Planetary Health Check 2025

A Scientific Assessment of the State of the Planet

Planetary Boundaries
SCIENCE

In the past century, more has been learned than ever before about what makes Earth suitable for life, especially human life, in a fiercely inhospitable universe.

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Acknowledgements

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The Planetary Boundaries Science (PBScience) project was launched in 2023 to address critical gaps in our understanding and monitoring of the Earth system. Utilizing advanced simulation modeling, incorporating the latest available measurement datasets and synthesizing new insights from Earth system science literature, PBScience provides annual Planetary Health Checks based on the Planetary Boundaries framework. Collaborating closely with the Planetary Guardians and other partners, PBScience strives to elevate global awareness and drive action towards maintaining planetary stability.

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Disclaimer

In 2025 we aim to provide a concise, updated Planetary Boundaries assessment, offer a thorough explanation of the Planetary Boundaries framework and methods, and identify potential advancements. It is not possible in this report to produce a full review which encompasses all relevant literature on recent Planetary Boundaries research. We are currently developing the methods to advance Earth system review and analysis, and welcome and appreciate feedback to help us improve the accuracy and comprehensiveness of future reports. If you have any suggestions or corrections, please do not hesitate to contact us.

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The
Planetary Health
Check report is
more than data.

It's a call to action.

Foreword

In the past century, and mostly since the 1950s, more has been learned than ever before about what makes Earth suitable for life, especially human life, in a fiercely inhospitable universe. At the same time, more has been lost than ever before of the dynamic living systems that underpin the conditions that make possible our existence.

It is with deep urgency, and enduring hope, that I introduce this second edition of the *Planetary Health Check*. This report builds on the foundations that were laid last year, and on the vast amount of Earth system science conducted since the Planetary Boundaries were first introduced in 2009. While the focus remains on the whole Earth system, this report places special emphasis on the ocean – not only in recognition of new findings, but as a reflection of the ocean's foundational role in planetary stability.

Most of the ocean is unexplored, and many questions remain about how the ocean shapes planetary processes – but clearly, without the ocean, the blue Earth would resemble our bleak red neighbor, Mars. After all: No water, no life. The ocean makes up over 99% of the Earth's habitable water, a liquid medium that is vital to the existence of life everywhere, from the tops of mountains to the deepest lakes, the driest deserts, the most populous cities.

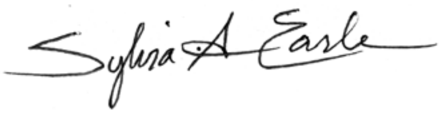
Industrial extraction of ocean wildlife, addition of toxic wastes, plastics, lost or tossed fishing gear, and unprecedented noise since the 1950s have contributed to the loss of about half of the ocean's life, from coral reefs and forests of kelp, from charismatic megafauna to microscopic organisms. The living ocean is the planet's largest carbon sink, climate stabilizer, and source of oxygen. We need a healthy ocean to have a healthy planet, but it cannot protect us if we do not protect it. The growing scale of impacts – rising acidity, deoxygenation, warming, and biodiversity loss – threatens to disrupt these essential functions.

This year's report brings sobering news: For the first time, we have crossed the Planetary Boundary for Ocean Acidification. This paints a grave picture – not just for marine ecosystems, but for the entire Earth system that depends on a healthy ocean.

Recent global discussions – whether on the future of deep-sea mining, or on the proposed cuts to Earth system science funding – remind us that without robust, transparent, and long-term ocean observation systems, we simply cannot conduct the kind of scientific assessments this report aims to provide. Knowledge is power – but only if we commit to gathering it.

The Planetary Health Check report is more than data. It's a call to action. With each new insight comes greater responsibility – to protect the global commons, to invest in restoration and renewals, and to empower a new generation of planetary stewards. Through the Planetary Guardians, we are building bridges between knowledge and leadership, from coral reefs to climate summits. We invite you to explore this report, grounded in scientific rigor yet written for everyone. By understanding the boundaries that keep Earth stable, we can make better choices – before tipping points become points of no return.

Thank you for your attention, your action, and your courage. The blue Earth is changing. But together, so can we.



Sylvia A. Earle, Planetary Guardian

Oceanographer, National Geographic Explorer
Founder, Mission Blue; Founding Ocean Elder

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Key Terms

Scientific Term	Scientific Definition
Planetary Health	Refers to how well the planet sustains the conditions necessary for life on Earth, including humans. Healthy means it supports stable conditions, has the ability to recover from disruptions (resilience), and supports essential processes for life (life-support functions).
Safe Operating Space	Refers to the range of environmental conditions in which humanity can safely live, grow, and prosper long-term. Staying within this space ensures Earth's systems remain stable and supportive of life. Going outside it is very different from anything humans have experienced in approximately the last 12,000 years, a stable period called the Holocene Epoch.
Planetary Boundary / Boundaries (PB/PBs)	Refers to the thresholds that keep life on Earth within a safe operating zone or safe boundaries. If you pass over, or transgress, the boundaries you increase the risk of losing stability, life support and nature's ability to absorb shocks and damage. The Planetary Boundaries framework identifies the nine Earth system processes essential for maintaining global stability, resilience and life-support functions.
Zone of Increasing Risk	Refers to the stage when human activities push Earth beyond the Planetary Boundaries, entering a "Zone of Increasing Risk." In this zone, the further boundaries are exceeded, the greater the chance of causing serious damage, destabilizing key Earth system processes, and disrupting life-support functions.
High-Risk Zone	Refers to Earth entering the "High-Risk Zone," where there is a strong possibility of severe, irreversible damage to key planetary functions that support life. In this zone, immediate action becomes critical to prevent locking in permanent changes and moving even further away from the stable conditions of the Holocene epoch (a period of stability on Earth covering approximately the last 12,000 years).
Control Variable (CV)	Refers to measurable indicators used to check whether an Earth system process is staying within its safe operating zone (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.
Tipping Point	Refers to a critical point at which small changes can suddenly trigger large, often irreversible shifts in Earth's environment. Once a tipping point is crossed, self-reinforcing (positive feedback) processes drive the system further away from its previous state, increasing the magnitude and extent of change. For example, melting ice exposes less reflective ocean water, which absorbs more sunlight and accelerates melting, creating a self-reinforcing cycle.
Tipping Element	Refers to major Earth subsystems that, if pushed past their tipping points, shift into a qualitatively different state which can cause dramatic changes to the entire planet. Examples include large ice sheets (Greenland or Antarctica), major ocean currents (like the Gulf Stream), or critical ecosystems (such as the Amazon rainforest). When these elements cross tipping points, it can trigger widespread, possibly permanent environmental shifts.
Drivers of Transgression	Refers to human actions that push the Earth beyond its safe limits (Planetary Boundaries), such as excessive fossil fuel burning (driving climate change), deforestation (affecting biodiversity, climate and land system change), unsustainable agriculture (affecting nutrient cycling), and overuse of freshwater resources. These activities threaten Earth's stability and our ability to thrive.

Executive Summary

The Planetary Health Check (PHC) report provides an assessment of the state of our planet. It is based on the Planetary Boundaries (PBs) – the nine processes that are known to regulate the stability, resilience (ability to absorb disruptions) and life-support functions of our planet. Each of these processes, such as Climate Change or Ocean Acidification, is currently quantified by one or two control variables. The 2025 PHC report concludes that **seven out of nine Planetary Boundaries have been breached**, with all of those seven showing trends of increasing pressure – suggesting further deterioration and destabilization of planetary health in the near future (Fig. ES 1).

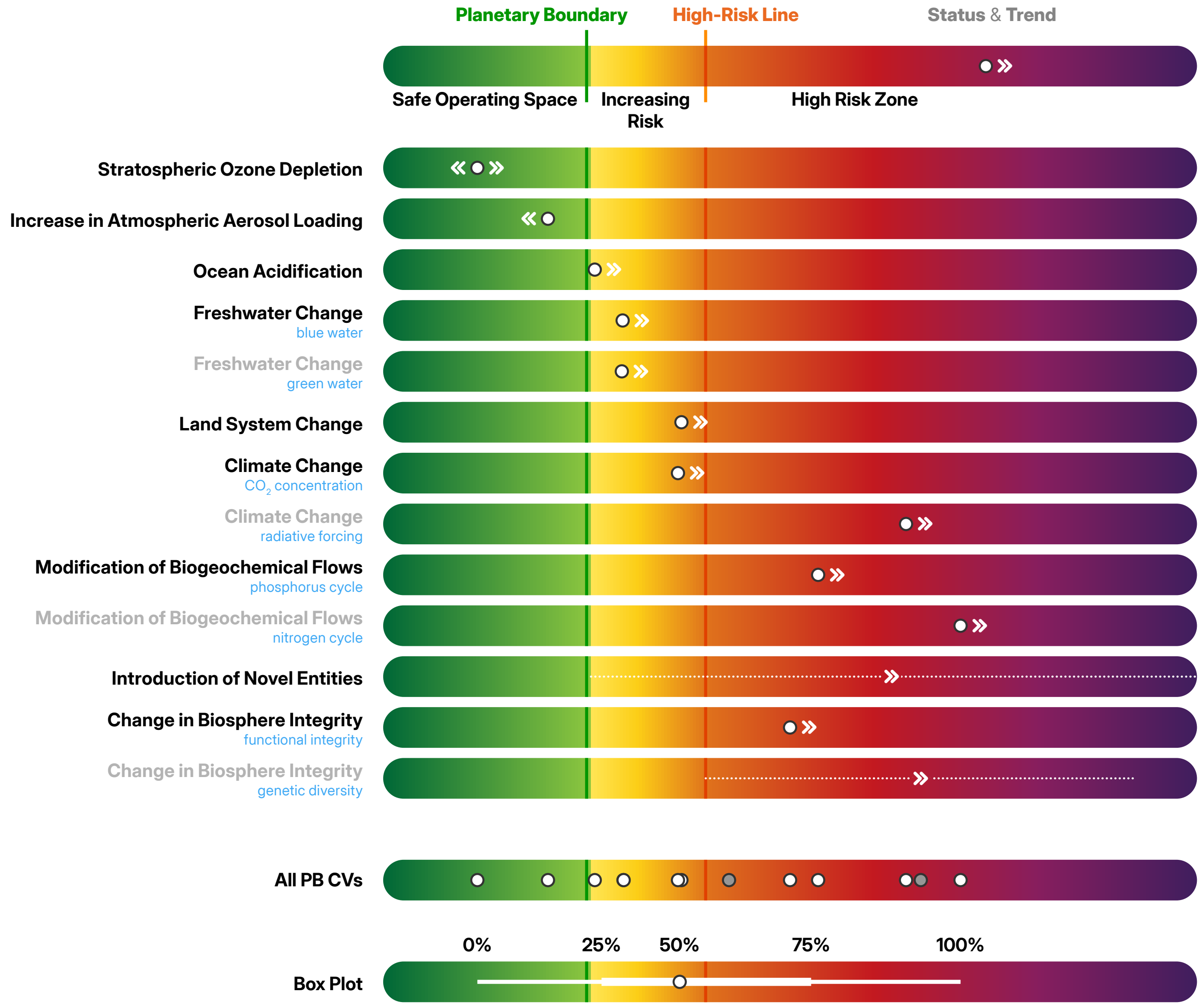


FIGURE ES 1 - Planetary Health at a glance. Just as a blood test provides insights into a human body's health and identifies areas of concern, this Planetary Health Check evaluates the 13 measured control variables across the 9 Planetary Boundary (PB) processes to report on Earth's stability, resilience, and life-support functions – the overall health of our planet. The 2025 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 increasing 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. ES 2) summarizes all of these findings, showing the Planet's overall health at a glance.

The Basics of Planetary Boundaries

For over 10,000 years, humanity has thrived within a period of climatic stability and a resilient Earth system. This epoch is called the Holocene, and it provided conditions that enabled the rise of agriculture, urbanization, and complex civilizations. However, since the mid-20th century, we have entered a new epoch marked by what is called "The Great Acceleration", where both socio-economic activity and environmental impact have surged exponentially (see Ch. 2.1). This was the beginning of the Anthropocene – the current era, in which human activity has become the dominant force of shaping the Earth system.

Human activities have collectively pushed Earth beyond its Safe Operating Space.

The Earth system possesses an intrinsic capacity for self-regulation that has historically helped maintain Holocene-like conditions favorable to civilization (see Ch. 2.2). This resilience stems from tightly coupled interactions and feedback processes among the biosphere, climate, and other planetary processes, evident in the long-term stability of the Holocene and previous interglacial periods. Over the past 150 years, this resilience has absorbed more than half of human-induced greenhouse gas emissions through land and ocean carbon sinks. However, mounting evidence shows that this carbon uptake capacity is weakening: Natural carbon sinks on land are saturating or turning into carbon sources, global warming appears to be accelerating, and early warning signs of tipping behavior are emerging in key systems. This loss of planetary resilience is further compounded by regional-scale ecological regime shifts and reduced functional integrity in ecosystems.

Human activities have collectively pushed Earth beyond its Safe Operating Space (see Ch. 2), driven by interconnected stressors such as fossil fuel combustion, land-use changes, and pollution. These interactions (see Ch. 2.4) amplify negative effects across multiple boundaries, such as climate change intensifying biodiversity loss or land degradation triggering severe droughts and heatwaves. Crucially, these pressures increase the risk of crossing critical tipping points – thresholds at which Earth system components can shift irreversibly to destabilized states, such as the collapse of major ice sheets, disruption of ocean currents, or the degradation of vital ecosystems like the Amazon rainforest (see Ch. 2.3). For instance, synthetic pollutants like plastics disrupt ocean ecosystems, weakening their capacity to sequester carbon and potentially accelerating tipping behavior. Likewise, deforestation and land degradation reduce vegetation's ability to moderate local climates, increasing vulnerability to tipping points and regime shifts that could trigger widespread ecological collapse. Understanding these interconnected drivers and their tipping potential through a systems-based approach reveals leverage points where targeted interventions can yield broad, systemic improvements. Effective solutions (see Ch. 3.3) must therefore recognize and address these interconnections and tipping risks, integrating local, regional, and global efforts, supported by robust measurement and monitoring, to return humanity safely within Earth's planetary boundaries.

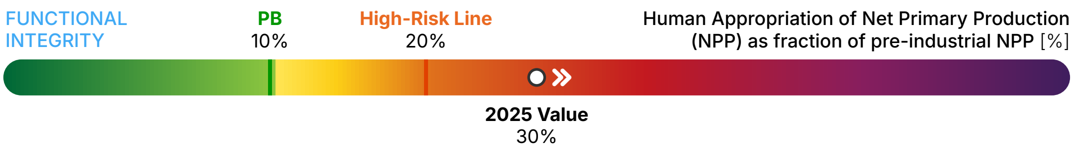
Current Status and Updates of Each Planetary Boundary

Climate Change

Earth's climate is in the danger zone: Greenhouse gas concentrations have reached record levels, global warming appears to be accelerating, and conditions are continuing to worsen.

Key Drivers: Fossil fuel burning, processes leading to non-CO_2 greenhouse gas emissions, Land System Change, Change in Biosphere Integrity, Increase in Atmospheric Aerosol Loading.
Atmospheric CO_2 is now at 423 ppm in 2025, far above the Holocene baseline and the Planetary Boundary of 350 ppm, while total anthropogenic radiative forcing stands at about +2.97 W/m², twice the high-risk threshold of +1.5 W/m². Both variables have increased since 2024, with atmospheric CO_2 also approaching the High Risk Zone. Global warming appears to be accelerating with no sign of stabilization. PHC2025 introduces global maps and graphs attributing temperature anomalies and emissions to sectors and locations, shows the Arctic warming fastest with urban-industrial regions as emission hotspots, and highlights the rising importance of methane and nitrous oxide. Recent research draws urgent attention to tipping points like abrupt shifts in the Amazon, Atlantic Meridional Overturning Circulation, and polar ice sheets, calling for early-warning indicators and the integration of ocean heat content in Planetary Boundaries assessments.

Change in Biosphere Integrity



Nature's safety net is unraveling: Extinctions and loss of natural productivity are far above safe levels, and there is no sign of improvement.

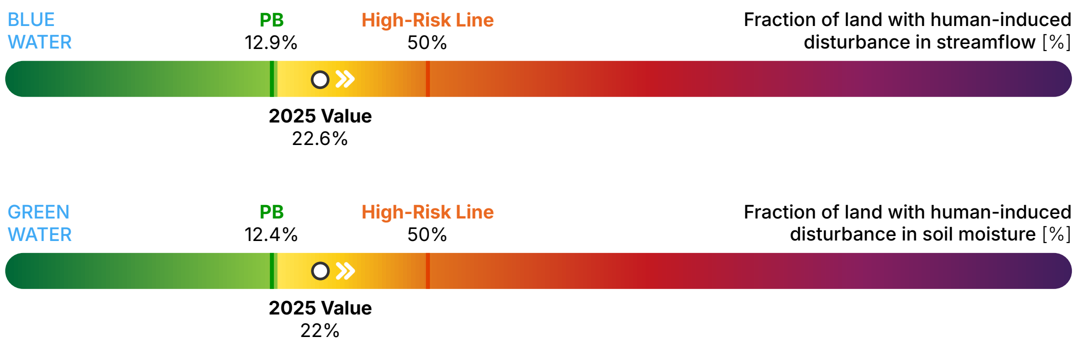
Key Drivers: Harvesting of biomass (agriculture, forestry, fishing), introduction of invasive species, Land System Change, Climate Change, Freshwater Change, Modification of Biogeochemical Flows, Introduction of Novel Entities, Ocean Acidification.
The extinction rate remains above 100 E/MSY, far beyond the Planetary Boundary of 10 E/MSY, while Human appropriation of net primary production (HANPP) sits at 30% – triple the 10% Planetary Boundary and above the 20% high-risk level. This situation has persisted or slightly worsened since 2024, with ongoing loss of genetic diversity and ecosystem function. PHC2025 debuts the first global SEED index map showing severe biocomplexity declines, introduces the EcoRisk indicator (with up to 60% of land exceeding either local HANPP or ecosystem risk), and shows converging hotspots of degradation across multiple metrics. The report also expands focus on the ocean biosphere's regulatory role and prepares for a future marine functional integrity measure.

Land System Change

Earth's forests are shrinking, and most are already below safe levels, with the overall trend still negative – although the pace of forest loss has slowed.

Key Drivers: Expansion of cropland and livestock grazing, wood harvesting, expansion of settlements and infrastructure, Climate Change, Freshwater Change, Biosphere Integrity.
Global forest cover has fallen to ~59% – well below the 75% safe minimum – and all major biomes have breached their safety thresholds. While the rate of decline has slowed, the situation remains deep in the Zone of Increasing Risk (approaching high-risk at ~54% cover), with ongoing deforestation and degradation keeping land-system health on a gradually worsening trajectory. PHC2025 stresses the importance of forest quality, ecological connectivity, and function, calls for future PHCs to include fragmentation and forest integrity, and considers recalibrating boundaries as biome data improves.

Freshwater Change

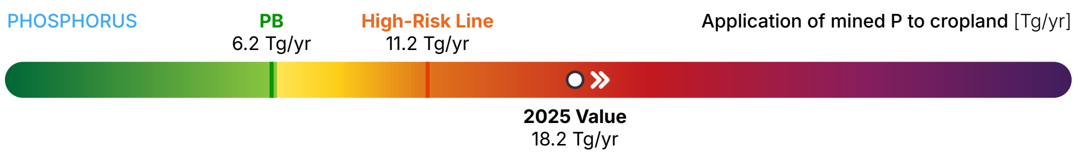


Human impact on rivers and soil moisture is growing, pushing water systems further from stability and heightening drought and flood risk.

Key Drivers: Irrigation and agriculture, industrial water use, household water use, Climate Change, Increase in Atmospheric Aerosol Loading, Land System Change.

More than a fifth of global land area now faces significant dry or wet deviations in streamflow (22.6%) and soil moisture (22.0%), roughly twice the preindustrial-like baseline state and far beyond the safe levels (12.9% and 12.4%). Both indicators are rising, putting freshwater firmly in the Zone of Increasing Risk, with major river basins such as the Indo-Gangetic Plain and North China exceeding safe levels and more pronounced extremes undermining water availability and resilience. PHC2025 introduces basin-scale mapping of blue and green water boundary transgressions. It revises the control variable-specific boundaries and data, reflecting the current status of conditions from 2010 to 2019 (an update from the 1995 to 2005 conditions in PHC2024). PHC2025 also identifies climate change as the dominant driver of freshwater instability and provides new explanations of feedback effects and implications.

Modification of Biogeochemical Flows

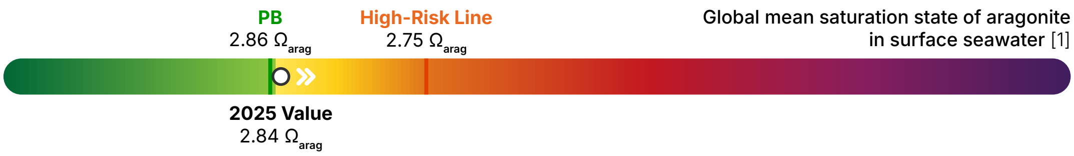


Fertilizer overuse continues to overload land and water with nitrogen and phosphorus, causing pollution and dead zones with no improvement in sight.

Key Drivers: Application of mined mineral phosphorus to fields as fertilizer, application of industrially-fixed nitrogen to fields as fertilizers, cultivation of nitrogen-fixing crops.

