variables. *Journal of Oceanography* **77**, 323–358 (2021).
347 Japan Meteorological Agency. JMA Ocean CO2 Map (v2025). 2026.
348 Ma, D., Gregor, L. & Gruber, N. Four Decades of Trends and Drivers of Global Surface Ocean Acidification. *Global Biogeochemical Cycles* **37**, e2023GB007765 (2023).
349 Müller, J. D. & Gruber, N. Progression of ocean interior acidification over the industrial era. *Science Advances* **10**, eado3103 (2024).
350 Müller, J. D. *et al.* Decadal Trends in the Oceanic Storage of Anthropogenic Carbon From 1994 to 2014. *AGU Advances* **4**, e2023AV000875 (2023).
351 Bednaršek, N. *et al.* Integrated Assessment of Ocean Acidification Risks to Pteropods in the Northern High Latitudes: Regional Comparison of Exposure, Sensitivity and Adaptive Capacity. *Frontiers in Marine Science* **8** (2021).
352 Bednaršek, N. *et al.* Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience* **5**, 881–885 (2012).
353 McGovern, E. *et al.* Ocean acidification. in *The 2023 Quality Status Report for the North-East Atlantic* (OSPAR Commission, London, 2022).
354 Bednaršek, N., Nguyen, T., Pelletier, G. & Gracey, A. Extreme Sensitivity of Early Life Stage Dungeness Crabs to Combined Ocean Acidification and Hypoxia. *ACS ES&T Water* **6**, 3095–3110 (2026).
355 Gruber, N., Boyd, P. W., Frölicher, T. L. & Vogt, M. Biogeochemical extremes and compound events in the ocean. *Nature* **600**, 395–407 (2021).
356 Canadell, J. G. *et al.* Global Carbon and other Biogeochemical Cycles and Feedbacks. in *IPCC AR6 WGI, Final Government Distribution* chapter 5 (2021).
357 Hofmann, M. & Schellnhuber, H.-J. Oceanic acidification affects marine carbon pump and triggers extended marine oxygen holes. *Proceedings of the National Academy of Sciences* **106**, 3017–3022 (2009).
358 Planchat, A., Bopp, L., Kwiatkowski, L. & Torres, O. The carbonate pump feedback on alkalinity and the carbon cycle in the 21st century and beyond. *Earth System Dynamics* **15**, 565–588 (2024).
359 Barrett, R. C. *et al.* Biological Responses to Ocean Acidification Are Changing the Global Ocean Carbon Cycle. *Global Biogeochemical Cycles* **39**, e2024GB008358 (2025).
360 Müller, J. D., Schneider, B. & Rehder, G. Long-term alkalinity trends in the Baltic Sea and their implications for CO2 -induced acidification: Baltic Sea Alkalinity Trends. *Limnology and Oceanography* **61**, 1984–2002 (2016).
361 Findlay, H. S. & Feely, R. A. Revisiting the ocean acidification planetary boundary. *National Science Review,* nwag173 (2026).
362 Bednaršek, N. *et al.* Systematic Review and Meta-Analysis Toward Synthesis of Thresholds of Ocean Acidification Impacts on Calcifying Pteropods and Interactions With Warming. *Frontiers in Marine Science* **6** (2019).
363 Dorey, N. *et al.* Ocean acidification and temperature rise: effects on calcification during early development of the cuttlefish Sepia officinalis. *Marine Biology* **160**, 2007–2022 (2013).
364 Thor, P. & Dupont, S. Transgenerational effects alleviate severe fecundity loss during ocean acidification in a ubiquitous planktonic copepod. *Global Change Biology* **21**, 2261–2271 (2015).
365 Ventura, A., Schulz, S. & Dupont, S. Maintained larval growth in mussel larvae exposed to acidified under-saturated seawater. *Scientific Reports* **6**, 23728 (2016).
366 Vargas, C. A. *et al.* Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. *Nature Ecology & Evolution* **1**, 0084 (2017).
367 Vargas, C. A. *et al.* Upper environmental pCO2 drives sensitivity to ocean acidification in marine invertebrates. *Nature Climate Change* **12**, 200–207 (2022).
368 Von Schuckmann, K. *et al.* Heat stored in the Earth system 1960–2020: where does the energy go? *Earth System Science Data* **15**, 1675–1709 (2023).
369 Forster, P. *et al.* The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. in *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Masson-Delmotte, V. et al.) 923–1054 (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021).
370 Minière, A., von Schuckmann, K., Sallée, J.-B. & Vogt, L. Robust acceleration of Earth system heating observed over the past six decades. *Scientific Reports* **13**, 22975 (2023).
371 Storto, A. & Yang, C. Acceleration of the ocean warming from 1961 to 2022 unveiled by large-ensemble reanalyses. *Nature Communications* **15**, 545 (2024).
372 Merchant, C. J., Allan, R. P. & Embury, O. Quantifying the acceleration of multidecadal global sea surface warming driven by Earth's energy imbalance. *Environmental Research Letters* **20**, 024037 (2025).
373 Pan, Y. *et al.* Ocean Heat Content Sets Another Record in 2025. *Advances in Atmospheric Sciences* (2026).
374 World Meteorological Organization (WMO). State of the Global Climate 2024. Tech. rep. ISBN 978-92-63-11368-5 (World Meteorological Organization (WMO), Geneva, Switzerland, 2025), 42.
375 Le Grix, N., Burger, F. A. & Frölicher, T. L. Surface and Subsurface Compound Marine Heatwave and Biogeochemical Extremes Under Climate Change. *Global Biogeochemical Cycles* **39**, e2025GB008514 (2025).