Regional phosphorus application is about 18.2 Tg P/year (triple the 6.2 Tg P/year Planetary Boundary and above the high-risk threshold), while intentional nitrogen fixation is at about 165 Tg N/year (over two times the Planetary Boundary and beyond the high-risk threshold). Both metrics remain in the High Risk Zone, with worsening trends. PHC2025 updates all data and boundaries, systematically details nutrient pathways, inefficiencies, and legacy pollution, and proposes shifting to agricultural surplus-based control variables for both N and P, as well as including uncounted sources like fossil fuel–derived nitrogen.

Ocean Acidification



The ocean is turning more acidic, threatening marine life as we cross into unsafe conditions with a worsening trend.

Key Drivers: Fossil fuel burning.
The global mean surface aragonite saturation state (Ω) is now 2.84, just below the revised Planetary Boundary of 2.86 (corresponding to 80% of the newly-updated preindustrial Ω). **This means that, for the first time, we assess that the Planetary Boundary for Ocean Acidification has been transgressed**. Marine organisms are at increasing risk, with evidence of shell damage already occurring today, especially in polar and coastal regions. PHC2025 applies up-to-date global Ω maps, adjusts the Planetary Boundary level upward (due to a better understanding of the preindustrial state of Ω), and underscores the need to monitor impacts on sensitive species and ecosystem functions as early warning signals.

Increase in Atmospheric Aerosol Loading

Air pollution differences between hemispheres are decreasing. This is a positive sign, as global air quality slowly improves.

Key Drivers: Fossil fuel burning, biomass burning, industrial activities.
The interhemispheric aerosol optical depth difference is now about 0.063 (lower than last year and well below the safe threshold of 0.10), meaning this PB remains within the Safe Operating Space. Global aerosol emissions are declining, even as some regions still face significant particulate pollution. PHC2025 includes new, high-resolution, chemically explicit datasets and models, explains aerosols' dual climate role (cooling from sulfates, warming from black carbon), and emphasizes health and justice issues tied to PM2.5 – even though these regional risks aren't yet fully captured in the Planetary Boundary metric.

Stratospheric Ozone Depletion

The ozone layer remains stable and is showing signs of slow recovery, maintaining protection against harmful UV radiation.

Key Drivers: Production/Emissions of Ozone-depleting substances, such as synthetic Chlorofluorocarbons and Nitrous Oxides.
Global ozone concentrations remain within the Safe Operating Space, averaging 285–286 Dobson Units, above the safe threshold of ~277 DU. Although recovery due to the Montreal Protocol continues, ozone remains below historical levels and the Antarctic ozone hole persists, so recovery is steady but incomplete. PHC2025 does not update the control variable given in the previous report, but more explicitly connects ozone recovery to Southern Hemisphere climate changes, notes emerging risks from space debris and rocket launches, and underscores the extra-polar ozone metric as most relevant for planetary health.

Introduction of Novel Entities

Human-made chemicals, plastics, and other novel entities continue to increase without sufficient testing or control, with environmental risks continuing to grow.

Key Drivers: Industrial production of artificial chemical compounds for industry, agriculture and consumer goods.

Each year, thousands of inadequately tested chemicals, plastics, and other novel entities are released into the environment, and the Planetary Boundary of zero untested entities remains persistently breached. This burden is worse than in 2024, as production and waste volumes increase and regulations lag behind. With the current control variable for novel entities remaining difficult to quantify, PHC2025 proposes to broaden the conceptual framework and propose measurable, impact-linked candidate indicators to support a multi-faceted risk assessment. This should include tracking stages such as production, release, fate, and Earth system effects, and refining these for key groups like plastics or genetically modified organisms. The assessment of novel entities should thus shift from isolated evaluation to a system-oriented approach that considers mixture effects, foregrounding interdependencies and ongoing scientific uncertainties.

Spotlight Chapters of This Year's Report

This year, three special chapters offer a deeper look into how Planetary Boundary transgressions intersect with real-world risks and opportunities for action:

The Ocean: The Unsung Guardian of Planetary Health

→ Chapter 3.1.

We examine the ocean's critical but underrepresented role in stabilizing the Earth system. Amid record ocean heat and coral bleaching in 2025, the ocean's role as climate regulator and life-support system is more visible – and more threatened – than ever. Storing most of the heat and a quarter of human-made CO_2 emissions, the ocean sustains planetary health. Yet it faces mounting stress from warming, acidification, biodiversity loss, and pollution, often interacting in ways that risk crossing tipping points. Integrating the ocean into Earth system governance is essential to ensure long-term resilience and stability.

Extreme Weather and Disasters in 2024/25 – an Attribution-Based Perspective

→ Chapter 3.2.

We explore how extreme weather events are becoming deadlier as climate change interacts with ecological degradation and social vulnerability. As 2024 marked the first year with global temperatures above 1.5 °C, extreme weather events claimed lives and caused widespread damage at an unprecedented level. But these disasters are not due to climate alone. They are intensified by the transgression of other Planetary Boundaries (like land-system change and freshwater use) and shaped by deep inequalities in exposure and vulnerability. Addressing both planetary instability and social risk is crucial for protecting people and ecosystems.

Putting Planetary Boundaries to Work: Emerging Practices, Actors and Tools

→ Chapter 3.3.

We map how governments, cities, businesses, and civil society are beginning to operationalize the Planetary Boundaries framework, translating global thresholds into practical strategies. A growing movement is bringing Planetary Boundaries into practice. From national climate targets and city planning to business strategies and financial risk disclosure, actors around the world are beginning to align decisions with Earth's boundaries. This shift signals not only a systems-based approach to environmental action, but a broader rethinking of how humanity operates on a finite planet.

Outlook – A Planetary Boundaries Initiative

We are living in an era of unprecedented scientific and technological opportunities, which we must harness given the urgency of the planetary crisis. To meet this challenge, Planetary Boundaries researchers around the world are currently forming the Planetary Boundaries Initiative (PBI). As a growing next-generation and multi-institutional platform, the PBI seeks to track, assess, and help to respond to the environmental risks identified in the Planetary Health Check. Therefore, it sets up 3 working clusters on 1) Diagnostics, 2) Solutions and 3) Communication in an integrative workflow.

Its core integrative engine, the **Planetary Boundaries Analyzer (PBAnalyzer)**, is a work-flow that links relevant empirical and modelled socio-economic and Earth system data as well as insights from literature inside an AI model and connects it with human expert feedback. The **PBAnalyzer** aims to deliver continuously refreshed diagnostics, maps causal leverage points, and offers interactive decision-support services within a **Planetary Mission Control Centre** for scientists, policymakers, and civil society. Lessons learned in practice, along with insights from domain experts will be fed back into the system to ensure that its results and recommendations are both scientifically rigorous and practically relevant.

The PBI is open for collaborations to constantly improve its products. Please contact: pbscience@pik-potsdam.de

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Conclusion – Planetary Health at a Glance

Our overall assessment of the health of the Planet in 2025 places the planet at the upper end of the (yellow) danger zone, pushing closer to the (red) high risk zone (Fig. ES 2). The 2025 assessment shows that we continue moving closer to the point where the planet as a whole exceeds the zone of increasing risk and enters the high risk zone (with higher certainty of large scale and irreversible changes). Nevertheless, Earth's current health – through its remarkable biological, physical, and chemical resilience – keeps the window open for returning to a safe operating space. However, this window is closing fast.

FIGURE ES 2 - 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. ES 1. The thin 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.

1

The State of the Planet

1.1 Defining Planetary Health

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.

Planetary Boundaries Framework

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:

Stability

The Earth system's ability to not disrupt 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.

In this report, "Planetary Health" refers to how well the Earth maintains these three key aspects, which are essential for keeping humanity within a "Safe Operating Space" (Ch. 2.1). Scientists have defined this space by setting boundaries for critical processes that regulate stability, resilience, and life-support functions.

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 and resilience (Ch. 1.2.). The Planetary Boundaries framework also identifies zones of increasing and high risk (Info Box 1). Gradual changes, interactions, or tipping points (Ch. 2.3) 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.[1] However, the PB processes are significantly influenced by human activities, which have proliferated since the mid-20th century, causing Earth to transgress seven out of the nine Planetary Boundaries today. This "Great Acceleration"[2] (Fig. 6) 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[1] and refined in 2015[3] and 2023[4] following significant scientific advancements across all disciplines involved. Since 2024, Planetary Boundaries Science (PBScience) publishes 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. 2.1).
- 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.

Human activities, especially since the mid-20th century, have driven the transgression of seven of the nine Planetary Boundaries.

1.2 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. PBs assessments use representative variables, called "control variables", to describe the state of all nine crucial Earth system processes. 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. 2. To date, the PBs framework uses 1-2 control variables per PB (see tables in Ch. 6.1).

Climate Change

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

1

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.

2

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.

3

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.

4

5

Modification of Biogeochemical Flows

The disruption of natural nutrient cycles, such as nitrogen and phosphorus, affects soil health and water quality, potentially triggering dead zones in freshwater and marine systems.

6

Ocean Acidification

Changes in ocean conditions, such as acidification, impact marine biodiversity and the ocean's capacity to regulate climate.

7

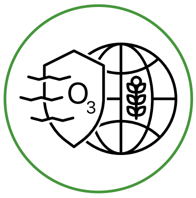
Increase in Atmospheric Aerosol Loading

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

8

Stratospheric Ozone Depletion

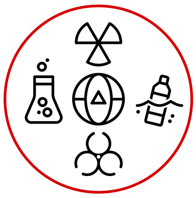
The thinning of the ozone layer in the upper atmosphere, primarily due to human-made chemicals, increases harmful UV radiation that can reach Earth's surface.



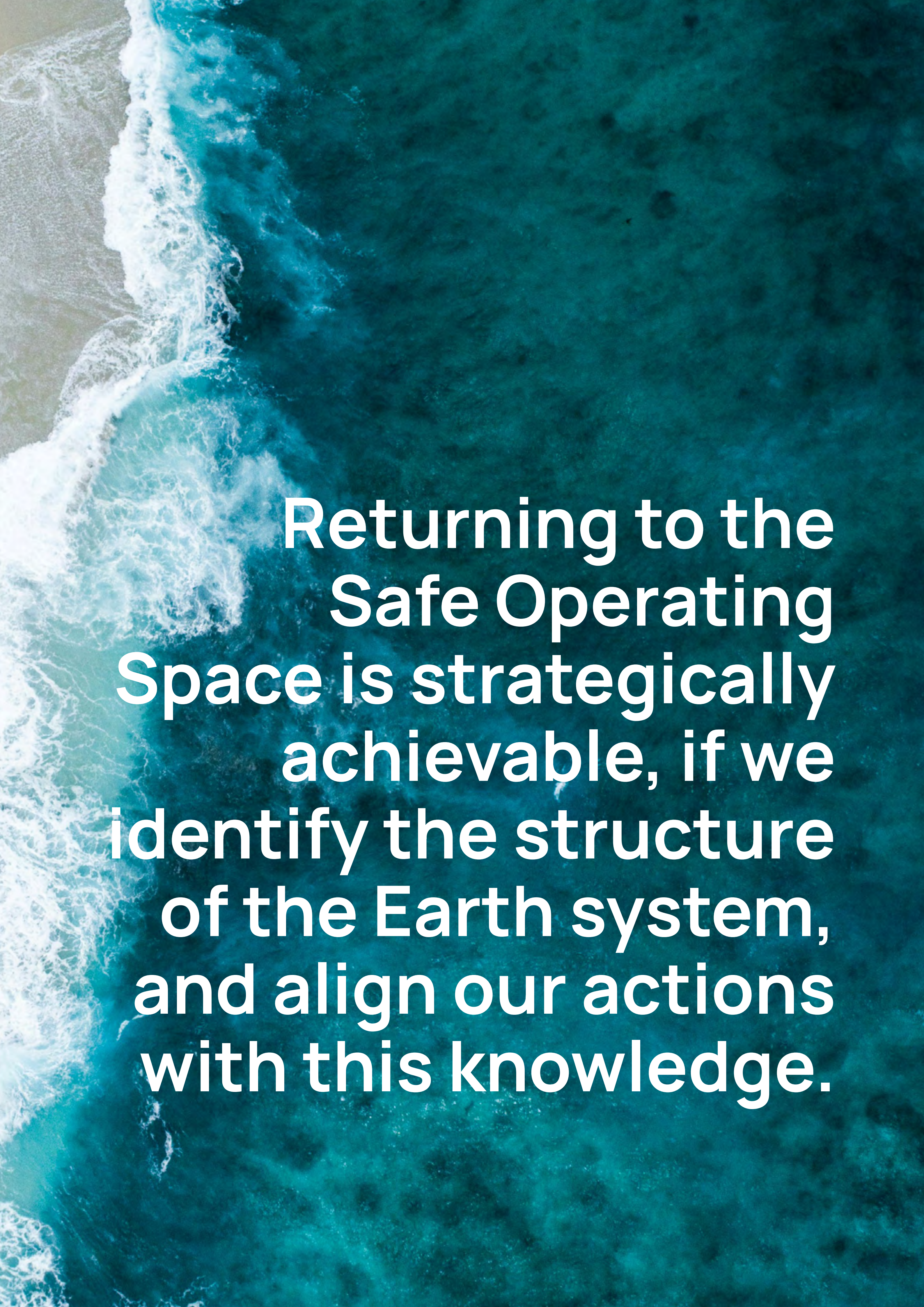
9

Introduction of Novel Entities

The introduction and accumulation of human-made substances, such as plastics and synthetic chemicals, along with the alteration of the biogeochemical cycling of naturally occurring elements, can disrupt other 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. 4).



Returning to the Safe Operating Space is strategically achievable, if we identify the structure of the Earth system, and align our actions with this knowledge.

1.3 Planetary Health Check 2025 at a Glance

Seven out of the nine Planetary Boundaries (PBs) have been breached, indicating significant environmental stress and potential for irreversible changes (Figs. 1 & 2). 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.
- **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 2025 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. 1). By re-arranging the Planetary Boundaries diagram into a collection of bar charts resembling a blood test result, the official Planetary Health Check Diagram (Fig. 2) 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. 3) is a summary of this diagram, in the form of a box plot. How to read the diagrams is explained in Info Box 1.

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 (see also Ch. 2.1) 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, liveable 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 top-level 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. 2.3). At a lower level, this damage involves destabilising specific PB processes and undermining PB 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.[4]

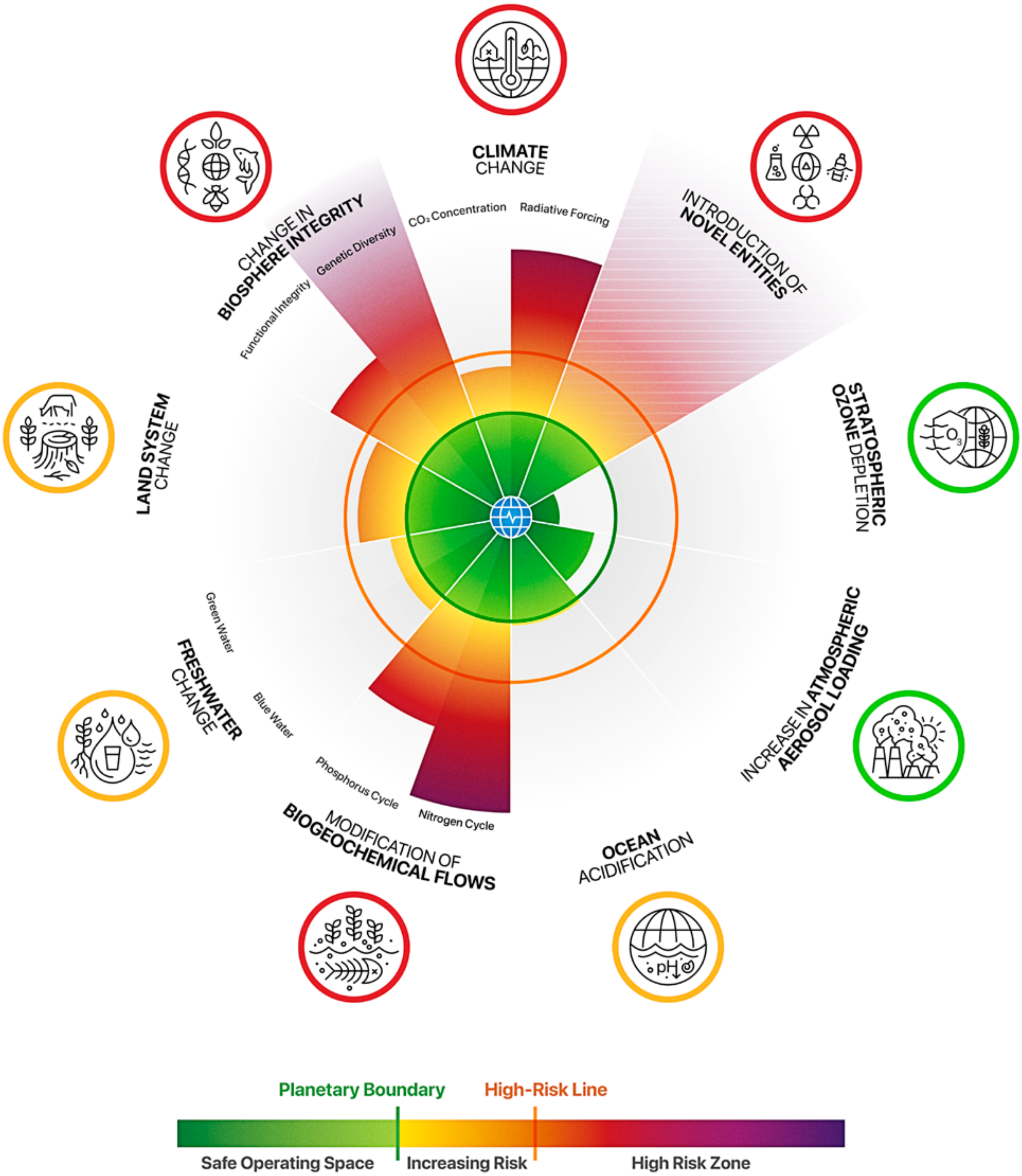


FIGURE 1 - **The iconic Planetary Boundaries (PBs) diagram** visually represents the current status of the nine PB processes that regulate our planet's health. Each process is quantified by one or more control variables based on observational data, model simulations and expert opinions.

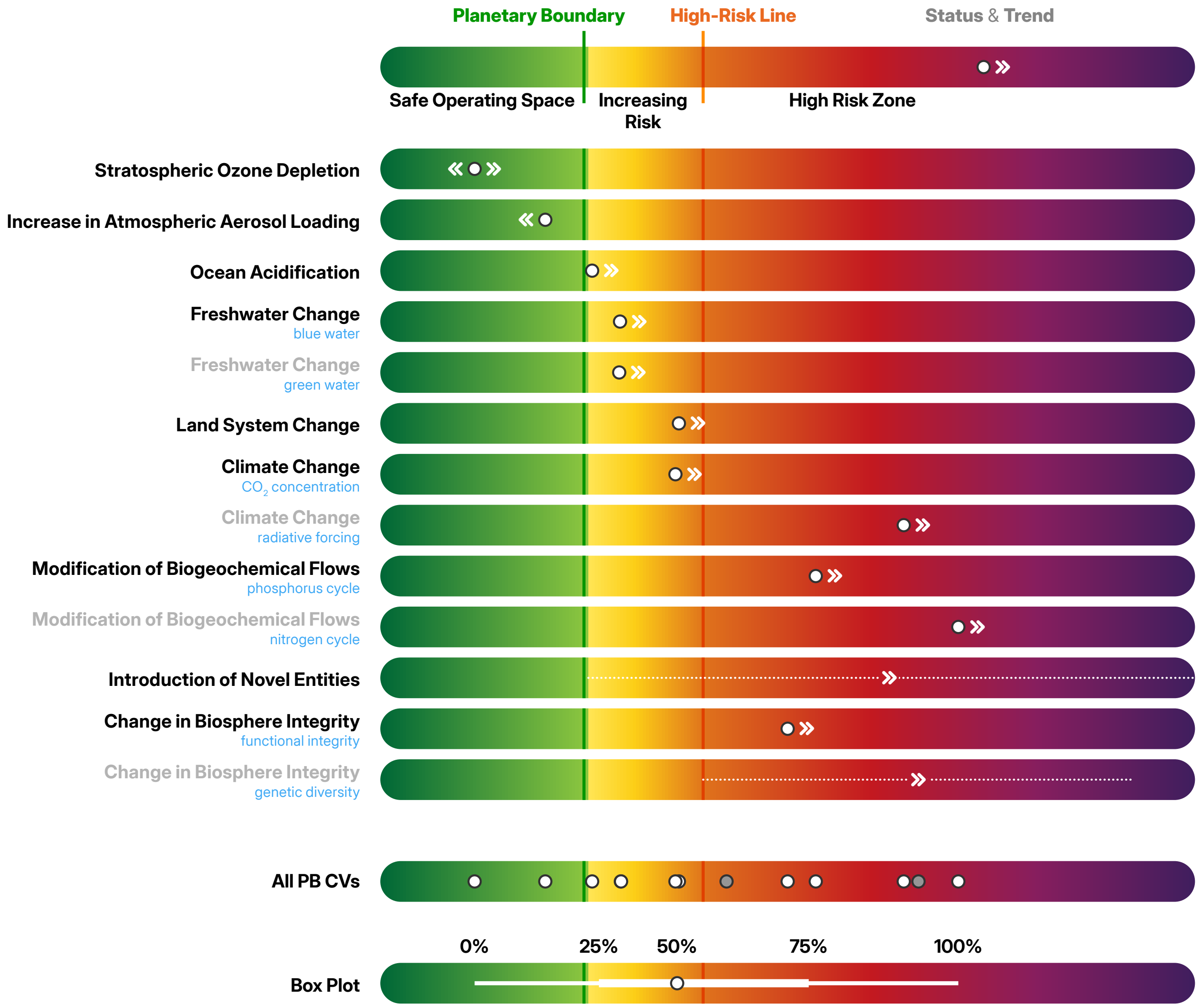


FIGURE 2 - Planetary health at a glance. Just as a blood test provides insights into a human body's health and identifies areas of concern, this Planetary Health Check evaluates the 13 control variables across the 9 Planetary Boundary (PB) processes to report on Earth's stability, resilience, and life-support 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. 3) 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 final assessment of the health of the Planet in 2025, when integrating the position of all nine Planetary Boundaries, is that we are in danger, with the planet placed at the upper end of the (yellow) danger zone, pushing closer to the (red) high risk zone (Fig. 3). The 2025 assessment shows that we continue moving closer to the point where the planet as a whole exceeds the danger zone and enters the zone of high risk (with higher certainty of large scale and irreversible changes). Nevertheless, Earth's current health – through its still remarkable biological, physical, and chemical resilience – keeps the window open for returning to a safe operating space, although that window is closing fast.