376 Pörtner, Hans-Otto, Roberts, D. C. & Masson-Delmotte, V. The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change 1st ed. (Cambridge University Press, 2019).
377 Hülse, D. & Ridgwell, A. Instability in the geological regulation of Earth's climate. 2025.
378 Gobler, C. J. & Baumann, H. Hypoxia and acidification in ocean ecosystems: coupled dynamics and effects on marine life. *Biology Letters* **12**, 20150976 (2016).
379 Breitburg, D. *et al.* And on Top of All That… Coping with Ocean Acidification in the Midst of Many Stressors. *Oceanography* **28**, 48–61 (2015).
380 Grégoire, Marilaure *et al.* Ocean Oxygen: the role of the Ocean in the oxygen we breathe and the threat of deoxygenation. Tech. rep. Version Number: June 2023 (Zenodo, 2023).
381 Ferrer, E. M. *et al.* Why aquatic deoxygenation belongs in the planetary boundary framework. *PLOS Climate* **4**, e0000619 (2025).
382 Mahowald, N. Aerosol Indirect Effect on Biogeochemical Cycles and Climate. *Science* **334**, 794–796 (2011).
383 Haywood, J. & Boucher, O. Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review. *Reviews of Geophysics* **38**, 513–543 (2000).
384 CAMS global reanalysis (EAC4).
385 Bond, T. C. *et al.* Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres* **118**, 5380–5552 (2013).
386 Klimont, Z. *et al.* Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics* **17**, 8681–8723 (2017).
387 Smith, S. J. *et al.* Anthropogenic sulfur dioxide emissions: 1850–2005. *Atmospheric Chemistry and Physics* **11**, 1101–1116 (2011).
388 Li, J. *et al.* Scattering and absorbing aerosols in the climate system. *Nature Reviews Earth & Environment* **3**, 363–379 (2022).
389 Hwang, Y.-T., Frierson, D. M. W. & Kang, S. M. Anthropogenic sulfate aerosol and the southward shift of tropical precipitation in the late 20th century. *Geophysical Research Letters* **40**, 2845–2850 (2013).
390 Lau, K. M., Kim, M. K. & Kim, K. M. Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau. *Climate Dynamics* **26**, 855–864 (2006).
391 Kalisoras, A. *et al.* Decomposing the effective radiative forcing of anthropogenic aerosols based on CMIP6 Earth system models. *Atmospheric Chemistry and Physics* **24**, 7837–7872 (2024).
392 WHO global strategy on health, environment and climate change: the transformation needed to improve lives and well-being sustainably through healthy environments. Tech. rep. (WHO, Geneva, 2020).
393 Wang, J. & Christopher, S. A. Intercomparison between satellite-derived aerosol optical thickness and PM2.5 mass: Implications for air quality studies. *Geophysical Research Letters* **30**, 2003GL018174 (2003).
394 Neethu, C., Tharammal, T. & Bala, G. A model-based assessment of the regional safe aerosol boundary for the South Asian monsoon region. *Environmental Research Letters* **20**, 124057 (2025).
395 Inness, A. *et al.* The CAMS reanalysis of atmospheric composition. *Atmospheric Chemistry and Physics* **19**, 3515–3556 (2019).
396 Eyring, V. *et al.* Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development* **9**, 1937–1958 (2016).
397 Collins, W. J. *et al.* AerChemMIP: quantifying the effects of chemistry and aerosols in CMIP6. *Geoscientific Model Development* **10**, 585–607 (2017).
398 Changing State of the Climate System. in *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (ed Intergovernmental Panel on Climate Change (IPCC)) 287–422 (Cambridge University Press, Cambridge, 2023).
399 Copernicus Climate Data Store. Ozone monthly gridded data from 1970 to present derived from satellite observations. 2020.
400 Rowland, F. S. Stratospheric ozone depletion. *Philosophical Transactions of the Royal Society B: Biological Sciences* **361**, 769–790 (2006).
401 Ravishankara, A. R., Daniel, J. S. & Portmann, R. W. Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. *Science* **326**, 123–125 (2009).
402 Tian, H. *et al.* A comprehensive quantification of global nitrous oxide sources and sinks. *Nature* **586**, 248–256 (2020).
403 Smith, R. C. *et al.* Ozone depletion: ultraviolet radiation and phytoplankton biology in antarctic waters. *Science (New York, N.Y.)* **255**, 952–959 (1992).
404 Scientific Assessment of Ozone Depletion: 2022. GAW Report **No. 278** (World Meteorological Organization (WMO), Geneva, 2022).
405 Schmidt, D. F. & Grise, K. M. The Response of Local Precipitation and Sea Level Pressure to Hadley Cell Expansion. *Geophysical Research Letters* **44**, 10, 573–10, 582 (2017).
406 Banerjee, A., Fyfe, J. C., Polvani, L. M., Waugh, D. & Chang, K.-L. A pause in Southern Hemisphere circulation trends due to the Montreal Protocol. *Nature* **579**, 544–548 (2020).
407 Jepson, P. D. *et al.* PCB pollution continues to impact populations of orcas and other dolphins in European waters. *Scientific Reports* **6**, 18573 (2016).
408 Tian, Z. *et al.* A ubiquitous tire rubber–derived chemical induces acute mortality in coho salmon. *Science* **371**, 185–189 (2021).
409 Brinkmann, M. *et al.* Acute Toxicity of the Tire Rubber-Derived Chemical 6PPD-quinone to Four Fishes of Commercial, Cultural, and Ecological Importance. *Environmental Science & Technology Letters* **9**, 333–338 (2022).
410 MacLeod, M., Arp, H. P. H., Tekman, M. B. & Jahnke, A. The global threat from plastic pollution. *Science* **373**, 61–65 (2021).
411 Srivani, G. *et al.* Unraveling pesticide impacts on pollinators: a global challenge for sustainable crop protection. *The Science of Nature* **113**, 38 (2026).
412 PlasticsEurope. European plastic industry market data. 2025.
413 European Chemical Industry Council (Cefic). Cefic Facts and Figures 2025. Brussels, Belgium, 2025.
414 Naghavi, M. *et al.* Global burden of bacterial antimicrobial resistance 1990–2021: a systematic analysis with forecasts to 2050. *The Lancet* **404**, 1199–1226 (2024).
415 Simon, P. *et al.* POPE: a Global Gridded Emission Inventory for PFAS 1950–2020. *Earth System Science Data Discussions* **2024**, 1–41 (2024).
416 European Environment Agency. Europe's environment 2025: knowledge for resilience, prosperity and sustainability. (Publications Office, LU, 2025).
417 Australian Climate Service. Australia's National Climate Risk Assessment. Tech. rep. (Australian Government, 2025).
418 Government of the United Kingdom. Global biodiversity loss, ecosystem collapse and national security – Anational security assessment. Tech. rep. (2026).
419 Lind, A. & Carus Andersen, L. K. Planetary Politics: From global to national boundaries. Tech. rep. (Concito, Copenhagen, 2024).
420 Rockström, J. *et al.* The planetary commons: A new paradigm for safeguarding Earth-regulating systems in the Anthropocene. *Proceedings of the National Academy of Sciences* **121**, e2301531121 (2024).
421 Raworth, K. A Safe and Just Space for Humanity: Can we live within the doughnut? ISBN: 978-1-78077-059-8 (Oxfam International, 2012).
422 Diamond, R. et al. A Weakened AMOC Could Cause Southern Ocean Temperature and Sea-Ice Change on Multidecadal Timescales. *Journal of Geophysical Research: Oceans* **130**, e2024JC022027 (2025).