FIGURE 3 - 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. 1 and 2). 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.

1.4 What's New in This Year's Report

General Advances

The Planetary Health Check (PHC) aims to provide the most up-to-date and policy-relevant assessment of the state of our Planetary Boundaries. Building on the first edition published in 2024, this year's report updates and expands the Planetary Boundaries assessment, explores new scientific directions for evolving the framework, and features improved explanatory chapters as well as "spotlights chapters" into specific relevant topics. This work is made possible through the broad expertise of an international team of authors, which has doubled in size since last year.

Improvements in this year's report include:

- Improved spatial resolution: PHC2025 introduces more spatially explicit data products (e.g., temperature/emissions attribution maps, freshwater basin-scale maps, ecosystem risk zones).
- More model-based and multi-variable diagnostics: New tools like the SEED Index and EcoRisk indicator expand assessment beyond the classical control variables.
- First application of attribution frameworks (e.g. for extreme weather and fossil emissions).
- Stronger focus on early warning and tipping risk concepts, especially for biosphere and climate processes.
- The ocean is more centrally featured, both as a newly transgressed boundary (**Ocean Acidification**) and as an integral part of the Earth system.

Spotlights: Exploring Risks and Responses

This year's report includes three spotlight chapters that connect boundary transgressions to real-world risks and opportunities for transformation:

The Ocean: The Unsung Guardian of Planetary Health: Amid record-breaking ocean heat and mass coral bleaching, we spotlight the ocean's vital but underrecognized role in regulating Earth's climate and supporting life. As pressures mount (from warming and acidification to biodiversity loss), integrating the ocean into Earth system governance becomes more urgent than ever.

Extreme Weather and Disasters in 2024/25 – An Attribution-Based Perspective: 2024 was the first year with global temperatures exceeding 1.5 °C, unleashing deadly extreme weather. But climate alone does not tell the full story. Interactions with ecological degradation and deep social vulnerabilities amplify these disasters, underscoring the need for integrated, justice-centered responses.

Putting Planetary Boundaries to Work: Emerging Practices, Actors and Tools: A growing number of governments, cities, businesses, and civil society actors are beginning to operationalize the Planetary Boundaries framework. From climate goals and land use to financial disclosure and risk management, this systems-based shift shows how global thresholds can be translated into meaningful action.

Boundary-by-Boundary: What's New in the 2025 Information Sheets

Planetary Boundary	What's New in 2025
Climate Change	New headline values (CO_2 423 ppm, RF ~+2.97 W/m^2); global attribution maps; consideration of CH_4 and N_2O; early-warning indicators flagged (e.g. ocean heat)
Change in Biosphere Integrity	New SEED Index and EcoRisk prototype maps; marine biosphere inclusion discussed
Land-System Change	Recommendation to add forest quality, connectivity, degradation, fragmentation; biome area data update flagged
Freshwater Change	New ISIMIP3a baseline (119 years); updated thresholds and values; new spatial maps; focus on blue/green water and climate feedbacks
Modification of Biogeochemical Flows	Proposal to shift toward surplus-based control variables; inclusion of fossil-fuel reactive N; expanded discussion on inefficiencies and legacy loads
Ocean Acidification	New aragonite baseline (Ω_{1750} = 3.57); tighter boundary (Ω = 2.86); **transgression noted for the first time**; biological monitoring proposed
Increase in Atmospheric Aerosol Loading	Higher-resolution, chemically disaggregated AOD data; emphasis on $PM_{2.5}$ health inequity; no boundary change
Stratospheric Ozone Depletion	Links to Southern Hemisphere circulation; rocket launches and satellite debris flagged as emerging risks
Introduction of Novel Entities	Suggestions of measurable indicators for plastics, GMOs, etc.; proposal of "community completeness" as a systemic ecological signal

1.5 Assessing Planetary Boundaries

Planetary Boundary (PB) control variables are measured in complex and multifaceted ways, often requiring a diverse array of observational methods and technologies across various scientific disciplines. From satellites orbiting high above the Earth's surface to sensors buried deep in the ground to simulation models on high performance computers, scientists employ numerous techniques to study the Earth system.[5] These observations are crucial for monitoring the state of all PBs. The methods used depend on several factors, including the part of the Earth system being assessed and different requirements like the temporal and spatial resolution.[6]

Each assessment method faces challenges, such as technological limitations, environmental conditions, and data interpretation complexities, which must be managed to ensure the data's accuracy and reliability.

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

- **Ground-Based Observations**: Directly recording information from the Earth's dynamics, including biological and ecological monitoring or soil moisture measurements. For example, the US National Oceanic and Atmospheric Administration (NOAA) has monitored atmospheric CO_2 concentrations at the Mauna Loa Observatory in Hawaii at daily resolution since the late 1950s. In-situ measurements and observations are considered highly precise and accurate when it comes to data acquisition; however, their coverage is often limited in both time and space, and they can be expensive and labor-intensive to collect.[7]

- **Remote Sensing**: Collecting data using satellites or flying platforms, for variables such as forest cover and soil moisture. For example, the Soil Moisture and Ocean Salinity (SMOS) mission, operated by the European Space Agency, has significantly enhanced our understanding of the global water cycle and improved weather forecasting capabilities. Satellite-based remote sensing can provide extensive and continuous coverage across both space and time. However, many control variables, such as those related to nitrogen and phosphorus flows, are not directly observable from space, making it necessary to integrate multiple measurement methods for a comprehensive assessment of PBs.[8]

- **Earth System Modeling**: In the context of PBs, using computer models that simulate how different parts of the Earth, such as the atmosphere, oceans, and ecosystems, interact over time and space. These models can be used to estimate control variables like green and blue water flow, which are not directly measurable.[9]

- **Data Integration and Statistical Modeling**: Integrating data from various sources, and supplementing them with statistical modeling is often needed to fill data gaps over time and space, or to set reference values.

Using Artificial Intelligence to Monitor the Planet

Artificial intelligence (AI) presents a promising avenue for more seamless data integration and improved accuracy in Earth system assessments.[10] 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 dynamics, and uncover patterns across vast areas. AI-powered systems that monitor the Earth in near-real time are already transforming how we track key environmental changes. Applications now span sub-daily CO_2 emissions estimates,[11] biomass modeling[12], ecosystem stress detection, and more. Using AI techniques to combine satellite data, historical climate records, and activity-based signals could improve how quickly and precisely we can monitor changes across the land, ocean, atmosphere, and living systems.

Monitoring Planetary Boundary control variables requires integrating diverse methods, including ground-based sensors, satellites, Earth system models and AI, to provide accurate and timely assessments of the planet's health.

In this context, one of the primary objectives of the Planetary Boundaries Science (PBScience) Lab is the development of a "Planetary Mission Control Center" platform (see also Ch. 5). This platform aims to harness advanced AI approaches and to analyze and integrate multi-source datasets, delivering annual, and ideally near-real time assessments of PBs. Such a platform could serve as an interactive decision-support environment, assisting policymakers and stakeholders to make informed, evidence-based decisions. With faster, more detailed information, we can respond more quickly to environmental challenges and better protect people and our planet.

Conclusion

Due to the size and complexity of observing the whole planet, PBScience relies on external partners from the different Earth observation communities to provide data. One of our main goals is to ensure that the PHC is based on continuous, high-quality data streams for each of the PB control variables. In this report, we list some of the most up-to-date data sources available (see also Tab. 4 in Ch. 6.1).

We are committed to improve and increasingly automate the assessment and monitoring workflow, and are actively seeking new partners for Earth system observation and analysis – both for conventional and AI-based methods. PBScience is always open for new partners and encourages any engagement.

2

A Safe Operating Space for Humanity

2.1 Humanity's Journey on Earth

The **Safe Operating Space** is an Earth system state that allows humanity to develop and thrive for generations to come.[1,4,3] It includes conditions similar, though not necessarily identical, 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 warm planetary conditions compared to the colder and more variable environmental, ice age conditions in the preceding Pleistocene (Fig. 4).[13]

The challenge for humanity is to sustain the healthy functions that keep our planet in a relatively warm, stable, interglacial state, as characterized by the Holocene. Scientific evidence suggests that if we avoid crossing too many irreversible tipping points – which could lead to self-amplified warming and the deterioration of life-support systems on Earth – we will likely have another 50,000 years of a Holocene-like planet, before Earth naturally moves toward the next ice age.[14] It is this stable interglacial state, the Holocene, during which agriculture and modern civilizations developed. Human activities of the last centuries are, however, shifting the Earth system away from such a stable state at an alarming rate (Fig. 5).

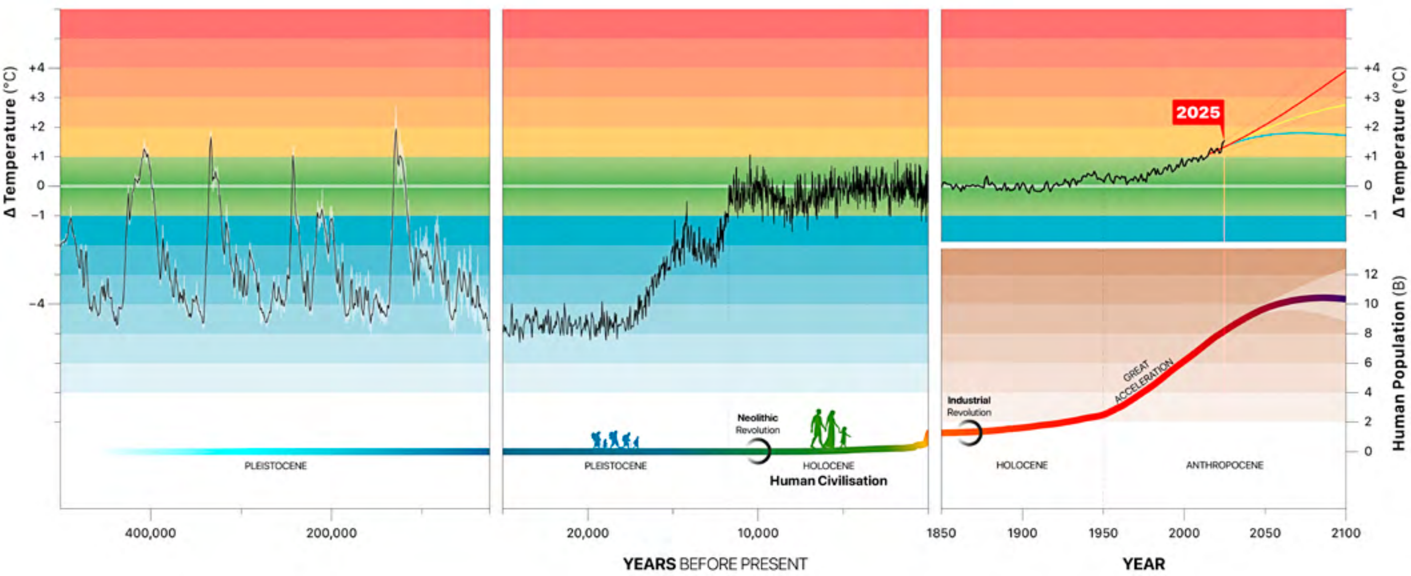


FIGURE 4 - Humanity's journey on Earth – Human population size and global temperature from 500,000 years before present (BP) until 2100. The figure is a composite of different data sets including paleo data estimates, recent measurements, and future projections. For a full detailed description of this figure, please see Supplementary Materials. Data from: Jouzel et al. 2007,[15] Masson-Delmotte et al. 2010,[16] Morice et al. 2021,[17] Osborn and Jones 2014,[18] CRU 2024,[19] IPCC Summary for Policymakers 2021,[20] Fyfe et al. 2024,[21] Ritchie et al. 2024,[22] Sjödin et al. 2012,[23] UN World Population prospects 2022.[24]

***Key takeaway:** For over 10,000 years, humanity lived in a very stable climatic period (the green corridor) in which it evolved and adapted its technologies and cultures. By transgressing several Planetary Boundaries, including the one for Climate Change, this period has ended, and we are entering a new and dangerous terrain in which a still-growing world population must safeguard human well-being.*

From Holocene to Anthropocene

During the Holocene Epoch, large parts of the Earth experienced predictably moderate climates,[25,26,27] which were suitable for agriculture and settlement. Freshwater was consistently available across many regions, although with pronounced regional patterns and intermittent shifts in large-scale circulation patterns.[28,29] Biogeochemical cycles (such as carbon, nitrogen, and phosphorus) operated within balanced ranges, sustaining plant nutrients and ecosystem health. While biodiversity during the Holocene was subject to various fluctuations,[30] the Holocene is considered an epoch of high biological resilience,[31] 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.[24] In recent decades, human activities have intensified,[2] potentially surpassing Earth's capacity to sustain its stability. This shift marks the beginning of the Anthropocene, a period characterised by our dependence on fossil fuels, industrial agriculture, and the unsustainable use of resources which disrupts Earth's delicate balance. This has led to rapidly increasing pressures on the planet, a phenomenon known as the "Great Acceleration" (Fig. 5).[2] Respecting Planetary Boundaries is of critical importance to safely navigate the Anthropocene and ensure sustainable development for future generations in a stable and resilient Earth system.

From Safe to Safe and Just Operating Space

In 2023, the Earth Commission published its concept of "Safe and Just Earth System Boundaries."[259] Building on the Planetary Boundaries, 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 are already facing severe climate-related impacts below this threshold. Accordingly, the just boundary is set at 1.0°C of warming, which already is 100% higher than the warmest temperature on Earth since human civilisations started 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. 5) shows that the frameworks broadly agree on boundary transgressions – demonstrating the robustness of the two approaches.

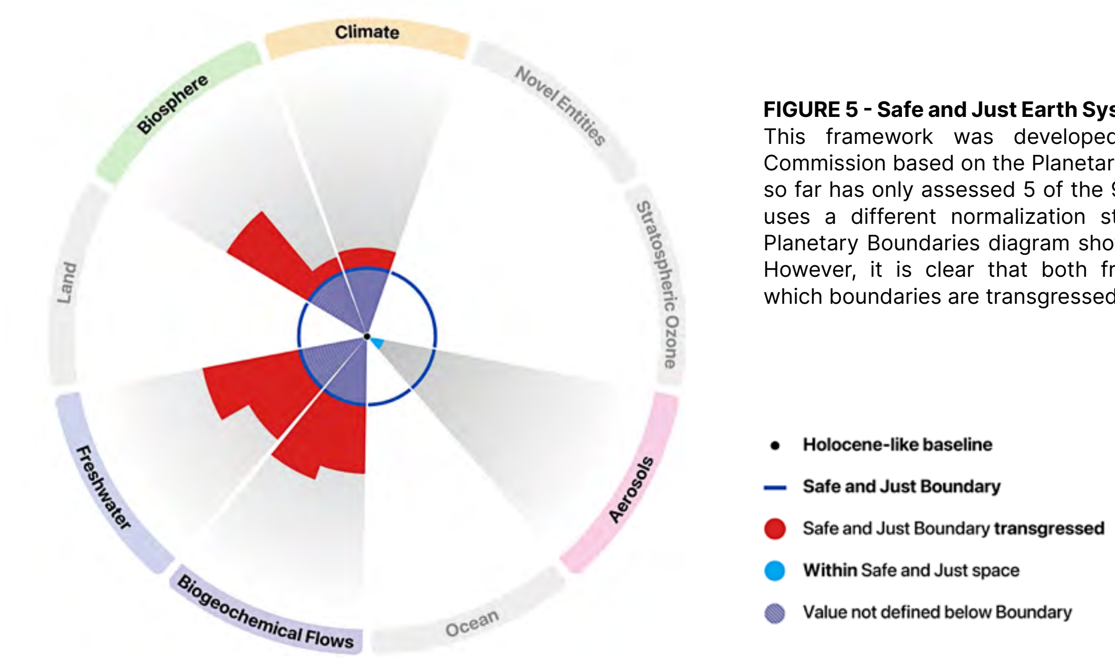


FIGURE 5 - Safe and Just Earth System Boundaries. This framework was developed by the Earth Commission based on the Planetary Boundaries and so far has only assessed 5 of the 9 PBs. This figure uses a different normalization strategy than the Planetary Boundaries diagram shown in this report. However,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

The Great Acceleration

Socio-Economic Trends Since 1750

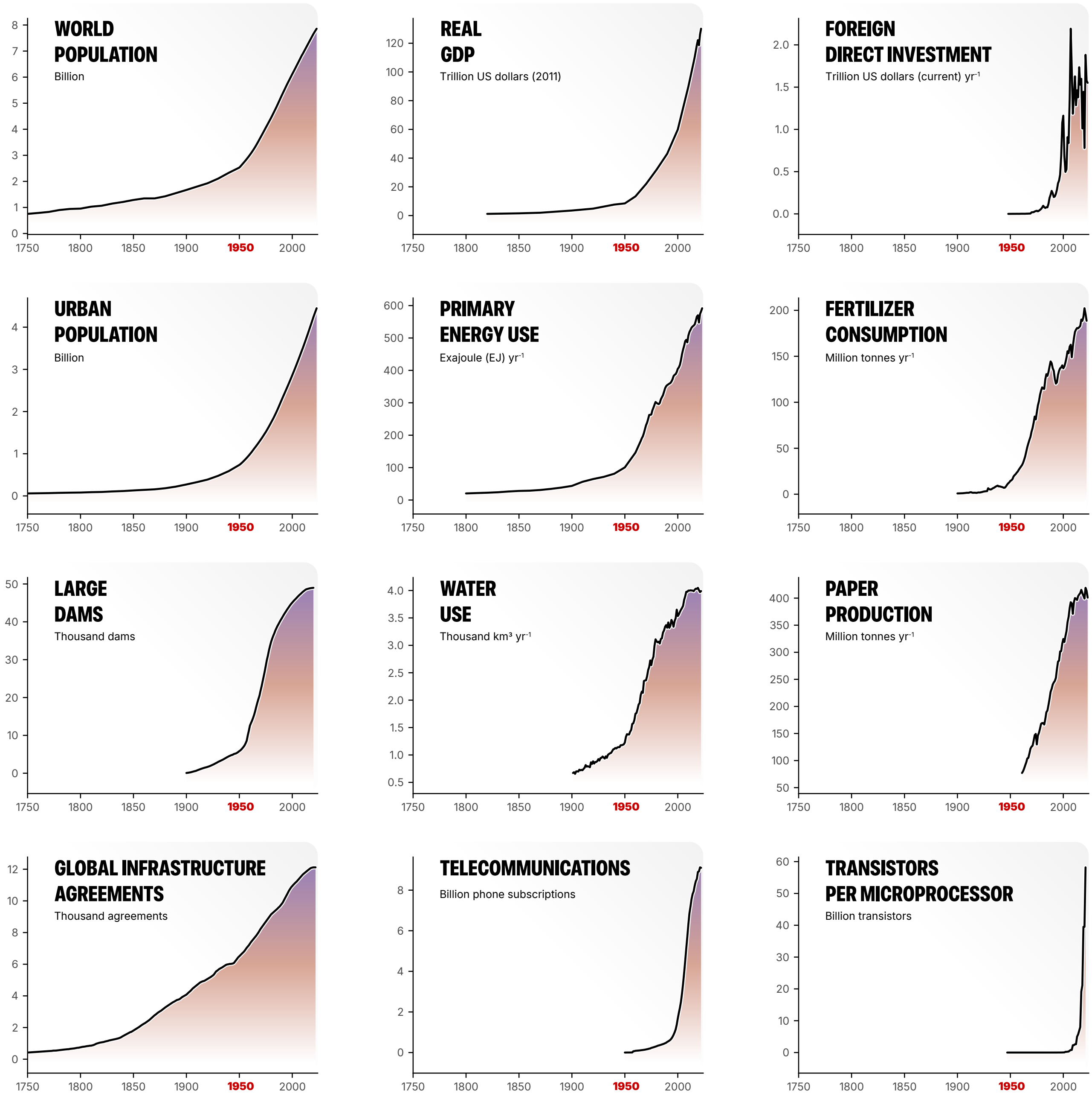
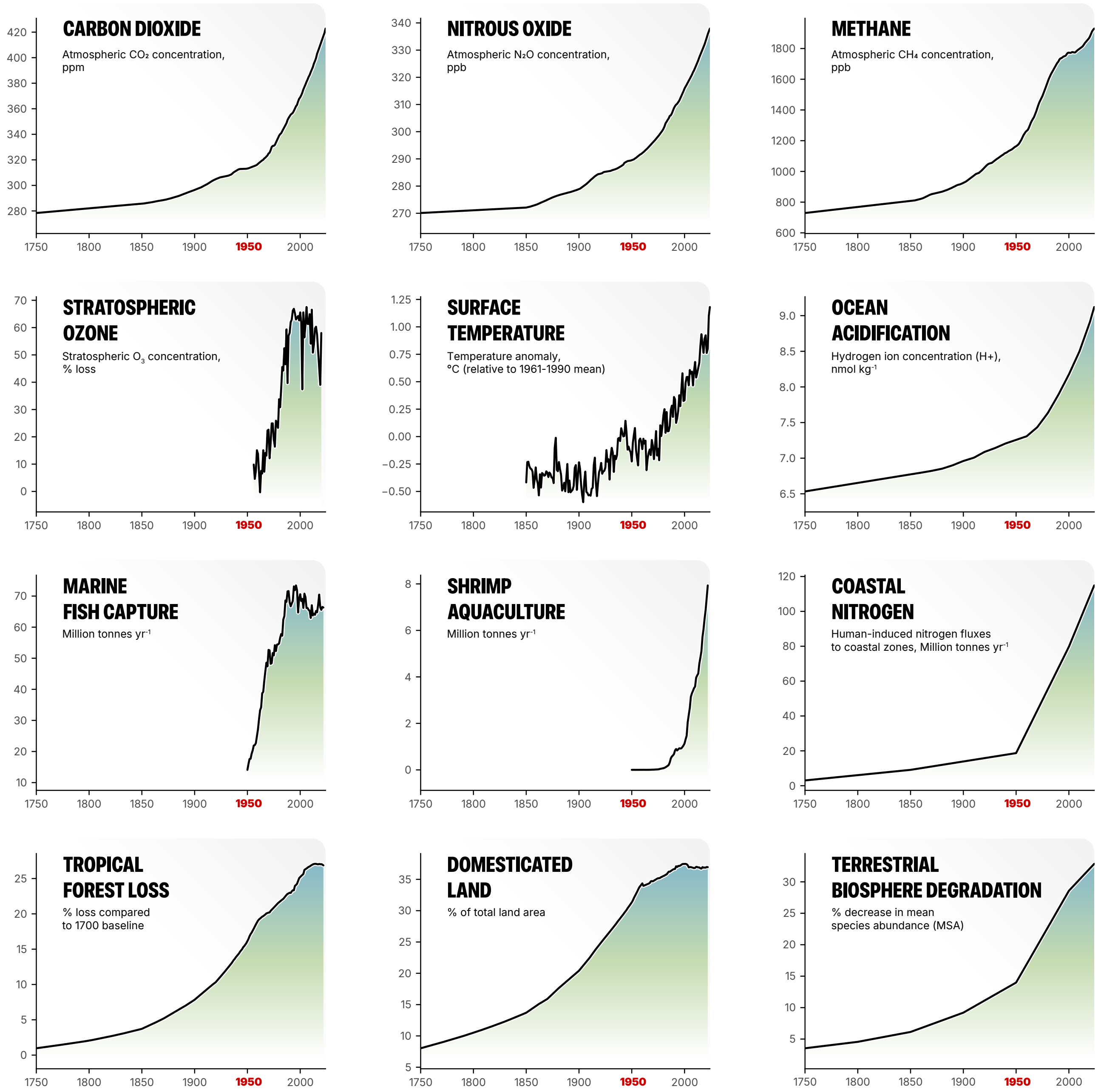