EDITORS: Niklas Kitzmann, Boris Sakschewski, Levke Caesar, and Johan Rockström

AUTHORS: Levke Caesar*, Boris Sakschewski*, Lauren Seaby Andersen, Yuge Bai, Govindaswamy Bala, Nina Bednarsek, Tim Beringer, Arthur Beusen, Maik Billing, Benjamin Leon Bodirsky, Svetlana Botsyun, Johanna Braun, Denise Breitburg, Heindriken Dahlmann, Fabrice DeClerck, Donovan P. Dennis, Miriam L. Diamond, Jonathan F. Donges, Xinyu Dou, Sam Dupont, Shivani Ehrenfeucht, Axel E. Eriksson, Simon Fahrländer, Ingo Fetzer, Helen S. Findlay, Daniel J. Ford, Thomas Frölicher, Véronique Garçon, Jacob Geersen, Dieter Gerten, Nicolas Gruber, Tim Heckmann, Willem Huiskamp, Annika Jahnke, Samantha Joye, Jonas Kaiser, Niklas H. Kitzmann, Dana Kühnel, Nicole C. Laureanti, Chaohui Li, Zhu Liu, Sina Loriani, Josef Ludescher, Sabine Mathesius, Nele Matz-Lück, Jens Daniel Müller, Nicholas J. Murray, Clara Nicolai, Friederike Otto, Alex Pielaet, Dimitry Pokhotelov, Kasra Rafiezadeh Shahi, Emmanuel Raju, Karoline Ramin, Lukas Röhrich, Masoud Rostami, Christian Schmidt, Anna Shalin, Jamie D. Shutler, Norman J. Steinert, Fabian Stenzel, Heicko Stuckas, Luisa Teixeira, Thejna Tharammal, Liad Ben Uri, Vili Virkki, Zhanyun Wang, Katrin Wendt-Potthoff, Johan Rockström
*equal contributors to this work and designated as co-first authors

REVIEWERS: Felicitas Beier, Patrick Beukema, Svetlana Botsyun, Michael Crawford, Jonathan Donges, Georg Feulner, Fred Hattermann, Jakob Harteg, Sophie Hebden, Andrew Howe, Michael McLachlan, Dimitry Pokhotelov, Hadrien Sablon, Ted Schmitt, Delphine Tardif, Stephen Wirth

ART & FIGURES: GLOBAÏA
LAYOUT DESIGN: neon-bold.de

SPECIAL THANKS go to all supporters of PBScience, including those who have provided financial contributions, in-kind support, and other resources that enable us to carry out our research and produce this report. We would also like to thank all those who contributed in various other ways to the success of this report. Thanks also to Katherine Richardson, Miriam Sinnhuber and Gunter Stober for helpful scientific input, as well as Lotta Bergfeld, Reinhild Costa, Özge Kart Tokmak, Bruce Phillips, and Hannes Rauhe for editorial and organizational support. We gratefully acknowledge Mattias Klum for generously allowing the use of his photographs (6, 10, 40, 54, 102, 106 and the front inner cover) in this report at no charge. This work is licensed under a CC BY 4.0 license unless otherwise credited.