FIGURE 6 - The Great Acceleration - Recent dramatic trends in the Earth system. This updated figure extends the original "Great Acceleration" analysis by Steffen et al. (2015)[3] with new data up to 2024, incorporating new datasets and, in some cases, revised or additional indicators. For a list of data sources, see Supplementary Materials. The left-hand side shows the exponential 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, ocean acidification, and biodiversity decline. These coupled trends, which accelerated markedly after 1950, signify the onset of the Anthropocene and highlight the intensifying

Earth System Trends Since 1750



pressure humans place on planetary systems. Updating these trajectories reinforces the urgency of remaining within the Planetary Boundaries to safeguard Earth's resilience. 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, underscoring the intensifying human pressure on planetary systems. These coupled trajectories define the post-1950 onset of the Anthropocene and reinforce the urgency of respecting the Planetary Boundaries to protect Earth's resilience.

2.2 Planetary Stability and Resilience

The Earth system possesses an intrinsic capacity for self-regulation that can absorb disturbances, adapt, and maintain the Holocene-like conditions we now enjoy. So far, it has helped to avoid crossing critical thresholds that could lead to irreversible change due to human pressures. This buffering capacity is created by the tightly intertwined interactions and feedbacks connecting life, climate and other planetary systems on Earth. These regulatory dynamics are evident in the relative stability of past climates such as the interglacial states of the Pleistocene and Holocene, and a general tendency for greater stability as life has evolved over geological time.[32,33] Earth's resilience (more precisely, the resilience of the Holocene-like Earth system regime) refers to its ability to maintain conditions supportive to life in the face of natural variability and human-induced pressures (Info Box 2). However, paleoclimate research shows that planetary resilience has been reduced during natural global warming events of the past tens of millions of years. This illustrates the potential for destabilization of Earth system climate regimes.[34]

Over the past 150 years, Earth's resilience has absorbed more than half of human greenhouse gas emissions by sequestering them in land and ocean carbon sinks.[35] However, recently there are increasing signs that cracks are emerging in this buffering capacity,[36] including a weakening of natural carbon sinks,[37,38,39,40,41] rapid global warming in 2023 and 2024,[42,43] albedo changes and shifts in cloud feedbacks.[44] This planetary-scale loss of resilience is accompanied and potentially reinforced by an increasing number of local to regional-scale regime shifts in ecosystems.[45,46] In parallel, Earth system tipping elements (see Ch. 2.3) show early warning signs of declining resilience, increasing the risk of abrupt and potentially irreversible transitions.[47,48,49]

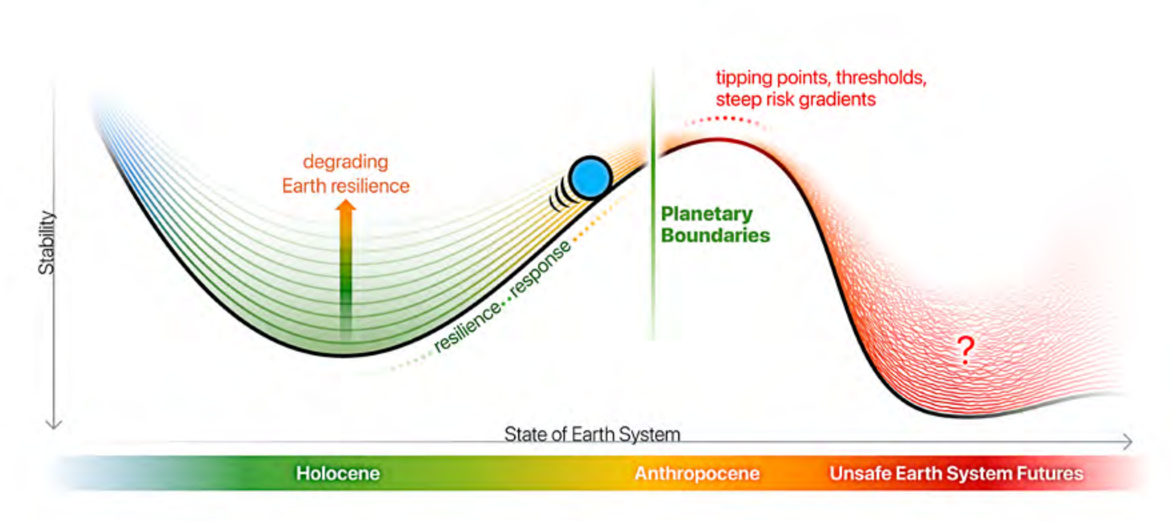
The recent acceleration of the effects of human actions on Earth is challenging the stability of the current climate-biosphere regime. Currently, major human influences, including greenhouse gas emissions and large-scale land-use changes, are destabilizing the Earth system. These changes are driving a shift from the relatively stable conditions of the last 12,000 years (called the Holocene) into the new era of the Anthropocene, where humanity has become a planetary force of change.[50] However, we still know little about how resilient our planet will be in the future as people and nature continue to interact in complex ways (see Info Box 2). At present, we can only conclude that our current trajectory is unprecedented – but a more stable Holocene-like state is still within reach. It is unclear how and under which conditions increasing human pressures could unleash reinforcing feedback loops and tipping dynamics that could cause irreversible shifts away from the Earth's current state (Info Box 2; see also Fig. 2 in Ch. 2.3). Understanding what might cause such a shift and how it would unfold remains an open, challenging, and critical scientific question.

Substantial knowledge gaps remain in the processes and feedback mechanisms contributing to the Earth system's stability and resilience responses on different temporal and spatial scales,[51] particularly regarding the role of the biosphere (in which humans are embedded) and intertwined climate-biosphere interactions. Better understanding and quantifying Earth resilience, hand in hand with advancing research on Earth system tipping points, is essential to better inform Planetary Boundaries and to direct ways for various actors to regenerate planetary health.

INFO BOX 2

Earth Resilience

Earth resilience is the capacity of the biogeophysical Earth system to absorb human pressures (anthropogenic greenhouse gas emissions, degradation of biosphere integrity, land use changes, etc.) such that the system remains in (or returns to) a Holocene-like state. Only this state can provide the essential structures and functions that are the foundation for sustainable development of human societies. Staying within a habitable Holocene-like state will require active stewardship to revitalize and strengthen Earth's resilience.



2.3 Tipping Points in the Earth System

Tipping points are built-in thresholds in individual, large-scale Earth system components such as the Amazon rainforest or the Atlantic Meridional Overturning Circulation (AMOC). Beyond such a threshold – e.g., a critical level of global warming or regional deforestation – the dynamics of the system change fundamentally, shifting from a set of feedbacks that keep the system stable to another set that forces the system into an entirely new state (see Info Box 3). These feedbacks thus reinforce any initial, small changes, amplifying them to the extent that the system evolves in a self-perpetuating fashion. The consequence is that even gradual changes in forcing or internal variability can lead to an abrupt response, with substantial, widespread and long-lasting impacts.[52,53,54,55]

Imagine a tipping point as a cliff at the end of a road. If a driver continues without braking, they may drive over the cliff, a point from which it is quite difficult (if not impossible) to return. Tipping points are properties of the biophysical system, marking the border between two qualitatively different versions of the system. Scientific uncertainty about the potential existence and location of the tipping point, i.e. the critical level of global warming or land use change, means that we have indications for where this cliff might be for specific systems, but do not yet know with certainty.

In this analogy, Planetary Boundaries serve as stop signs on the road, which ensure safety and avoid pushing Earth's systems too far. They define and quantify the safe levels of change for all biophysical processes that regulate the state, resilience, and life support on Earth. Within these boundaries, the Earth system may remain stable and continue to support human life as it exists today, and close to a Holocene state (see Fig. 7). Crossing a boundary does not imply immediate disaster, but it does increase the risk of serious and often unpredictable changes in Earth's systems.

Tipping points and Planetary Boundaries are related in that Planetary Boundaries can be set at a safe distance to avoid crossing tipping points. Tipping point science can therefore inform the safe boundary levels, complementing other lines of evidence such as the maximum range of variability over the past 12,000 years, known as the Holocene. The **Climate Change** boundary, which aims to keep global warming below levels that could trigger irreversible ice melt or ecosystem collapse, thus factors in the risk of crossing Earth system tipping points – a risk that increases strongly between 1-2°C of global warming above pre-industrial climate conditions. We have already entered this risk zone, and current emission trajectories take us even further into it, far beyond the safe level of 350 ppm CO_2 in the atmosphere. Similarly, scientific evidence suggests the risk of crossing biome tipping points for excessive land system change due to critical deforestation levels in the Amazon rainforest,[56] and regional regime shifts for transgression of the nutrient and freshwater boundaries. While there is a clear link between large-scale tipping points, more local regime shifts and the Planetary Boundaries framework,[3] a systematic quantification of the safe boundary levels based on tipping points science is subject to ongoing research.

The consequence is that even gradual changes in forcing or internal variability can lead to an abrupt non-gradual response, with substantial, widespread and long-lasting impacts.

Many of the Earth's systems feature feedback loops that could lead to tipping behaviour under continued anthropogenic pressures. Below and in Fig. 8, we highlight several examples of such feedback loops for selected systems. Comprehensive overviews can be found in Armstrong McKay et al (2022),[52] Lenton et al. (2023)[58] and the first Planetary Health Check.[57]

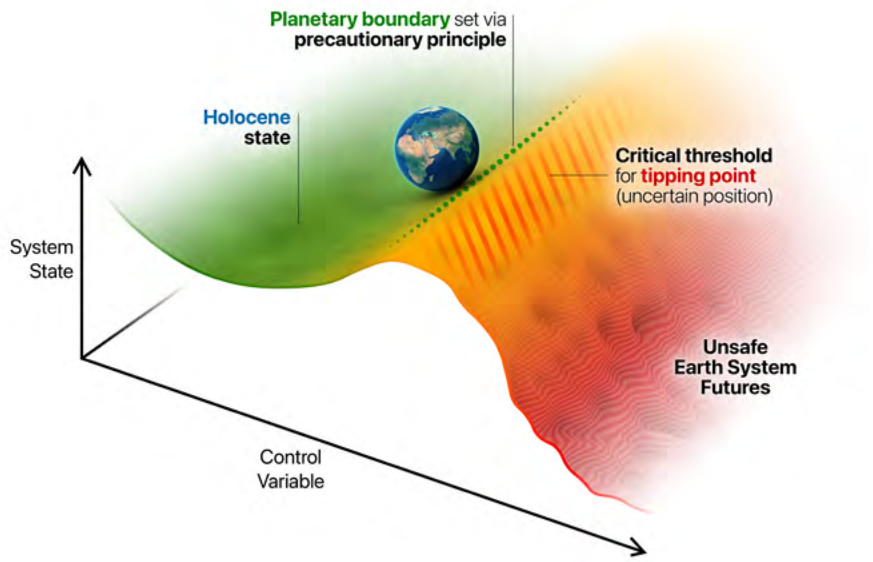


FIGURE 7 - Stylized stability landscape of the Earth system. Tipping points and Planetary Boundaries are interconnected – both address Earth system stability, but they serve distinct roles. Beyond a *tipping point*, a system fundamentally changes due to a shift in feedback dynamics: When stabilizing 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.

INFO BOX 3

Nonlinearities and Feedback Loops

How does a system – e.g., an ecosystem, machine, or social group – respond to external stimuli? Many of the systems around us respond ***non-linearly***, wherein gradually changing the external conditions does not lead to a gradual change in the system. Instead, the resulting change depends, in complicated ways, on the magnitude and/or rate of the external stimulus *and* the current state of the system.

Feedback loops can cause or perpetuate such non-linear behaviour. They can either keep things steady (negative feedback) or push them further away from their original state (positive feedback). A ***negative feedback*** counteracts changes and returns the system to its original state. It functions as a self-correcting or regulating mechanism. Therefore, negative feedbacks facilitate system stability and avoid drastic changes. Think of body temperature regulation as a real-world example: When you get hot, you sweat to cool down; when you get cold, you shiver to warm up. A ***positive feedback*** amplifies changes, pushing the system further from its starting point. Instead of correcting the change, it amplifies it. Positive feedbacks can thus destabilize systems, causing them to transition into new states, in often irreversible ways. A real-world example would be the audio feedback of a microphone that picks up sound from a speaker and sends it back through the speaker – the sound escalates to a high-pitched noise.

When there is a critical forcing threshold, beyond which positive (amplifying/destabilizing) feedbacks strengthen enough to outweigh the negative (stabilizing) feedbacks, we speak of a ***tipping point***[52,58] (see Fig. 7). Beyond this point, a tipping system rapidly and nonlinearly shifts to a new state from which it cannot easily return.

Understanding feedbacks, their mechanisms and consequences in a Planetary Boundaries context is therefore essential for mapping out the risk space associated with increasing forcing or system pressure. Where and when does a change in a control variable lead to a gradual response in parts of the Earth system? And where do we expect to push these components beyond a critical threshold, triggering nonlinear change?

On the planetary scale, this means that strong connections between different Planetary Boundaries and tipping elements are conceivable.

Among the most vulnerable potential tipping elements are parts of the Antarctic and Greenland ice sheets, warm-water coral reefs, regions of high-latitude permafrost and the oceanic gyre circulation in the North Atlantic (the Subpolar Gyre). For this shortlist, numerous studies and reviews estimate critical thresholds already in the range of 1-1.5°C global warming.[52] At temperatures that are likely to be reached within the 21st century (2°C and more), more systems are suspected to be at risk of tipping. In particular, the interactions of different tipping elements (via a cascade[59]) or a combination of stressors (such as climate change and land use) increase the tipping risk for a wider range of systems, such as the Amazon rainforest. These systems are all susceptible to the possibility that large, positive feedbacks will drive self-sustained change (see Fig. 8 for selected examples).

The different parts of the Earth system interact, such that changes in one system can change others (see Ch. 2.4). On the planetary scale, this means that strong connections between different Planetary Boundaries and tipping elements are conceivable. Here we sketch one possible interlinkage between the **Climate Change** boundary, two major tipping elements and the boundaries for **Change in Biosphere Integrity** and **Land System Change** (see Fig. 9).

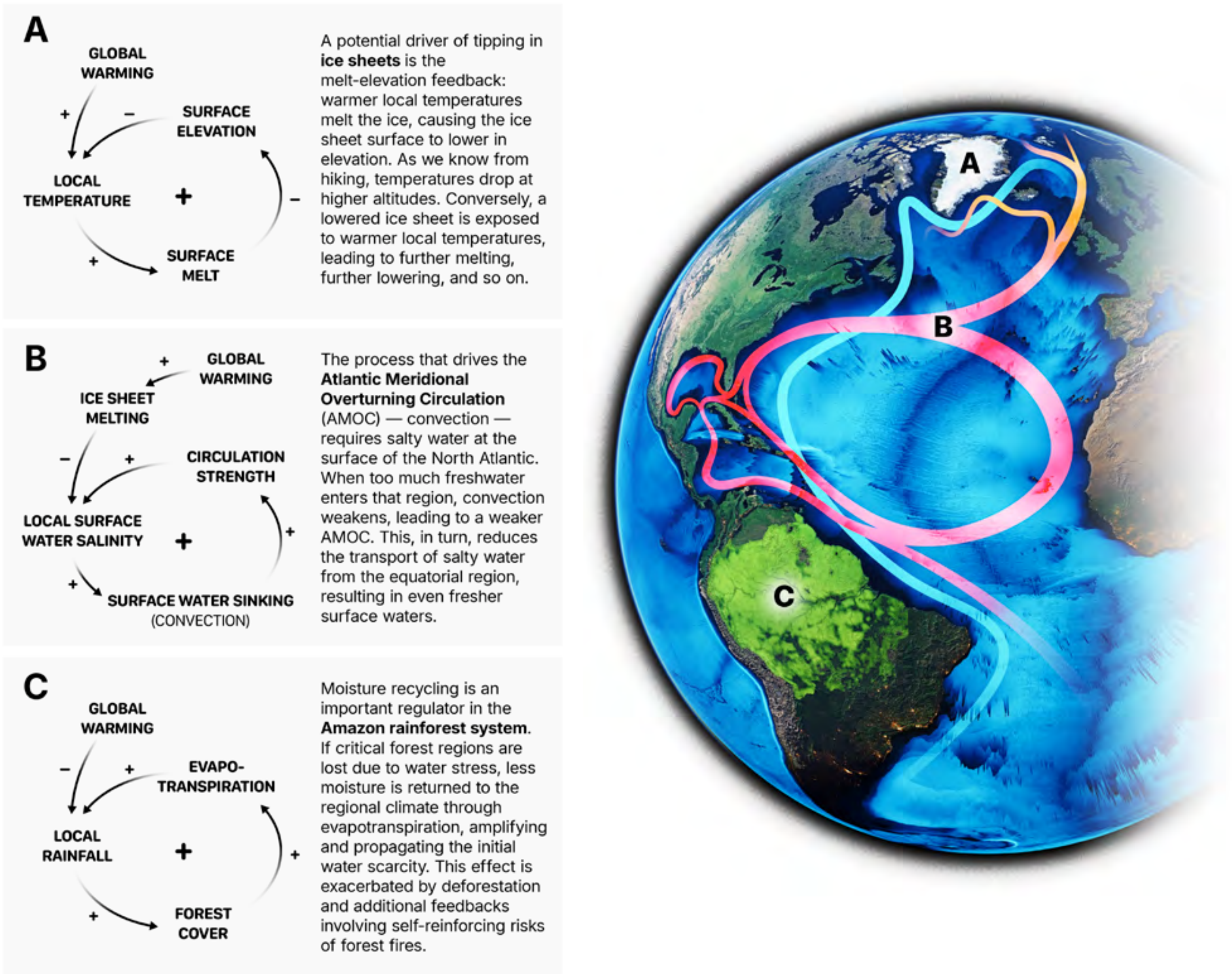


FIGURE 8 - Feedback loops leading to tipping points in the Earth system. The feedback mechanisms of three major tipping elements are shown. Arrows denote the influence from one element to another: Those marked with a plus show a strengthening influence – e.g., more forest cover leads to more evapotranspiration. Minus signs indicate a weakening influence – e.g., more global warming leads to less rainfall.

Earth's radiative balance is massively modified by human activity, primarily via the emission of greenhouse gases that accumulate in the atmosphere. As a consequence, the **Climate Change** boundary has been transgressed (step 1 in Fig. 9). This is evident from both control variables – atmospheric CO_2 concentration and total radiative forcing at the top of the atmosphere (see Ch. 4.1). The ensuing global warming reaches levels that take the planet deep into the risk zone of triggering several climate tipping elements.[94] For example, sustained current atmospheric CO_2 concentrations of 420 ppm, far beyond the safe level of 350 ppm, would lead to a warming of 2.5-3°C if continued unabated.[95]

This exceeds the critical temperature thresholds estimated for a wide range of tipping elements (step 2 in Fig. 9). For example, evidence suggests the potential for tipping behaviour at 1.5-2°C global warming for the Greenland ice sheet and convection in the subpolar ocean circulation gyre. The collapse of either system would have catastrophic consequences for the North Atlantic region (e.g., altered climate within Europe) and worldwide (e.g., sea level rise or changes in precipitation patterns). Furthermore, this would exert a destabilising pressure on the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is a vital ocean current in the Earth system, which plays a key role in the distribution of heat and energy between the northern and southern hemispheres. It is driven by temperature and salinity gradients in the North Atlantic, such that freshwater influx from melting ice sheets and changed climate conditions could weaken or potentially even collapse it.

Due to its contribution to heat and freshwater transport between the North Atlantic and the tropics, the AMOC is a key link in potential chain reactions between tipping elements.[59] One such cascading interaction (see Ch. 2.4) could be Amazon rainforest tipping triggered by a weakening AMOC (step 3 in Fig. 9): A weakened AMOC may reduce Atlantic moisture transport into South America, shifting the Intertropical Convergence Zone (ITCZ) southward.[60,61] The ITCZ is an important source of rainfall necessary to maintain the Amazon biome, and even a slight shift can highly impact the region, albeit with stark regional differences.[62,63] Given that a significant fraction of the Amazon rainforest relies on an internally-driven moisture recycling network, destabilization following continued droughts could lead to a self-perpetuating rainforest system collapse.

A large-scale dieback of the Amazon rainforest system would have significant impacts beyond the region, not least via the release of carbon currently in the form of vegetation. The rainforest's core ecological functions like carbon sequestration, moisture recycling and providing wildlife habitats would be reduced. Furthermore, as the rainforest harbours more than 10% of global terrestrial biodiversity,[64] its loss would exacerbate the currently observed decrease in genetic diversity and functional integrity. It is clear that a tipping of the Amazon rainforest would significantly impact other boundaries like **Change in Biosphere Integrity** and **Land System Change** (step 4 in Fig. 9, see also Ch. 2.4).

This example singles out one potential cascade of Earth system changes, triggered by the transgression of the **Climate Change** boundary. Of course, the dynamics of the individual systems and their interactions can be stated only with limited confidence. For example, there is ample scientific evidence (including geological records) for the tipping potential of the AMOC, but the value of the critical temperature threshold

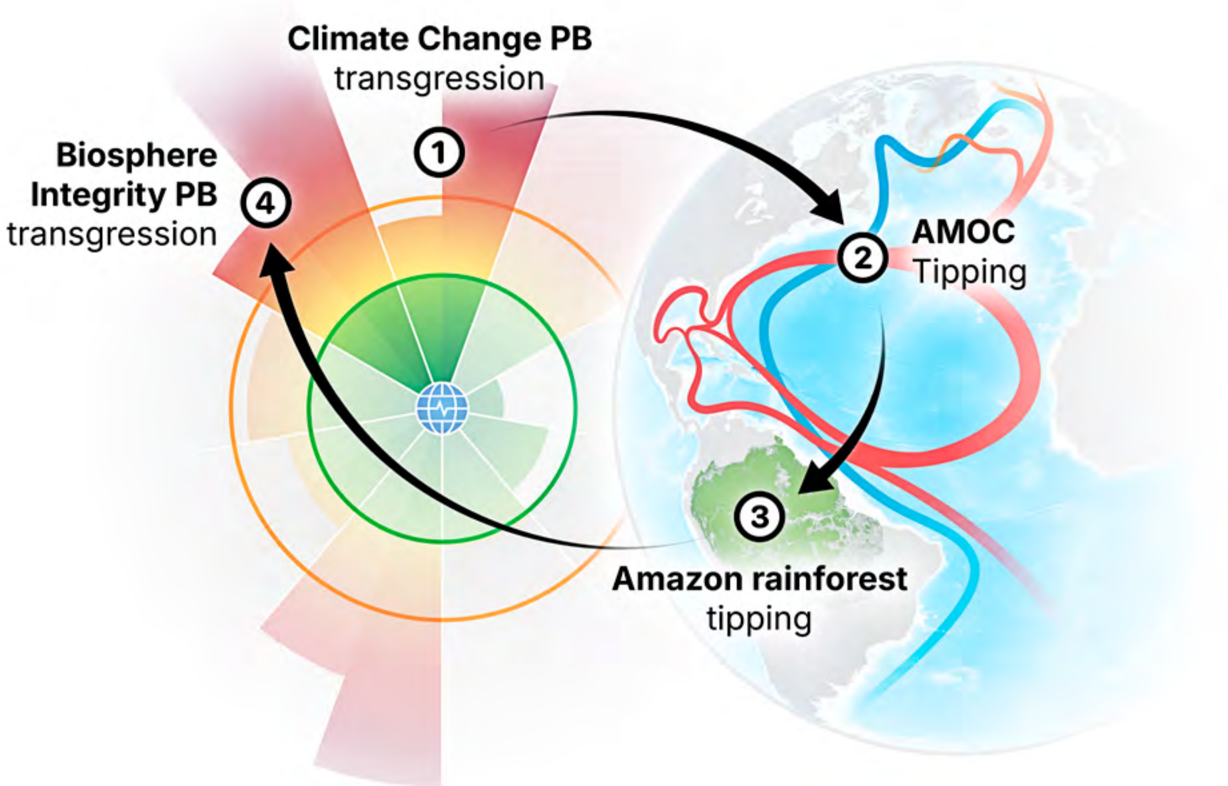


FIGURE 9 - Example of how different Planetary Boundaries and tipping elements may be linked in a cascade. Increasing **Climate Change** (1) triggers tipping dynamics in the Atlantic Meridional Overturning Circulation (AMOC; 2). This disturbs the precipitation patterns in the Amazon rainforest (3), leading to a tipping dynamic here as well and degrading **Biosphere Integrity** (4).

remains subject to active research.[65] It is clear however that the risk of crossing tipping points increases with increasing transgression of the **Climate Change** boundary.

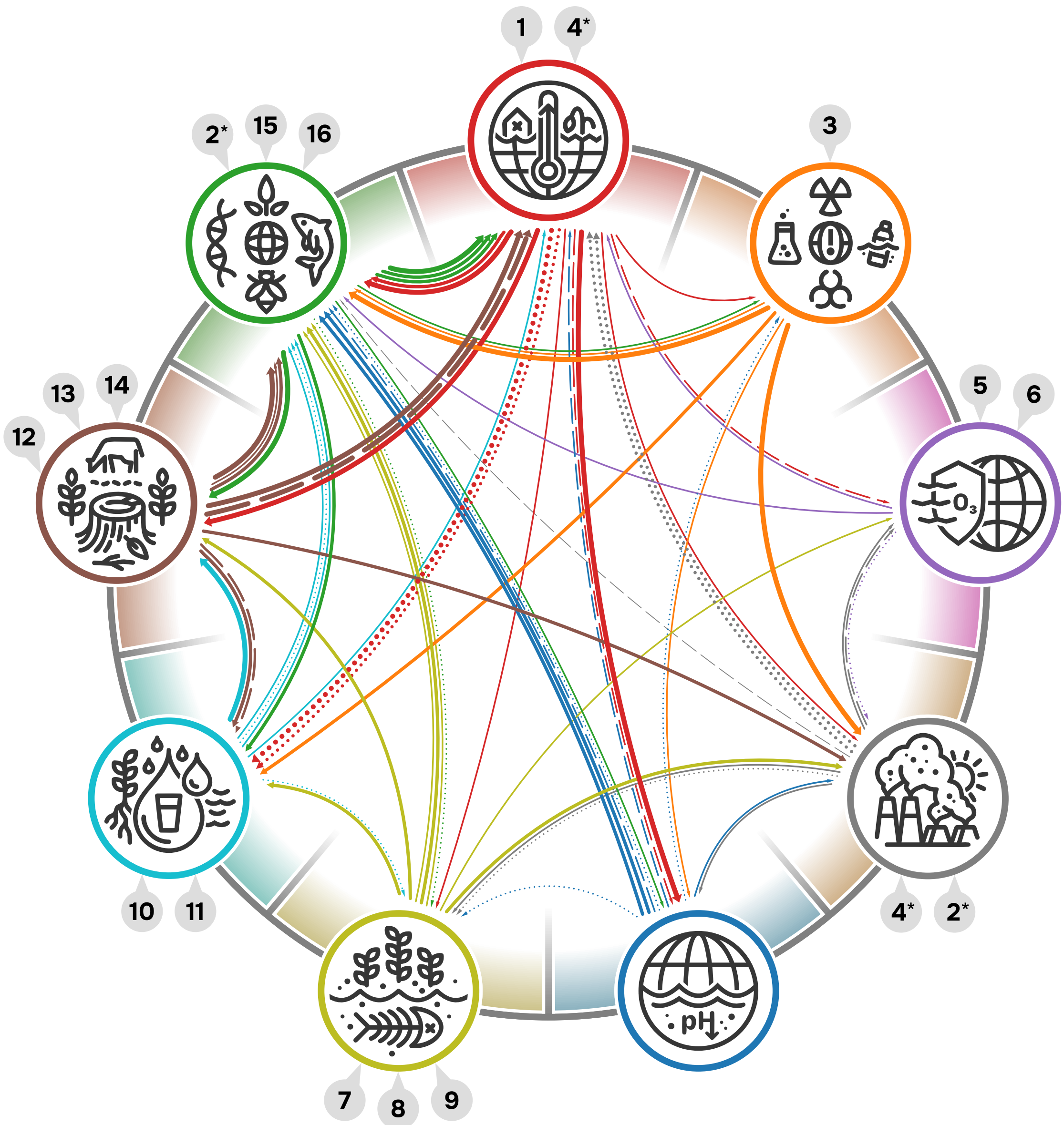
Many tipping systems are under pressure by multiple Planetary Boundary transgressions. For example, research shows that biodiversity is an important factor in maintaining the Amazon rainforest system's functioning.[66] Alongside climate-change-induced modifications to precipitation patterns, deforestation (captured by the **Land System Change** boundary) is the prime reason for forest degradation. A critical deforestation threshold of 40%, possibly leading to a tipping of the system, has been proposed,[56] which is effectively lowered to 20-25% when combined with global warming levels within the Paris range.[67]

In summary, science on tipping points can provide important information needed to set Planetary Boundary levels. To date, climate tipping points have been informing the **Climate Change** boundary, more regional regime shifts have informed the setting of other terrestrial Planetary Boundaries, and first assessments strive for a more comprehensive mapping of the other Planetary Boundaries to Earth system tipping points.[58] Going forward, dedicated modeling work and systematic quantifications of critical thresholds are needed – e.g, via the Tipping Points Modelling Intercomparison Project, TIPMIP.[55]

2.4 Interactions of Planetary Boundaries

Human activities have driven Earth beyond its Safe Operating Space.[1,3] This transgression is not due to individual single causes, but to a network of interlinked drivers like fossil fuel combustion, land use change, and unsustainable resource use that collectively push control variables, such as atmospheric CO_2 or species extinction rate, past safe thresholds for life on Earth. To confront these challenges, it is not enough to track symptoms. To find effective solutions, we must understand how the underlying drivers are all interlinked in, what we call, the causal network of the Earth system.[68,69,70,71,72] This network connects stressors and responses across domains: from local land degradation to regional hydrological shifts, from global trade patterns to atmospheric dynamics (Fig. 10).

Mapping and analyzing this network reveals not just where things go wrong, but also where and how they can be made right. In this chapter, we look at examples of how different Planetary Boundaries are linked through the causal network of the Earth system, and explore how a systems-based approach can reveal leverage points for making positive change.



PB INTERCONNECTIONS

COLOR — Planetary Boundaries

WIDTH — Interconnection Relevance

SOLID LINE — Connection increasing transgression

DASHED LINE — Connection decreasing transgression

DOTTED LINE — Connection with both effects possible

PB DRIVERS

* same driver shown twice for different PBs

1 **Emission of non-CO_2 greenhouse gases** (other pathways than fossil fuel burning)
2 **Biomass burning**
3 **Release of untested synthetic chemicals**
4 **Fossil fuel burning**
5 **Emissions of synthetic chlorofluorocarbon molecules**
6 **N_2O release to the atmosphere** (in multiple contexts, mainly agriculture)
7 **Application of industrially-fixed N to fields as fertilizers**
8 **Cultivation of N-fixing crops**
9 **Application of mined mineral P to fields as fertilizers**
10 **Industrial and household water use**
11 **Irrigation and agriculture**
12 **Expansion of livestock grazing**
13 **Expansion of cropland**
14 **Expansion of settlements and infrastructure**
15 **Introduction of invasive species**
16 **Harvesting biomass**

FIGURE 10 - The causal network of Planetary Boundary processes. The diagram shows the most significant and best understood interconnections between Planetary Boundary (PB) processes and the most important drivers of transgression. Colored arrows indicate a connection between two PB processes, with the color denoting the source PB process. The width of the arrow represents the estimated relative strength of the connection, while the line style (solid, dashed, dotted) indicates the nature of the connection (positive, negative, or both). Numbers associated with PB processes denote the most important drivers of PB transgression, as defined above. These drivers can be linked to multiple PBs simultaneously. For a tabular overview of the considered PB connections, see Supplementary Materials.

Key takeaway: *The interconnections between PBs are multidirectional and vary in strength. Addressing one issue often implies the need to address several others at the same time. For example, reducing global warming to 1.5°C is linked to managing all PB processes together. When this is done correctly, what initially seems like a challenging task can lead to significant benefits across different processes.*

Novel Entities: How Synthetic Chemicals and Plastics Undermine Biosphere Integrity and Accelerate Climate Change

Every year, vast quantities of novel entities, such as plastics, pharmaceuticals, pesticides, and industrial chemicals, quietly make their way into all environmental domains, including the ocean.[73,74] This pollution is often invisible and overlooked. Pollutants accumulate steadily across ecosystems and impact biodiversity and ecosystem functioning in profound ways.[73,75,76] In the ocean, for instance, plastics break down into microplastics, which are ingested by organisms from plankton to fish, causing internal damage, reducing reproductive success, and altering feeding behavior.[77] Plastics also release complex mixtures of chemicals, some of which are toxic.[78] Pharmaceuticals, pesticides and industrial chemicals similarly impair physiological processes, weaken immune systems, and disrupt hormonal balances within marine life.[79,80] These substances bioaccumulate and significantly disturb metabolic, reproductive, and immunological functions in marine organisms, accelerating **Change in Biosphere Integrity**.[81]

Collectively and in combination with other stressors (such as overfishing, invasive species or climate change), these disruptions contribute to a cascading decline in biodiversity, diminishing the resilience and functionality of marine ecosystems.[80,82] As a direct consequence, ecosystems show reduced efficiency in carbon sequestration, resulting from disturbed photosynthesis and biological carbon pumps (the process of carbon sedimentation and sequestration mediated by life).[83,84] Plastics disrupt the biological carbon pump by altering the sinking behavior of "marine snow", which is made up of dead organisms, waste and sediments. This disruption not only decreases carbon transfer to the deep ocean but also reduces nutrient supply of deep sea organisms.[85,76] The weakening of the biological carbon pump ultimately fuels **Climate Change**.

Tackling these interconnected challenges necessitates integrated management strategies, including stricter regulatory frameworks to limit pollutant release, advanced waste management systems, and proactive restoration of critical marine habitats such as seagrass beds, mangroves, and coral reefs.[86,84,87] Best practice examples, including marine protected areas in combination with pollutant reduction programs, show how comprehensive, multi-faceted approaches try to effectively safeguard ocean health, restore biodiversity, and mitigate climate impacts simultaneously.[87]

How Interactions Between Land Use, Vegetation, and Climate Trigger Droughts and Heat Waves

Dry and hot weather conditions often persist longer over already dry landscapes, creating a destructive vicious circle that can lead to extreme weather events. Several interconnected processes contribute to this feedback loop:[88,89,90,91,92,93]

1. When landscapes become dry, there is less water available to evaporate into the air. This means less evaporative cooling, hence a warmer landscape surface.
2. With less water vapor, fewer clouds form, and more sunlight reaches the ground directly, heating it even more.
3. More sunlight and higher temperatures can lead leaves to wilt, which reduces their cooling shade and further amplifies temperatures.
4. Hotter land surfaces warm the air above them, often making local weather systems more persistent and less likely to move on. This extends the hot and dry conditions.
5. Less water evaporating into the air also means reduced amounts of water for rainfall either locally or downwind, causing drought conditions to worsen even further.

Vegetation, particularly deep-rooted forests, plays a key role in moderating these effects. Healthy forests act like natural bridges, connecting deeper soil moisture with the atmosphere.[94] Via their roots they draw water from deep soil layers and release it into the atmosphere via leaf transpiration, helping to maintain atmospheric moisture levels.[95] This moisture recycling stabilizes local climates, buffers temperature extremes, and supports rainfall patterns.[95]

Climate Change itself threatens this benefit by increasing temperatures and altering precipitation patterns, directly harming vegetation and reducing its functional integrity. Even temporary droughts or heatwaves can leave vegetation significantly weakened (**Change in Biosphere Integrity**), resulting in permanently lower transpiration even when conditions improve.[96,97] This means that landscapes become inherently more susceptible to future extreme events. Additionally, **Land System Change,** including deforestation, land degradation, and conversion to agriculture or grasslands, amplifies these impacts by replacing resilient, deep-rooted vegetation with shallow-rooted plants and crops, which are less effective at recycling moisture.[95,92,97] Together, these factors significantly weaken the buffering capacity of ecosystems. Numerous scientific studies confirm these interconnections. In simulation, experiments with land-atmosphere models demonstrate that soil moisture depletion explains a large part of the intensity and persistence of past European heatwaves such as in 2003 and 2018.[88,91] For example, dry springs in Europe significantly increase the probability of heat waves and droughts later in the year due to decreased soil moisture-atmosphere coupling as described above.[89,98,90] In the western U.S., recent research shows that dry soils reduce local evaporation and transpiration while retaining more heat, resulting in amplified heatwaves and extended warm conditions.[89] In the Amazon, deforestation has significantly reduced regional rainfall and increased the frequency of droughts due to lower evaporation and transpiration, which in turn disrupts long range moisture recycling.[92]

Besides global efforts to tackle **Climate Change** by reducing fossil emissions, **Land System Change** is also a strong lever to bolster against future weather extremes: In addition to protecting existing forests, strategic afforestation and reforestation with resilient tree species can help rebuild the "green ocean" effect and stabilize local climates.[87] Monitoring networks that integrate satellite-derived and modelled soil moisture, vegetation health, and atmospheric circulation metrics help implement such plans.

Harnessing Interconnectedness for Planetary Stewardship

Solving the planetary crisis requires more than isolated fixes. Each Planetary Boundary is part of a causal network, where disturbances in one can amplify or dampen others.[1,3] Losing biodiversity weakens carbon sinks; clearing forests collapses moisture recycling; acidifying oceans reshape food webs. Despite their potentially devastating impacts, these feedbacks can also be harnessed. By working with the Earth system's interdependencies, we can spark positive cascades. Targeting key leverage points spreads benefits across multiple Planetary Boundaries through shared drivers, pressures, states and impacts.[99,70,71] Systemic risks imply systemic solutions.[100]

While Planetary Boundary control variables (CVs) offer diagnostics of the system state,[4] it is the inclusion of human society-related variables (for example related to consumption patterns, land-use practices, material usages or technologies) that open the door to meaningful intervention.[101,102,103] To connect the PBs framework with meaningful action, a comprehensive and quantified causal network of the Earth system is needed.

By working with the Earth system's interdependencies, we can spark positive cascades. Targeting key leverage points spreads benefits.

There are commonly known examples, for instance that tree planting helps sequester carbon (**Climate Change** CV), reduces surface temperatures, increases atmospheric moisture (influencing precipitation and **Freshwater Change** CVs), and restores habitats (**Change in Biosphere Integrity**).[95,104] The same is true for regenerative agriculture, which restores soil carbon, retains water, and reduces nutrient runoff (**Modification of Biogeochemical Flows**).[105,106] Well-designed climate change mitigation policies reduce fossil fuel use, decreasing air pollutants and restoring biosphere resilience, which in turn improves carbon uptake, accelerating mitigation.[107]

These are very high level examples. But to implement solutions on local levels, they have to acknowledge local contexts. Hence, solutions tailored for the end user are needed in each instance. In general, however, a circular economy that closes material, water, and carbon loops, offers a profound strategy to reduce pressure on multiple Planetary Boundaries at the same time. From redesigning products to creating closed urban resource loops, this vision aligns human systems with ecological wisdom.[108,109] Already today, circular economy initiatives are trying to minimize waste and pollution from novel entities while reducing the pressure to extract raw materials – which directly benefits land systems and biodiversity.[110,111] These efforts need to be scaled up across all levels, from households to companies and states.