DOI: 10.48485/pik.2026.25

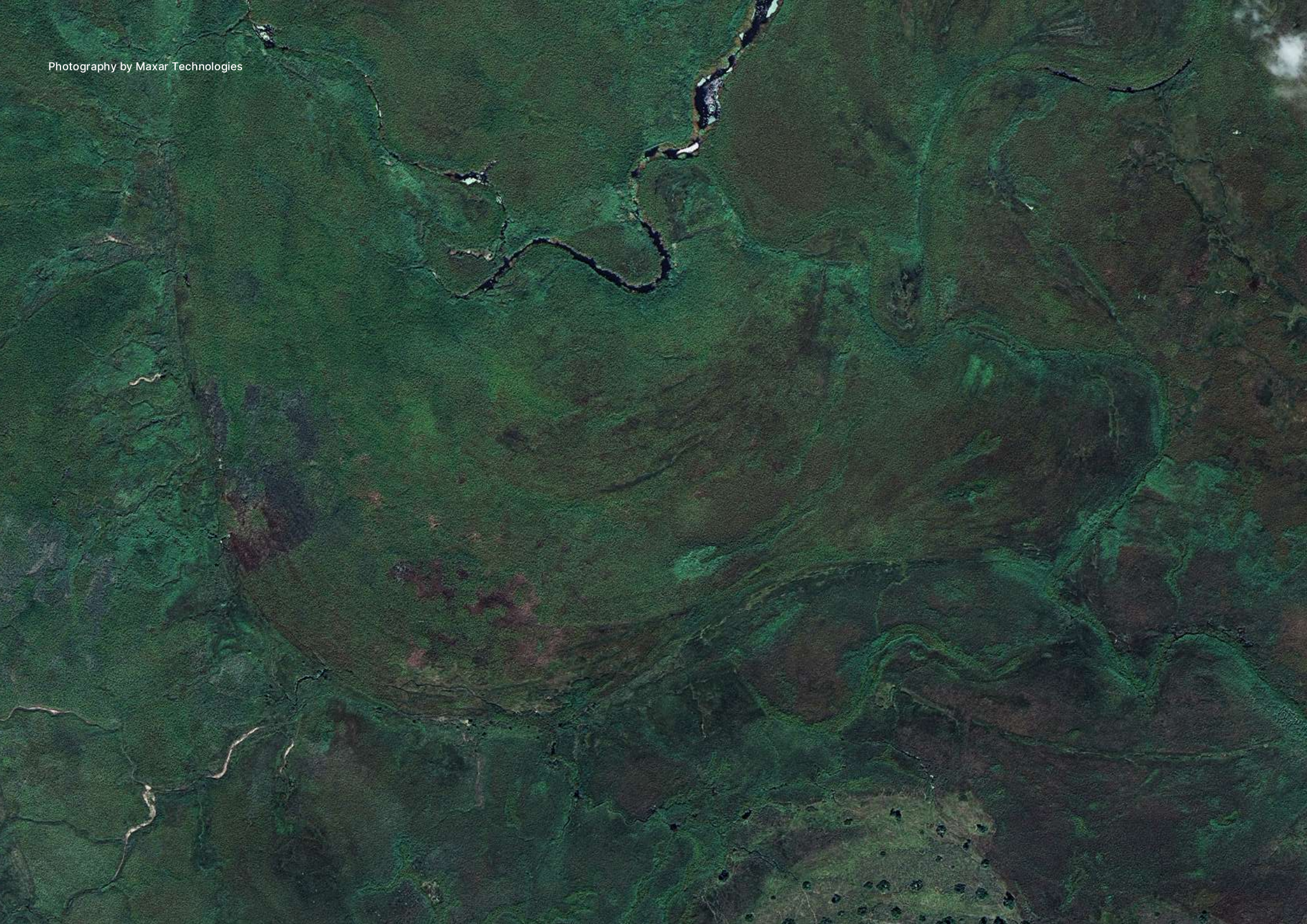
Portions of this work were facilitated by the use of AI-based tools, which supported literature synthesis and text drafting. All outputs were critically reviewed and revised by the authors to ensure accuracy and integrity.

CONTACT: pbscience@pik-potsdam.de

P I K

Potsdam Institute for Climate Impact Research

Planetary® Guardians


Photography by Maxar Technologies

For additional details, and access to the short-length version of this report, please visit **planetaryhealthcheck.org**