To enable systemic interventions, the priority should be placed on drivers which are common across scales, relatively straightforward to address and connected to most positive impacts across PBs. Examples can be found throughout the literature:

- Citizens adjusting their diets to include less animal products or supporting local food systems reduce emissions, eutrophication, and land use pressure.[112]
- Cities redesigning transport and waste systems can lower climate impact, reduce novel entities, and improve public health.[113]
- Businesses optimizing supply chains can positively affect multiple PBs simultaneously.[114]
- States setting sustainable cross-sectoral policies unlock synergies between energy, land, and water transitions.[115]
- Global collaboration can align finance, trade, and climate goals to support whole systems transformation.[116]

What works locally may inspire national policy. What succeeds in one domain may spark progress in others. This multi-level dynamic is essential: The Safe Operating Space is not just an abstract concept. It must be constructed from below and maintained from above.[117]

As PBScience advances its mission, it will map and quantify this causal network in greater detail. Doing so will illuminate not only where the planet is at risk, but where interventions can catalyze the greatest positive change in line with scientific evidence, ecological reality, and societal potential.

Returning to the Safe Operating Space is strategically achievable, if we identify the structure of the Earth system, and align our actions with this knowledge.

3

Spotlight Chapters

3.1 The Ocean: The Unsung Guardian of Planetary Health

Beneath a shimmering blue surface lies an immense and dynamic regulator of planetary health: the ocean. Covering 71% of Earth's surface and holding roughly 1.3 billion cubic kilometers of water[118], the ocean is far more than expansive bodies of water; it acts as the planet's climate stabilizer, resilience builder, and life-support system. Yet, despite its crucial role, many ocean processes remain insufficiently understood due to the immense difficulty of observing such a vast and dynamic environment – particularly the deep sea, which poses unique challenges for sustained monitoring and data collection.

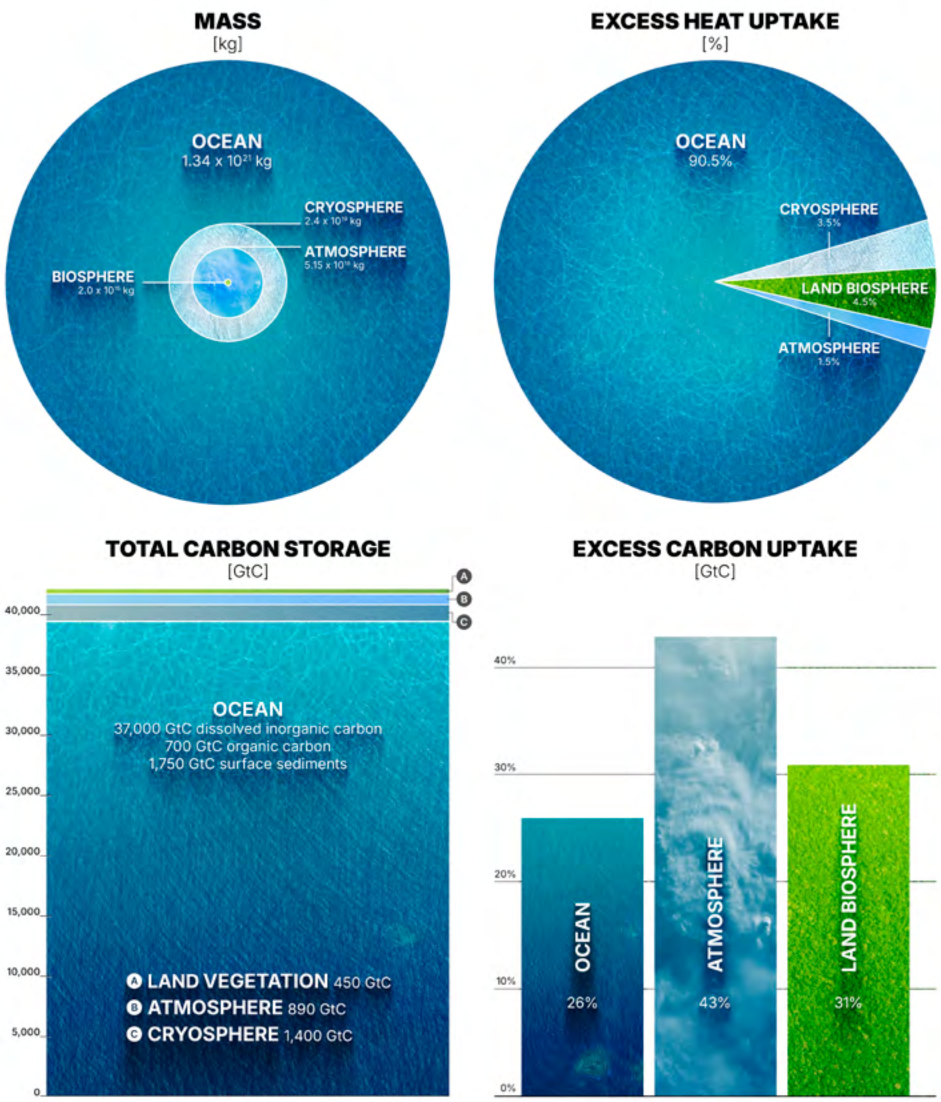


FIGURE 11 - Comparison of the ocean, atmosphere, land biosphere, and cryosphere in terms of volume, heat storage, and carbon storage. *Total storage* refers to the full amount of carbon that is held within the ocean, atmosphere, cryosphere, and vegetation on land. *Excess uptake* represents the percentage distribution of human-induced CO_2 emissions and greenhouse gas-driven heat among the Earth system's components (ocean, atmosphere, and land biosphere), particularly since the onset of the industrial era. The ocean has an important role in maintaining Earth's stability and habitability by absorbing anthropogenic heat and carbon.

The Ocean's Vital Role

The ocean uniquely influences Earth's stability, resilience, and habitability – three critical dimensions assessed within the Planetary Boundaries framework. These dimensions, while analytically distinct, are intricately connected through the ocean's key functions:

- **Stability**: The ocean absorbs and stores vast amounts of heat and carbon, moderating global surface temperature[119,120] and maintaining climate conditions similar to those that allowed human civilization to flourish.
- **Resilience**: Ocean biodiversity and ecological productivity help marine ecosystems withstand and recover from shocks such as climate extremes,[121] pollution, and biodiversity loss, and contribute critically to the resilience of the Earth system as a whole.
- **Habitability**: The ocean is fundamental in supporting life on Earth. Around half of the Earth's primary production (i.e. the conversion from sunlight into chemical energy) comes from marine phytoplankton,[122,123] which forms the base of the marine food web and supports nutrient cycles essential for life in the ocean and on land.[124,125,126]

These roles are foundational to keeping the Earth system within its Safe Operating Space.

The Ocean as Earth's Climate Regulator

Due to its vast heat capacity, the ocean has absorbed roughly 256 zettajoules (ZJ) of excess energy (see Fig. 12) generated by heat-trapping greenhouse gases in the atmosphere since the 1970s alone. This corresponds to approximately 89-93% of Earth's energy imbalance,[127,128] and has likely delayed the surface warming due to increased CO_2 by more than a decade.[129]

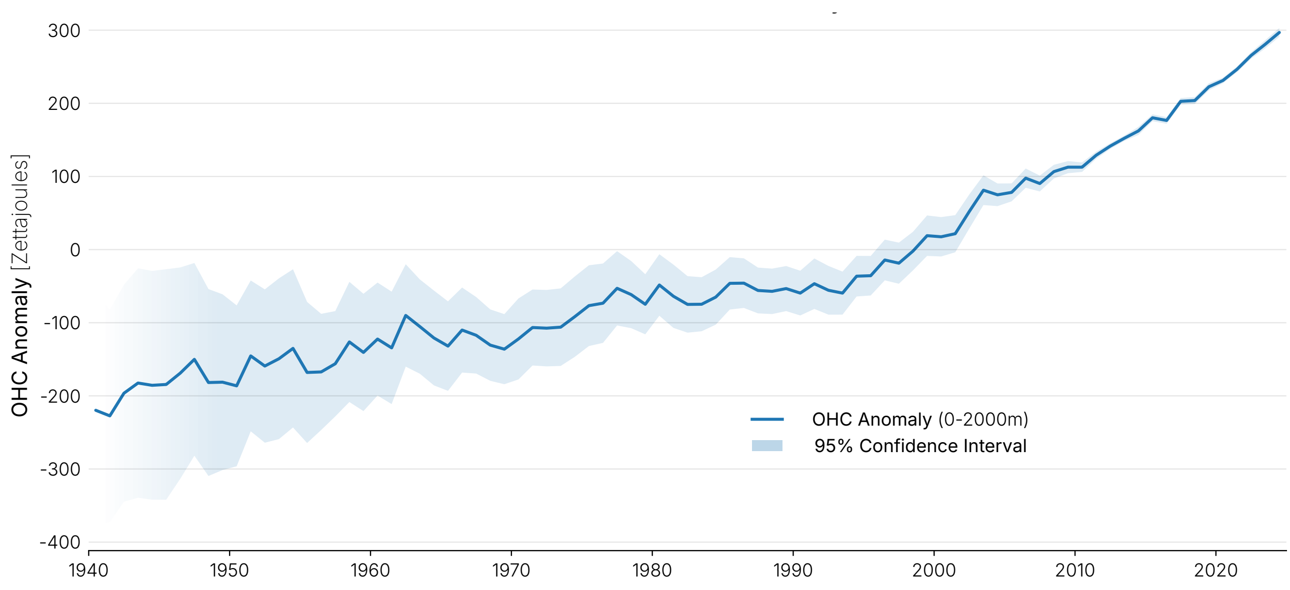


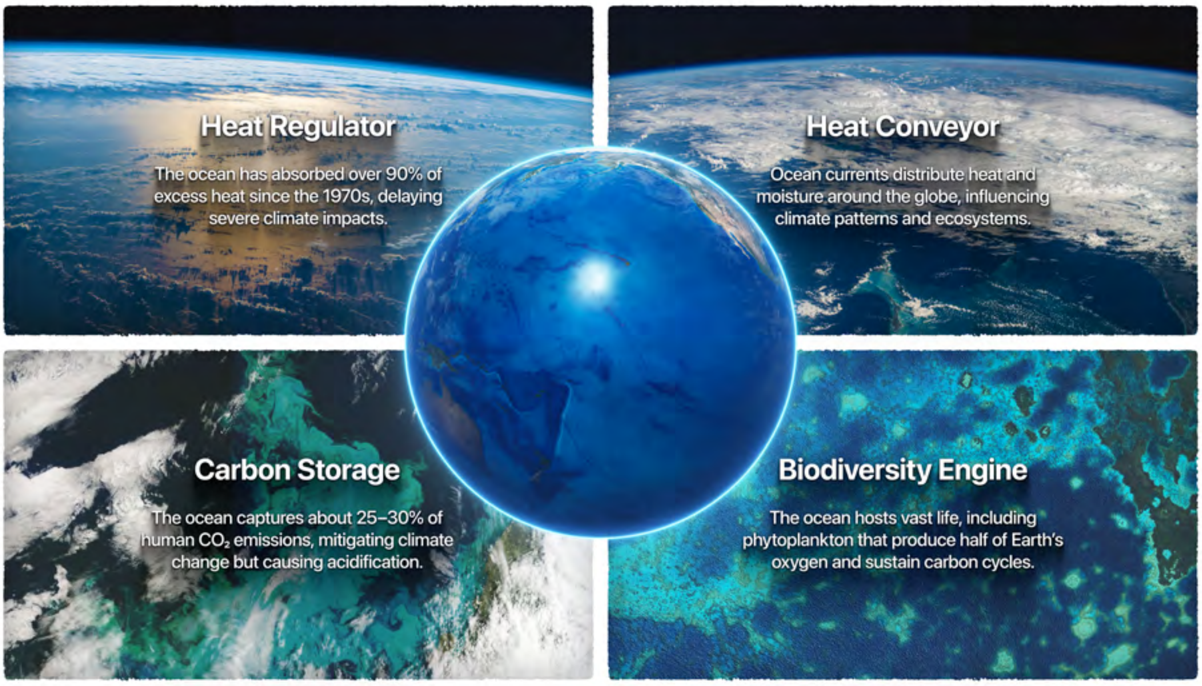
FIGURE 12 - Tracking Ocean Heat Content (OHC): 80+ years of ocean warming. This graph shows how the heat stored in the upper 2000 meters of the world's ocean has changed each year from 1940 to 2024. The line represents the amount of extra heat (compared to a baseline period from 1981 to 2010), measured in zettajoules. The shaded area around the line shows the uncertainty in the estimates: A wider band means less certainty, and a narrower band means more confidence in the data. Data Source: The data is provided by the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences, based on in-situ ocean temperature observations (IAP v4 dataset).

The Marine Carbon Sink

The ocean also acts as a critical carbon sink, capturing about 25–30% of human-generated CO_2 emissions annually. Since the Industrial Revolution, the ocean has absorbed roughly 185 gigatonnes of carbon.[15] Under simplified assumptions (e.g., carbon absorption on land staying the same) this amount of ocean uptake corresponds to an atmospheric CO_2 concentration of approximately 87 ppm (see Supplementary Materials). This illustrates the critical role the ocean plays in moderating climate change by limiting the accumulation of CO_2 in the atmosphere. Yet, this crucial service causes ocean acidification, harming marine life, disrupting food webs, and undermining ecosystem resilience.

Ocean Circulations: A Planetary Heat Conveyor

Ocean currents, notably the Atlantic Meridional Overturning Circulation (AMOC), redistribute heat and influence precipitation patterns around the globe, shaping regional climates and sustaining biodiversity.[130,131] Disruptions to major ocean currents such as the AMOC could profoundly alter global weather patterns, intensify climate extremes, threaten ice sheet stability, and undermine agricultural stability worldwide.[132,133,134]



Marine Biodiversity: Foundation of Life

Marine ecosystems host millions of species, most notably microscopic phytoplankton, which generate half of Earth's oxygen and drive the biological pump. The biological pump is a process vital for ocean carbon sequestration and nutrient cycling.[135,136] Maintaining marine biodiversity directly supports global ecological stability and resilience, underpinning human well-being.[137,138] Nevertheless, our understanding of ocean biodiversity remains incomplete, particularly in the vast and poorly explored deep ocean regions. This knowledge gap significantly limits our ability to accurately assess and quantify the global contributions of deep ocean ecosystems to key processes, as well as their vulnerabilities.

A System Under Pressure

Today, ocean health is facing unprecedented stress from both **long-term warming** (see Fig. 12) and increasingly frequent and intense extreme events. The steady rise in ocean temperatures has already triggered widespread ecological shifts: Species are migrating toward cooler waters, new ecosystems are forming, and long-established marine food webs are being disrupted.[139] Climate change is driving significant shifts in marine species distributions, with tropical and subtropical species moving poleward as ocean temperatures rise.[140,141] These shifts profoundly affect human-ocean interactions by forcing adaptations in fisheries, national quotas, and even diets.

On top of these gradual changes, marine heatwaves are becoming more frequent, longer-lasting, and more intense.[142] These bursts of extreme ocean warming, once rare, are now devastating vulnerable ecosystems like coral reefs and kelp forests. In 2016, a massive marine heat wave caused unprecedented bleaching across the Great Barrier Reef, and in 2025, over 80% of the world's coral reefs were affected by bleaching events.[143] In May 2023, scientists observed a sudden and still not fully understood rise in global sea surface temperatures.[144] This unexpected warming contributed to the record-breaking air temperatures that followed, making 2023 the first year in which the global average temperature exceeded 1.5 °C above pre-industrial levels.[145] Since then, sea surface temperatures have remained at historically high levels, as seen in both 2024 and 2025. These developments highlight how changes in the ocean can influence the broader climate system, with potential consequences for weather extremes, climate stability, and the overall resilience of the Earth system.

The ocean is under unprecedented stress from warming, deoxygenation, acidification, and biodiversity loss.

At the same time, the ocean is **losing oxygen**, a process called **deoxygenation**. As waters warm, their capacity to hold oxygen declines, and nutrient runoff from agriculture accelerates algal blooms that increasingly consume oxygen.[146] Since 1970 the ocean's oxygen content has decreased 1–3%.[147] In addition to the oxygen the ocean has already lost, it is expected to lose about four times more over the coming centuries – even if we stopped emitting greenhouse gases today.[148] If emissions are not halted, the ocean is expected to lose even more oxygen, with severe consequences for marine life. Deoxygenation reduces the resilience of the marine biosphere because many species cannot adapt to low oxygen levels. Already today, the expansion of low-oxygen zones, so-called "dead zones", creates conditions hostile to marine animals, e.g. fish and invertebrates, shrinking habitable zones and collapsing food webs.

Closely linked to these processes is **ocean acidification**, often called the "evil twin" of climate change. As the ocean continues to absorb CO_2 from the atmosphere, its chemistry is changing. Surface ocean pH has already fallen by approximately 0.1 units since the onset of the industrial era[149]. This is equivalent to a 30-40% increase in acidity.[150] This change threatens organisms that form calcium carbonate shells or skeletons, such as corals, mollusks, and key plankton species. The decline of these organisms can disrupt food webs and weaken the structure and function of marine ecosystems. Acidification also affects reproductive success, growth rates, and metabolic function across multiple marine groups, weakening both biodiversity and the ocean's long-term ability to regulate carbon.[151]

Compounding these chemical and thermal threats is the **decline in marine biodiversity**, much of it driven by overfishing. Roughly one-third of assessed fish stocks are now overfished, with many populations falling below sustainable levels.[152] Apex predators are disappearing from entire regions. As functional and genetic diversity is lost, ecosystems lose their ability to recover from disturbances.[82] In scientific terms, the ocean's ecosystem resilience is being depleted. This alters the ocean's capacity to sustain key biogeochemical functions.[137] This loss of ecosystem function impacts food security and livelihoods in coastal communities, particularly in low- and middle-income countries.[153,154]

Further adding to this pressure is the **proliferation of pollutants and novel entities**: Substances such as synthetic chemicals, plastics, pharmaceuticals, and heavy metals are now found in every part of the ocean, from surface waters to the deep sea. Microplastics are ingested by organisms at all levels of the food chain,[155] which can harm their ability to reproduce, weaken their immune systems,[156] and change how they eat.[157] Persistent organic pollutants accumulate in marine food webs, affecting everything from plankton to whales – and ultimately, human health.

Beneath the surface, **the seabed is also being reshaped and degraded** by human activity. Bottom trawling (a fishing technique that scrapes massive nets along the ocean floor) damages habitats on the ocean floor,[158] uproots deep-sea corals, and releases part of the carbon stored in the seabed.[159] Emerging industries like deep-sea mining pose new and largely unquantified threats, disturbing sediment dynamics and releasing plumes of potentially toxic materials. These practices fundamentally alter the structure and function of marine ecosystems and are similar in scale and impact to land-use change on land.

All of these pressures compound and amplify each other, pushing marine systems closer to tipping points, i.e. conditions beyond which recovery becomes uncertain or impossible.

The Ocean Within the Planetary Boundaries Framework

Currently, ocean acidification is the only explicitly defined marine boundary in the Planetary Boundaries framework, measured through the aragonite saturation state (Ω_{arag}), which is critical for organisms like corals and calcifying plankton. Other ocean-related processes are included only indirectly: Marine biodiversity is folded into the **Change in Biosphere Integrity** boundary but not distinguished from terrestrial systems, despite its vital role in carbon cycling, oxygen production, and ecological resilience. Plastic pollution and other synthetic chemicals affecting marine life fall under the **Introduction of Novel Entities** boundary, but there is no ocean-specific control variable. Similarly, the phosphorus control variable under the (Modification of) **Biogeochemical Flows** boundary accounts for ocean impacts like coastal dead zones and excessive algal blooms.

Table 1 - Current representation of ocean-related processes in the Planetary Boundaries framework, including their level of inclusion and associated control variables.

PB process	Ocean inclusion	Control variable (CV) used
Ocean Acidification	Included (only surface acidification)	Aragonite saturation state (Ω_{arag})
Change in Biosphere Integrity: Genetic Diversity	Combined terrestrial & marine extinction rates	Extinction rate (all ecosystems combined, expressed in E/MSY – extinctions per million species-years)
Introduction of Novel Entities	Implicit inclusion of marine plastics (and all other novel entities like PFAS, dioxin, etc.)	None specific to the ocean
Modification of Biogeochemical Flows	Phosphorus threshold partly ocean-based; Nitrogen takes also water quality into account	Global Phosphorus flow to the ocean

This means that, despite its vital role, one can argue that the ocean remains underrepresented in the Planetary Boundaries framework.[160] Several critical marine processes such as ocean heat uptake, marine biodiversity loss, deoxygenation, and seabed integrity loss are either only partially captured or entirely omitted. In some cases, this is due to the scientific challenge of defining global-scale thresholds or overlaps with existing boundaries. For instance, marine biodiversity is currently included under the broader **Change in Biosphere Integrity** boundary, without distinction from terrestrial systems. Likewise, pollutants such as plastics and industrial chemicals are captured under the **Introduction of Novel Entities** boundary. In other cases, marine processes, while highly important at regional or ecosystem levels, currently lack globally quantifiable thresholds or feedbacks that would justify their inclusion in the framework. Such processes may still demand urgent attention through regional or sectoral management but may not meet the criteria for defining a global boundary.

Addressing the Unknowns

While there is strong evidence that the ocean plays a critical role in maintaining global stability, major knowledge gaps remain.[161] Some key ocean processes are difficult to observe and model accurately due to their vast scale, complexity, and the logistical challenges of monitoring deep and remote regions. This limited understanding constrains our ability to fully represent ocean functions within the Planetary Boundaries framework and to assess how changes in marine systems may interact with broader Earth system dynamics. Although some processes, such as shifts in ocean circulation, have been identified as potential tipping elements, the scientific community has yet to reach consensus on whether other mechanisms, like disruptions to the biological carbon pump, qualify. As a result, our ability to anticipate critical thresholds or irreversible changes in the ocean remains limited.

Recognizing the Ocean as Central to Planetary Stability

To holistically understand the state of our planet, it is essential to acknowledge and address the uncertainties that remain in our understanding of ocean processes and their role in regulating the Earth system. Improved ocean monitoring, interdisciplinary research, and more integrated modeling efforts are key to identifying which ocean processes may significantly influence global dynamics when perturbed by human activity. The goal is to determine whether certain marine processes have the potential to affect the stability of the Earth system as a whole. Strengthening this knowledge base would not only support the refinement of the Planetary Boundaries framework, but also help anticipate and prevent large-scale, potentially irreversible changes in the ocean that could undermine planetary resilience and human well-being.

The ocean acts as the planet's climate stabilizer, resilience builder and life-support system.

3.2 Extreme Weather and Disasters in 2024/25

An Attribution-Based Perspective

Guest article by Friederike Otto and Emmanuel Raju from the World Weather Attribution project

Foreword From the Editors

The Planetary Boundaries (PBs) framework was developed to help define and quantify the environmental limits within which humanity can thrive. It is a science-based guide for maintaining the stability and resilience of the Earth system as a whole. Its focus is global and long-term: ensuring that the biophysical conditions that have supported human societies during the Holocene remain intact for future generations.

This means that the PBs are set entirely based on the best science we have on defining the stability and functioning of the planet. Setting this safe operating space for humanity on Earth is centered on the objective of securing life-support systems for all species on Earth and thus to secure the foundations for all human well-being. In this sense, Planetary Boundaries are the ultimate definition of justice: the right of every human being to have a life on a stable, healthy planet. Breaching boundaries undermines Earth's resilience, while also causing human impacts – from slow changes, like sea level rise and water scarcity, to fast changes, like human reinforced extreme weather events.

In this sense, Planetary Boundaries are the ultimate definition of justice - the right of every human being to have a life on a stable, healthy planet.

This guest article by Friederike Otto and Emmanuel Raju of the World Weather Attribution (WWA) initiative examines how breaching Planetary Boundaries is already contributing to more frequent and intense extreme weather events, and how these are affecting people's lives today, particularly those of the most vulnerable. The authors are leading figures in the science of extreme events and disasters. Through WWA, an open, rapid-response initiative founded in 2014, they and their colleagues have published over 100 scientific attribution studies on heatwaves, droughts, wildfires, storms, and extreme rainfall events worldwide. Their work includes dedicated studies for 12 of the 25 extreme events analyzed in this article.

While such a focus on near-term, unequal human impacts lies outside the core scope of the PBs framework, it provides critical insight: It reveals how planetary instability is already manifesting in ways that directly threaten lives and livelihoods, especially for those already socioeconomically or politically marginalized.

The article also serves as a vivid illustration of a core principle of Earth system science: Planetary Boundaries cannot be treated in isolation. Just as disasters often emerge from the collision of multiple local stressors, the stability of the Earth system itself is undermined by the interplay of multiple Planetary Boundary transgressions. Understanding these interactions is essential, both for responding to today's impacts, and for avoiding tomorrow's irreversible tipping points.

Introduction – From Physical Science to Human Impact

In 2024, for the first time, the global mean temperature exceeded 1.5 °C above pre-industrial levels for an entire calendar year. This alarming milestone reflects not only rising global energy and moisture levels, but also a corresponding increase in the frequency and intensity of extreme weather events. It was also the *wettest* year on record in terms of atmospheric water vapour.[162] Across the globe, unprecedented floods, storms, droughts and heatwaves set new records for **lives lost, livelihoods disrupted and assets destroyed**.[163] Many of these events were no longer *natural* in the strict sense: Attribution studies show they were *hotter, wetter or stronger* than they would have been without human-induced climate change.[164]

Yet hazard is only one side of the disaster equation. Disasters materialise where hazard meets *exposure* and *vulnerability* – two dimensions that are socially constructed and highly unequal within and between countries.[165] As we push beyond seven of the nine Planetary Boundaries (PBs), global and local boundary transgressions interact to amplify extremes.

In this chapter, we review the *most impactful* events of 2024/25, tracing the causal chain from Planetary Boundary transgressions, via changed hazard characteristics, to unequal impact on people.

INFO BOX 4

What is Extreme-Event Attribution?

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.[166,167] However, they all estimate the difference between 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 estimations are based on climate models and weather observations.[168,166] Attribution is easiest when the forcing is globally homogeneous (e.g., greenhouse gases); it is more challenging when drivers are local or regional (e.g., land-use change). The science has rapidly developed 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"*.[169]

The effects of Climate Change are relatively easier to quantify, largely because the atmosphere is indifferent to the geographic source of emissions. As a result, the impacts are global in nature and can be modelled with a reasonable degree of consistency and confidence. In contrast, the effects of other Planetary Boundary transgressions – such as for **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 attributions studies.

FIGURE 13 - Global map of the 25 most impactful extreme weather events from January 2024 to April 2025.

Key takeaway: *Extreme events occur around the globe. Their frequency and intensity has been greatly increased by Climate Change and other Planetary Boundary transgressions.*

(Un-)Natural Hazards of 2024-2025

We use the EM-DAT humanitarian disaster database to identify the ten worst extreme weather events from January 2024 to April 2025, categorized by (i) total number of deaths, (ii) total number of people affected, and (iii) total economic damages (Tables A1–A3). The lists show some overlap: Several events appear in multiple impact categories, and some entries describe the same event spanning multiple countries. The result is a set of 25 unique events, labeled A–Y, which are mapped in Fig. 13.

The Emergency Events Database (EM-DAT), maintained by the Centre for Research on the Epidemiology of Disasters, is the longest-running and most widely used global disaster database.[170,171] 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.[171] EM-DAT applies clear inclusion criteria to ensure consistency over time.[171] Despite its global coverage, EM-DAT has important limitations.[172,173] It relies on official statistics, which often lag behind by years and varies 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, that death toll as well as economic damages are severely underestimated in the database, probably by orders of magnitude. Nevertheless, it remains a key resource for global disaster risk research and international assessments.[171]

At first glance, the difference in public attention stands out. Events such as the hurricanes Helene (P)[174] and Milton (Q),[175] the two events with the highest economic damage, have been widely publicised. Others – such as a coldwave in Afghanistan (B) that was the second most deadly event of the period, droughts in southern Africa (J) or a series of flash floods in Asia – were often absent from public reporting.[176,177]

Of the 25 distinct events we identified, the vast majority have been made more intense and more likely because of human-induced climate change. This conclusion is supported not only by our general understanding of climate science, but also by a growing body of extreme event attribution studies that directly link many of these specific events to climate change.

Storms

The scientific evidence has particularly grown in the last couple of years with respect to tropical cyclones – the large, rotating storm systems that include hurricanes and typhoons. Many studies clearly link human-induced climate change to stronger and more destructive storms,[178,179] including hurricanes Helene (P),[174] Milton (Q)[175] and Beryl (S),[180] in the Atlantic, as well as typhoons Yagi (G), Gaemi (N)[181] and Trami (L)[182] in the Philippines. They consistently demonstrate that climate change has intensified rainfall, wind speeds, and the potential strength of these storms.

Many studies clearly link human-induced climate change to stronger and more destructive storms.

Among the other Planetary Boundaries influencing hurricanes, aerosols are particularly important to highlight. Although studies on their effects remain limited, existing research consistently indicates that very high levels of aerosol pollution can amplify the intensity of tropical cyclones. While no studies have yet examined the most devastating cyclones of the past year, earlier analyses, such as those on Hurricane Harvey,[183] found only modest effects, likely due to declining aerosol concentrations in the Northern Hemisphere. However, when higher aerosol levels were modeled, the intensifying impact became much more pronounced. This suggests that in regions like Asia, where aerosol pollution remains elevated, aerosols likely contribute to cyclone intensity alongside climate change.

Some areas, like the Bay of Bengal, have seen much fewer dedicated studies. For instance, cyclone Remal (O), which hit Bangladesh, has not been directly studied in detail. This is despite the fact that the cyclones Sidr and Nargis,[184] which hit the region in 2007 and 2008, were among the deadliest extreme weather events of this century. Nonetheless, some evidence from other cyclones in this region suggests increased rainfall linked to climate change.[185] This is no surprise: Warmer air can hold about 7 % more moisture for every degree of warming, supercharging downpours in tropical cyclones.[186] Given these well-established physical principles, we have strong reasons to believe cyclone Remal (O) – just like other cyclones globally – brought heavier rainfall due to human-induced climate change.

Heatwaves

The deadliest extreme events in 2024/25, as every year, were heat waves. In 2024, it was the extreme heat in Saudi Arabia (A) in June, during the Hadjj, with peak temperatures at the Grand Mosque reaching over 50°C, killing at least 1301 people and leading to 2700 cases of heat exhaustion in a single day.[187] Further extremely deadly heat waves have occurred in Bangladesh, India and Pakistan (E, F)[188] in the pre-monsoon season from March to June and in Arizona and the Southern United States (C)[189] later in the Summer. All of these heat waves have been made hotter, deadlier, costlier, and much more devastating by climate change. For some, the effect of global warming is so large that, in a world without global warming, they would not have occurred at all. Globally, climate change has already at least doubled the number of extreme heat days per year in four out of five states and territories.[190]

The impacts of heatwaves alone provide ample economic, humanitarian, and security arguments to stop burning fossil fuels now. No other type of extreme event is as deadly, and worsening as quickly. However, most countries lack even the basic extreme heat-related infrastructure – e.g., to prevent deaths by providing early warnings, and to estimate those that have not been prevented (see section on Disasters and Vulnerability below).

While climate change is a major driver of extreme heat, certain forms of land use change also significantly intensify heatwave temperatures, especially in and around cities.[191] This applies particularly to urbanization and to the fragmentation of continuous vegetation into mixed landscapes of buildings and green spaces.

Floods

The impacts of floods were high across all three categories. Floods in Valencia, Spain (R),[192] Rio Grande do Sul, Brazil (T),[193] and Houston, US (Y) were among the costliest events in 2024/25, while floods in Chad and Niger (D) as well as in Pakistan (H) and Afghanistan (I) cost many people their lives. Flash floods in India and Bangladesh (K) were among those events affecting the largest number of people.

Dedicated attribution studies show that climate change made most of these events, specifically those in Spain (R),[192] Brazil (T),[193] Chad, Niger (D),[194] Pakistan (H) and Afghanistan (I)[195] more severe (red symbols on map in Fig. 13). Events of this scale have become much more likely – for example, the floods in Chad and Niger (D)[194] are expected to recur every 5-10 years under current climate change conditions. No direct attribution studies exist for the flash floods in Bangladesh (K), the floods in Houston (Y), and the floods in Gujarat (M).

Attribution studies for floods are more challenging than those for storms and heatwaves, which follow similar patterns and causes in all regions of the world (see Info Box 4). In contrast, flooding can have different causes, which need to be studied separately and in detail for each event. One trigger of flooding is intense short-term rainfall, and many lines of evidence show that climate change is making these types of heavy rainfall more severe. However, above-average rainfall throughout a season can be another reason, which in some regions (such as Chad and Niger) can be strongly influenced by climate change. Evidence for climate change effects is absent or much weaker in other cases (e.g., in East Africa[196]).

Similarly, the human impacts of flooding events greatly depend on the local conditions. For example, the effects of land system change and the degradation of the biosphere, especially through deforestation, can greatly exacerbate the human impacts of excessive rainfall. Forest litter and root networks store and gradually release water, acting as a sponge for excessive rainfall and stabilizing the ground. In three recent studies on devastating flooding and landslides in Kerala,[197] India, Mindanao[198] in the Philippines and in Nepal,[199] we found that local deforestation significantly increased the risk of landslides and played a critical role in the resulting fatalities. Furthermore, altering the freshwater cycle by constructing channels and levees cuts rivers off from their natural floodplains, increasing catastrophic flood risk.[200,201]

These localized effects cannot be quantified without employing detailed, location-specific models. This does not imply that the impacts of transgressing the PBs for **Land System Change, Change in Biosphere Integrity** or **Freshwater Change** are any less significant. Rather, the challenge lies in how we often equate what is measurable with what is meaningful – leading us to underestimate the significance of things that are difficult to quantify.

Satellite Images recorded by Landsat 8 - OLI, before and after the flooding event in Valencia, Spain (R). Source: NASA

Droughts

Lastly, three drought events were among the most impactful extreme events last year. These events demonstrate that the role of climate change in droughts can be very different. The drought in Brazil (V)[202] was linked to extremely high temperatures as well as a lack of rainfall, and was shown to be made worse by climate change. Conversely, the drought in Southern Africa causing devastation in Zimbabwe, Zambia and Malawi (J)[203] was driven mainly by the El Niño-Southern Oscillation (ENSO) climate phenomenon. The ENSO is influenced by climate change in complex ways, likely strengthening it overall.[204] Seeing these varied outcomes, an attribution statement for the drought in the US (X) cannot be made robustly without a dedicated study.

While climate change is the central driver of worsening droughts, several other Planetary Boundary processes are significant as well. For example, the loss of forests and other ecosystems can contribute to hotter and drier weather conditions persisting for longer periods. This effect is linked to reduced evapotranspiration and the breakdown of vegetation-atmosphere feedbacks, which normally help to cool the land surface and maintain local moisture recycling.[205,206] Without this natural buffering, heat and drought can become more prolonged and severe (see also Ch. 2.4). Also, biodiversity loss weakens ecosystem resilience, meaning vegetation cannot rebound after drought; subsequent seasons start from a drier baseline, locking in chronic water stress.[97]

Disasters and Vulnerability

In 2024 and early 2025, record-breaking heatwaves highlighted the stark inequality in disaster impacts worldwide. Heatwaves, though less visually dramatic than floods or storms, often have the most devastating consequences, especially for vulnerable populations. However, adaptation strategies for heat remain less developed and funded compared to (already less-than-adequate) measures addressing floods and cyclones. Here, we thus highlight particularly the impacts of heat.

Across the world, there are many untold stories of how climate change impacts people's lives on an everyday basis. A striking example of this disparity was the South Sudan heatwave[207] in early 2025. Despite early warnings and precautionary measures like school closures, marginalized groups, including young children, the elderly, and women, faced severe hardships. The challenges caused by heat are exacerbated in conflict-affected areas like South Sudan, as instability limits adaptive capacities. In fragile and conflict-stricken zones, environmental degradation often compounds vulnerabilities, reducing opportunities for livelihoods and deepening poverty cycles.

Heatwaves highlight gender inequalities, as societal expectations increase women's caregiving roles during disasters. In India, women's access to heatwave early warnings correlated strongly with occupation, education, and income.[208] Informal sector workers, like female street vendors, faced livelihood losses when heat damaged their products. Outdoor workers, including agricultural and construction laborers, face high health risks and income losses from heat exposure.[209,210] Indoor workers in homes and factories also remain vulnerable due to inadequate cooling and limited social protections. Communities simultaneously experiencing multiple hazards, such as heatwaves and droughts, face compounded vulnerabilities.

Extreme weather events become disasters not solely because of their physical intensity, but largely due to underlying social vulnerabilities and exposure. Social factors determine who is most impacted, why certain groups suffer disproportionately, and how effectively communities can respond and recover. Understanding these social dimensions is essential to comprehending planetary health as a whole.

Conclusion

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 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 socio-economic 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, we must understand and address climate change and other Planetary Boundary transgressions collectively, not in isolation. This holistic approach is essential to building resilience, safeguarding vulnerable populations, and ultimately securing planetary health.

Table 2 - Studied extreme events of 2024/25. These data are taken from the EM-DAT humanitarian disaster database.[170,171] Since they represent collected official statistics, this data has some limitations – for example, death tolls and costs are often significantly underestimated, as described in the article. Information on the impact metric definitions is available on the EM-DAT website.[211] The attribution column states whether **Climate Change** has made a particular event more likely, and whether this assessment originates from a specific attribution study or a general scientific understanding of similar events ("causal field").

Deaths

Identifier	Event	Location	Date	Deaths	Attribution
A	Heatwave during Hadj	Saudi Arabia	June 2024	1,301 confirmed deaths	Yes (causal field)
B	Coldwave	Afghanistan	March 2024	1,197 confirmed deaths	No (causal field)
C	Heatwave	Arizona	April – October 2024	1,006 confirmed deaths	Yes (attribution study)
D	Flood	Chad, Niger	August – September 2024	972 confirmed deaths	Yes (attribution study)
E	Extreme pre-monsoon season	India and Bangladesh	March – June 2024	743 confirmed deaths	Yes (attribution study)
F	Heatwave	Pakistan	June 2024	568 confirmed deaths	Yes (causal field)
G	Typhoon Yagi	Myanmar	September 2024	460 confirmed deaths	Yes (attribution study)
H	Flood	Pakistan	May 2024	368 confirmed deaths	Yes (causal field)
I	Flood	Afghanistan	July / August 2024	357 confirmed deaths	Inconclusive (attribution study)

People Affected

Identifier	Event	Location	Date	People Affected	Attribution
E	Extreme pre-monsoon season	India and Bangladesh	March – June 2024	33,000,000 people	Yes (attribution study)
J	Drought	Zambia, Zimbabwe, Malawi	February 2024 – February 2025	23,500,000 people	No (attribution study)
K	Flash flood	Bangladesh	June + September 2024	10,950,000 people	Yes (causal field)
L	Tropical cyclone “Trami (Kristine)”	Philippines	October 2024	9,652,607 people	Yes (attribution study)
M	Flood Gujarat	India	August 2024	8,007,150 people	Yes (causal field)
N	Typhoon “Gaemi (Carina)”	Philippines	July 2024	6,100,000 people	Yes (attribution study)
O	Cyclone “Remal”	Bangladesh	May 2024	4,400,000 people	Yes (causal field)

Cost

Identifier	Event	Location	Date	Cost (in thousands of USD)	Attribution
P	Tropical Cyclone “Helene”	USA	September 2024	USD 56,000,000	Yes (attribution study)
Q	Hurricane “Milton”	USA	October 2024	USD 38,000,000	Yes (attribution study)
R	Valencia Floods	Spain	October 2024	USD 11,000,000	Yes (attribution study)
S	Hurricane “Beryl”	Caribbean	July 2024	USD 7,200,000	Yes (attribution study)
T	Flooding in Rio Grande do Sul	Brazil	April – May 2024	USD 7,000,000	Yes (attribution study)
U	Tornado Oklahoma	USA	May 2024	USD 6,600,000	Unclear
V	Amazon Drought	Brazil	2024	USD 6,050,000	Yes (attribution study)
W	Tornado Ohio	USA	March 2024	USD 5,900,000	Unclear
X	Drought Texas/ Oklahoma	USA	2024	USD 5,400,000	Yes (causal field)
Y	Houston Floods	USA	May 2024	USD 4,800,000	Unclear

3.3 Putting Planetary Boundaries to Work: Emerging Practices, Actors and Tools

Guest article by Tiina Häyhä and Albert Norström from the Stockholm Resilience Centre (SRC)

Foreword From the Editors

From governments to businesses, cities to civil society: A growing number of actors around the world are beginning to translate the Planetary Boundaries framework into action. While the pace of this uptake remains too slow to match the scale of the crisis, the diversity of efforts signals a wider recognition: that staying within Earth's limits requires deep, systemic change across all sectors of society.

This guest article, by Tiina Häyhä and Albert Norström of the Stockholm Resilience Centre, provides a structured overview of how the Planetary Boundaries concept is being operationalised in practice. Both authors are closely involved in international efforts to apply Earth system science in decision-making contexts. Häyhä's work focuses on translating Planetary Boundaries to national and sectoral scales, while Norström is Science Director of the Earth Commission and has extensive experience at the interface of research, policy, and sustainability transformations.

Science-led frameworks can be an essential guide to the complex realities of politics, economics, and institutional change.

The article provides an overview of a variety of initiatives, ranging from national biodiversity strategies to city-scale experiments and corporate target-setting, which apply the framework to inform real-world decisions. These examples reveal not only the growing uptake of Planetary Boundaries science, but also the practical challenges of applying them: translating global thresholds into local action, addressing uncertainty, ensuring fairness, and managing fragmented institutions. Just as transgressing one boundary can undermine others, isolated policy responses risk falling short. The article shows that applying a systems lens is not just scientifically appropriate, but practically necessary for making real progress. It is a reminder that science-led frameworks can be an essential guide to the complex realities of politics, economics, and institutional change.

Introduction

The concept of Planetary Boundaries provides a scientific framework for understanding the limits within which humanity can safely operate. As this most recent Planetary Health Check shows, seven of the nine Planetary Boundaries are breached, signalling a planetary emergency that requires immediate and coordinated action. While the scientific assessment portions of the Planetary Health Check provide the diagnosis, this chapter explores emerging treatments:

→ Who are the actors operationalising Planetary Boundaries?

→ How is the framework being applied in practice?

→ What emerging science-based tools and approaches are being used to track progress and impact?

Since the first publication on Planetary Boundaries, there has been growing interest in applying the framework across a variety of contexts and by a wide range of actors. The academic community, in particular, has worked to adapt the global framework to sub-global scales to improve its practical relevance. Fig. 14 presents an overview of case studies and initiatives that have attempted to implement the Planetary Boundaries framework, ranging from national and city levels to applications in the corporate and financial sectors.

In the following sections, we briefly review and illustrate the main approaches to operationalising Planetary Boundaries, categorised by actor types: government, corporate, financial, civil society, and community-led initiatives.

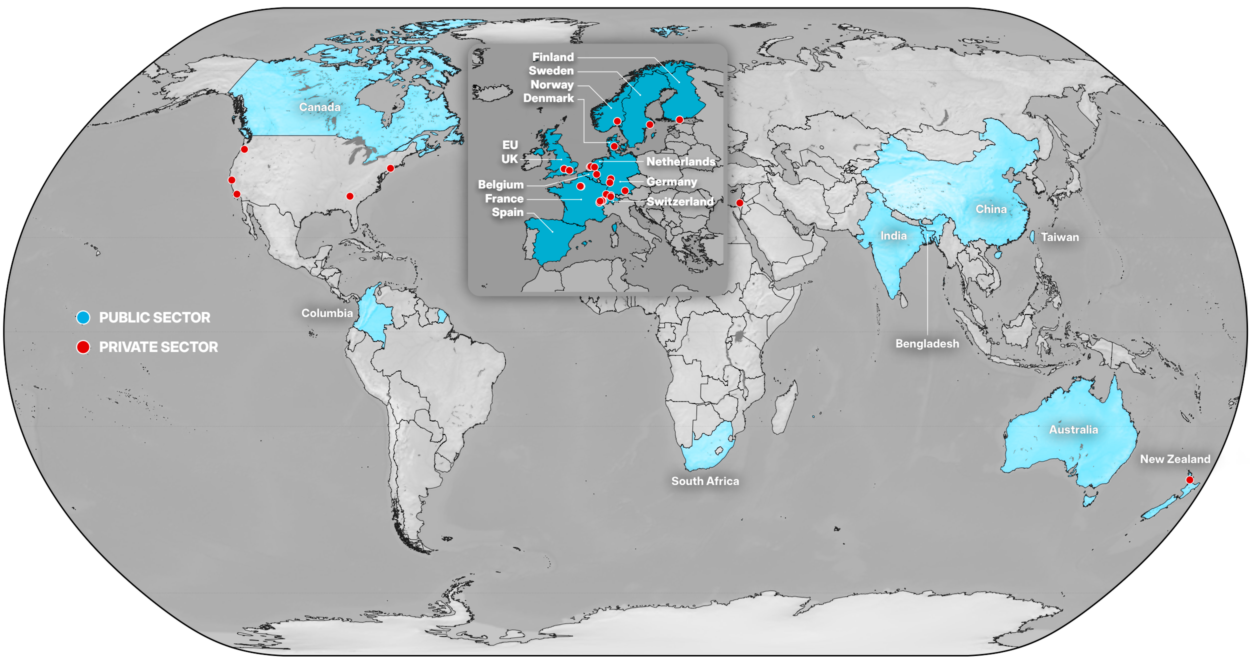


FIGURE 14 - Planetary Boundaries applied around the world. Attempts to operationalize the Planetary Boundaries framework in different national, regional and business contexts (not comprehensive).

Governmental Approaches: National and International Policies

The risks of global environmental change are increasingly acknowledged at the international policy level. Scientific insights from Earth system science, including the Planetary Boundaries framework, are informing major multilateral agreements that address critical challenges such as climate change, biodiversity loss, and ecosystem degradation. Fig. 15 illustrates how specific international agreements align with individual Planetary Boundary processes.

A key example is the Paris Agreement (adopted in December 2015), which aims to limit global warming to well below 2°C – preferably 1.5°C – above pre-industrial levels. This ambition is consistent with the Planetary Boundaries framework and has been translated into carbon budget estimates that underpin Nationally Determined Contributions (NDCs) and guide countries in planning emissions reductions over time, based on fair-share principles and modelled pathways. According to the UN, there are more than 100 countries, responsible for approximately 82 per cent of global greenhouse gas emissions, that have adopted net-zero pledges either in law, national climate action plan or long-term strategy, or in an announcement by a high-level government official. However, these commitments still fall short of what is needed to stay within a safe climate boundary.[212]

Another important milestone is the Kunming-Montreal Global Biodiversity Framework (adopted in December 2022), which sets ambitious targets to halt and reverse biodiversity loss by 2030. This includes the "30 by 30" goal, which aims to protect 30% of our planet's land and marine areas by 2030. These targets are closely aligned with the Planetary Boundaries for Change in Biosphere Integrity (genetic diversity) and Land System Change,[213] and are guiding the development of national biodiversity strategies and action plans. Governance frameworks are emerging to address chemical pollution – now increasingly recognized as the third planetary crisis in addition to climate change and biodiversity loss.[214] Key developments include:

Frameworks are often fragmented and issue-specific, rather than grounded in a systems-based approach.

- The Global Framework on Chemicals (2023),[215] which sets global targets for sound chemicals management;
- The establishment of the UN Science-Policy Panel on Chemicals, Waste and Pollution Prevention, tasked with delivering timely and policy-relevant scientific assessments;
- The EU Chemicals Strategy for Sustainability, part of the European Green Deal;
- Ongoing negotiations for a Global Plastics Treaty, and updates to conventions such as Basel, Rotterdam, and Stockholm to enhance control over hazardous substances.

Despite this progress, legal and policy gaps remain for several Planetary Boundaries. For instance, biogeochemical flows of nitrogen and phosphorus are addressed only partially through regional agreements[216] and fragmented sectoral instruments, which separately target issues such as air quality, wastewater management, agriculture, and spatial planning.[217]

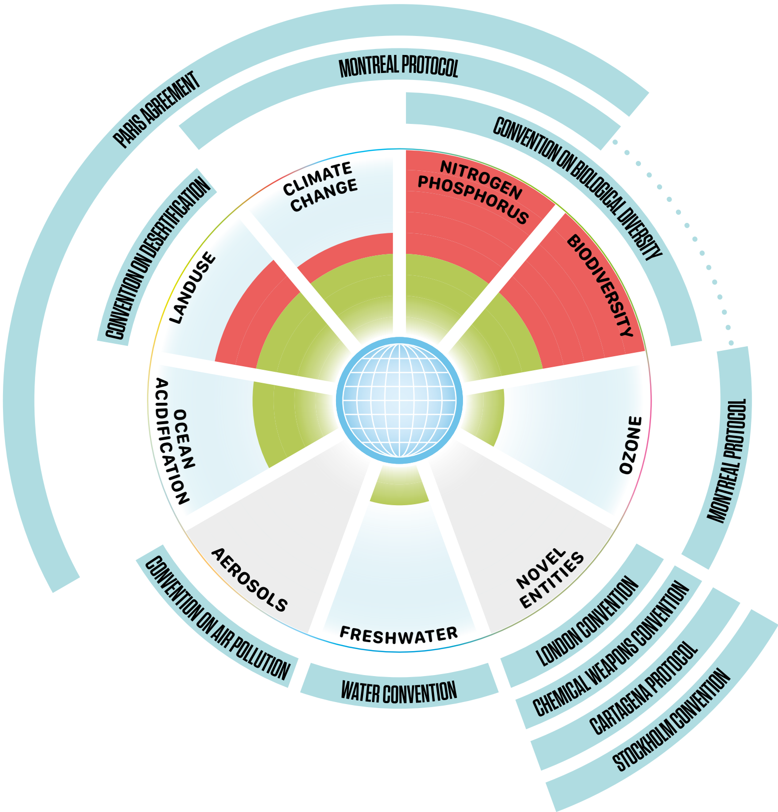


FIGURE 15 - International Agreements covering Planetary Boundary domains. There are international agreements related to each Planetary Boundary process, but they vary in terms of comprehensiveness, level of ambition and bindingness. Figure from Andersen et al. (2020).[218]

Overall, while most Planetary Boundary processes are covered by some form of international governance, the frameworks are often fragmented and issue-specific, rather than grounded in a systems-based approach. As a result, even though some policy frameworks address interactions, such as those between climate change, land use, and biodiversity, they often fall short of addressing the full complexity and interdependence of Planetary Boundary processes. Moreover, environmental trends continue to worsen for most boundaries,[4] and the gap between the current state of the environment and international policy goals continues to grow.

Effective governance will require more coherent policy integration, stronger coordination across levels of governance, and cross-sectoral collaboration. An example of promising transnational collaboration is the Wellbeing Economy Governments partnership, which brings together governments of Scotland, Iceland, New Zealand, Wales, and Finland (with Canada actively participating) to share knowledge and policy innovations aimed at building wellbeing economies within Planetary Boundaries.

Several national and regional governments have also explicitly drawn on the Planetary Boundaries framework in policy making (see Fig. 14). For instance, the Netherlands used the framework to conduct a quantitative assessment of environment-related SDGs in the national context, applying different fairness principles to translate Planetary Boundaries to the national level and accounting for both the territorial and consumption-based impacts of Dutch society.[219]

In New Zealand/Aotearoa the Ministry for the Environment commissioned a 2020 study to inform the country's current national policies and target-setting under the 2030 Agenda.[218] In Belgium, the framework has been translated to support national assessment of climate and environmental risks.[220] At the European Union level (EU), the Planetary Boundaries framework was operationalised to support the EU's 7th Environment Action Programme (EAP), "Living well, within the limits of our planet".[221,222] This framing continues in the EU's 8th EAP, which sets the 2050 objective for EU citizens to "live well, within Planetary Boundaries in a wellbeing economy".

INFO BOX 5

Translating Planetary Boundaries Across Scales: Nations, Cities, and Businesses

Translating the Planetary Boundaries framework into actionable targets, performance metrics and transformation pathways for different actors is an active area of transdisciplinary research. These "translation" efforts seek to bridge global scientific assessments with local and sector-specific decision-making.

Scholars have emphasized that effective operationalization needs to address three dimensions: biophysical, socio-economic, and ethical.[223] The biophysical dimension involves understanding the geographical characteristics and scales of planetary processes and the system interconnections: Local actions can have global effects. The socio-economic dimension evaluates environmental impacts created by production, consumption, and international trade. This means looking at environmental impacts both from a territorial production perspective as well as by taking the global impacts of local consumption into consideration. The ethical dimension focuses on equity and fairness, i.e., how the global safe operating space is shared, taking into account differences in countries' rights, capacities, and historical responsibilities.

Researchers also stress the importance of using scientifically rigorous and transparent methods, informed by Earth system science and global perspectives. This includes integrating principles of equity both within and in-between generations, applying precautionary approaches, and designing systems that are adaptive to new knowledge and conditions over time. Additionally, successful translation requires that targets are clear, motivating, and aligned across actors and scales, ensuring they are understandable, ambitious, and coherent.[224]

Aligning national environmental policies, city planning and business strategies with Planetary Boundaries is a transdisciplinary process between scientists and decision makers. More research efforts are needed to address uncertainties involved in nonlinear interactions among different boundaries, different socioeconomic contexts, consequences of different choices of sharing principles and procedures, and governance and accountability mechanisms.[225]

City and Subnational Government Initiatives

Urban areas are playing an increasingly important role in addressing Planetary Boundaries by experimenting with innovative governance models, advancing sustainable infrastructure, and serving as living laboratories for sustainability transitions. Pioneer cities include Amsterdam, Brussels, Melbourne and Copenhagen.

At the city scale, the Planetary Boundaries framework has often been operationalised through the concept of 'doughnut economics', which integrates the ecological ceilings defined by Planetary Boundaries with the social foundations needed for human wellbeing[109]. A leading example is Amsterdam, which in 2020 was the first city to adopt doughnut economics as a guiding framework for its post-COVID recovery and long-term planning. Amsterdam created a City Portrait that maps out the ecological and social impacts of its policies both locally and globally, including assessing how the city impacts Planetary Boundary processes (e.g. carbon emissions, nitrogen cycles, material use), as well as evaluating how the city meets social needs (e.g., housing, education, equity). The aim was that the model could guide city-wide strategies and developments towards ensuring a high quality of life for all while avoiding additional pressure on the planet.

Similar approaches are being piloted elsewhere. In Sweden, for example, the municipalities of Kalix, Tomelilla and Vadstena are currently experimenting to integrate ideas and tools from doughnut economic thinking in their energy and climate work.[226]

Business and Financial Sector Responses

Growing awareness of the need for societies to operate within Earth's safe operating space is prompting an increasing number of companies to translate the Planetary Boundaries framework into business strategies and operational practices. This shift reflects a broader recognition that long-term business viability depends on environmental sustainability across all sectors.

A range of companies – including Unilever, DSM, Walmart, H&M, Patagonia, Houdini, L'Oréal, Kering, Ericsson, Hitachi, McKinsey, Arup, and BCG – are engaging with Planetary Boundaries to guide decision-making and innovation.[213] In addition, initiatives such the World Business Council for Sustainable Development 2050 vision align with the Planetary Boundaries,[227] and the Business for Nature coalition is working towards action on global environmental sustainability.

One key avenue of how businesses are aligning with Planetary Boundaries is by setting science-based targets for nature. In particular, the Science Based Targets Network (SBTN) supports companies and cities in developing such targets to reduce their environmental impact in line with Planetary Boundaries by providing science-based guidance, tools and methods. Building on the success of the Science Based Targets initiative (SBTi) for climate, SBTN has expanded the scope to include nature-related issues such as biodiversity, freshwater, land use, and ocean health.

Despite this progress, voluntary adoption creates challenges for implementation. Science-based targets for climate are becoming increasingly mainstream in the corporate sector, but targets aligned with other Planetary Boundaries remain limited.[228] While there is a noticeable rise in the number of Fortune Global 500 companies acknowledging and addressing nature-related risks between 2022 and 2024, the majority have yet to set measurable ecological targets for their broader Earth system impacts (Fig. 16).

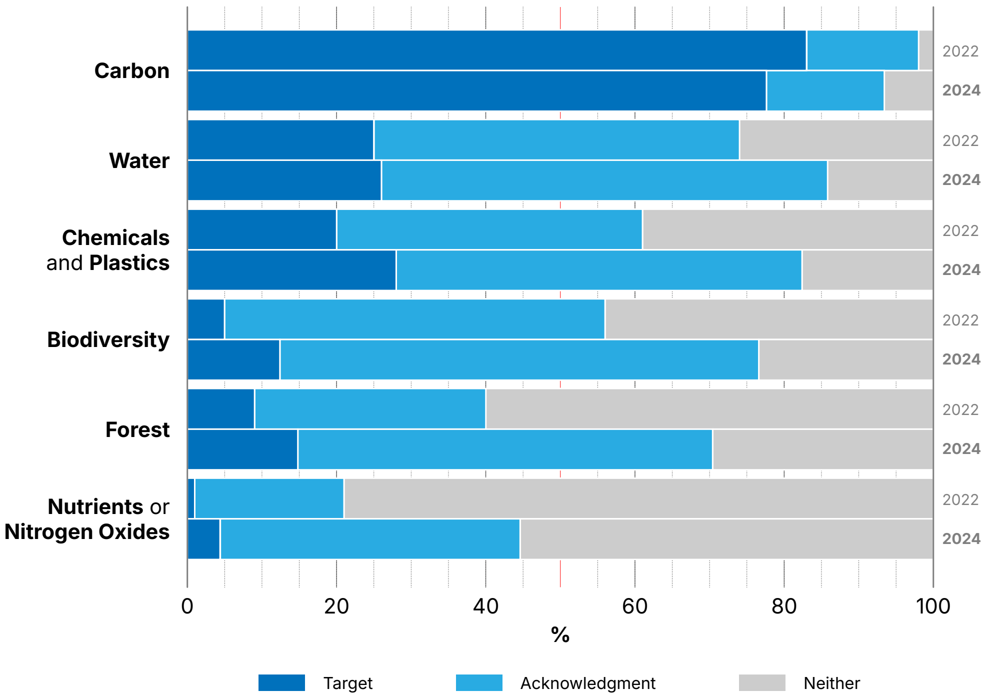


FIGURE 16 - Fortune Global 500 companies with nature-related targets or acknowledgements, 2022 vs 2024. Corporate targets are common for carbon emissions but far less common for other Planetary Boundaries. Adapted with permission from McKinsey & Company (2024). Copyright (c) 2025 McKinsey & Company. All Rights reserved.[228]

There is growing recognition of the financial sector's critical role in driving the transition to a more sustainable economy. New initiatives are pushing for better corporate transparency, accountability, and risk management related to sustainability. For example, the Global Reporting Initiative (GRI) promotes environmental (as well as social and economic) reporting standards that cover many Planetary Boundary processes, including climate, water, and biodiversity, even though it does not explicitly use the PBs framework. By asking companies to report their total environmental impacts, the GRI makes it possible to compare performance against science-based global limits.

Meanwhile, international frameworks are increasingly helping companies understand and disclose how environmental risks affect their business. The CDP (formerly the Carbon Disclosure Project) supports corporate disclosure of environmental data related to climate, water and forests impacts. The IFRS Sustainability Disclosure Standards, developed by the International Sustainability Standards Board (ISSB), establish a global baseline for sustainability reporting. These standards offer investors consistent information on sustainability-related risks and opportunities, including specific climate-related disclosure requirements. Expanding the focus beyond climate, the Taskforce on Nature-related Financial Disclosures (TNFD), launched in 2021, encourages companies to assess and report their dependencies and impacts on nature, both of which can pose financial risks. While these frameworks provide valuable insights on the sustainability of business, there is still room to improve the link between corporate activities and their impacts. In particular, aligning materiality assessments with actual environmental impacts and incorporating absolute metrics, alongside relative ones, would enhance the credibility and comparability of corporate sustainability reporting.[229]

INFO BOX 6

Tools and Approaches to Measure Company Progress in Relation to Planetary Boundaries

A growing number of tools are being developed to help companies measure and reduce their environmental impacts in line with the Planetary Boundaries framework.

One promising approach are the life cycle assessment (LCA) based methods for absolute environmental sustainability assessment.[230] These methods translate Planetary Boundaries to the scale of specific products, services, and systems, and convert quantified resource use and emissions into changes in the control variables of Planetary Boundaries. This approach allows companies to assess whether their impacts fall within their allocated share of each boundary. By enabling absolute sustainability assessments, rather than focusing solely on relative improvements, this approach helps businesses understand the full environmental impact of their operations. It also strengthens their ability to set science-based targets and to monitor progress in alignment with Planetary Boundaries.

Researchers have also proposed a set of Essential Environmental Impact Variables (EEIVs)[229] to guide corporate environmental reporting and disclosures. It works by translating resource use and emissions into changes in the Planetary Boundaries' control variables, enabling absolute sustainability assessments. This approach allows businesses to set science-based targets and track progress on their environmental impacts related to the Planetary Boundaries.

The Earth System Impact (ESI) score[231] integrates spatial data and accounts for interactions between different Planetary Boundaries. It provides location-specific estimates of a company's impacts on CO_2 emissions, land use, and water use. This helps identify environmental pressure hotspots on these three key dimensions and informs strategic sustainability planning.

The Planetary Risk and Opportunities tool, developed by SYSTEMIQ and the Planetary Guardians, supports companies in understanding their exposure to both physical and transition risks related to Planetary Boundaries. It aims to expand corporate strategies beyond climate alone, linking with frameworks such as the SBTi and SBTN to offer a more comprehensive risk and opportunity assessment aligned with Earth system science.

Similarly, WWF's One Planet Business Framework enables companies to assess and address environmental risks and opportunities in their operations, focusing on areas like climate change, resource use, and biodiversity.

These are examples of tools and approaches that are being developed to improve comparability, transparency, and accountability of corporate actions in relation to Planetary Boundaries. Eventually, they can also help contribute to finding targeted mitigation strategies.

Civil Society and Community-Led Approaches

Civil society organizations, communities, and social movements are playing a growing role in advancing planetary health through advocacy, education, and grassroots innovation. Around the world, diverse initiatives are translating the Planetary Boundaries framework into action, helping to reimagine how societies can thrive within Earth's limits while promoting social justice.

Integrating Planetary Boundaries into infrastructure design can support more sustainable and regenerative cities.

In urban design and planning, the Planetary Boundaries framework has guided city designers, engineers, consultants, and advisors in identifying new ways to design, build, and operate restorative urban systems that address both the causes and impacts of planetary crises. For instance, Arup[232] has shown how integrating Planetary Boundaries into infrastructure design can support more sustainable and regenerative cities.

Similarly, the doughnut economics model has been adapted to guide the construction industry. A recent manual[233] illustrates how architects and planners can use this framework to steer construction practices towards a safe and just space for humanity, balancing environmental integrity with social foundations.

Food systems are another domain where civil society has been particularly active. The EAT-Lancet Commission on Food, Planet, Health helped catalyze global attention on sustainable and healthy diets. Its recommendations are now being adapted by local communities and social movements around the world to promote plant-forward, culturally appropriate eating patterns that reduce environmental impacts while improving public health.

Educational campaigns and grassroots action are also gaining traction through frameworks such as WWF's One Planet Perspective, which aligns closely with Planetary Boundaries science. This initiative supports civil society efforts to promote sustainable consumption, biodiversity conservation, and circular economies. By offering a systemic lens on sustainability, it helps local actors drive change in infrastructure, markets, and public awareness.

Broader societal transformations are also being supported through initiatives like the "Good Life for All Within Planetary Boundaries" project.[102] This work provides a compelling visualization of how nations are performing relative to both social and planetary thresholds, and raises critical questions about how to achieve well-being for all without overshooting Planetary Boundaries.

Lastly, the Nature Positive Initiative – a coalition of major conservation organizations, scientific institutions, and businesses – has adopted Planetary Boundaries thinking in its call to halt and reverse nature loss by 2030 and achieve full recovery by 2050. This goal, aligned with the Kunming-Montreal Global Biodiversity Framework, is supported by practical tools and guidance for stakeholders across sectors.

These are just a few of the many ways in which civil society is mobilizing around the vision of living within Planetary Boundaries. While not exhaustive, they illustrate the breadth and creativity of bottom-up efforts to reconfigure systems for a more just and sustainable future.

Conclusion

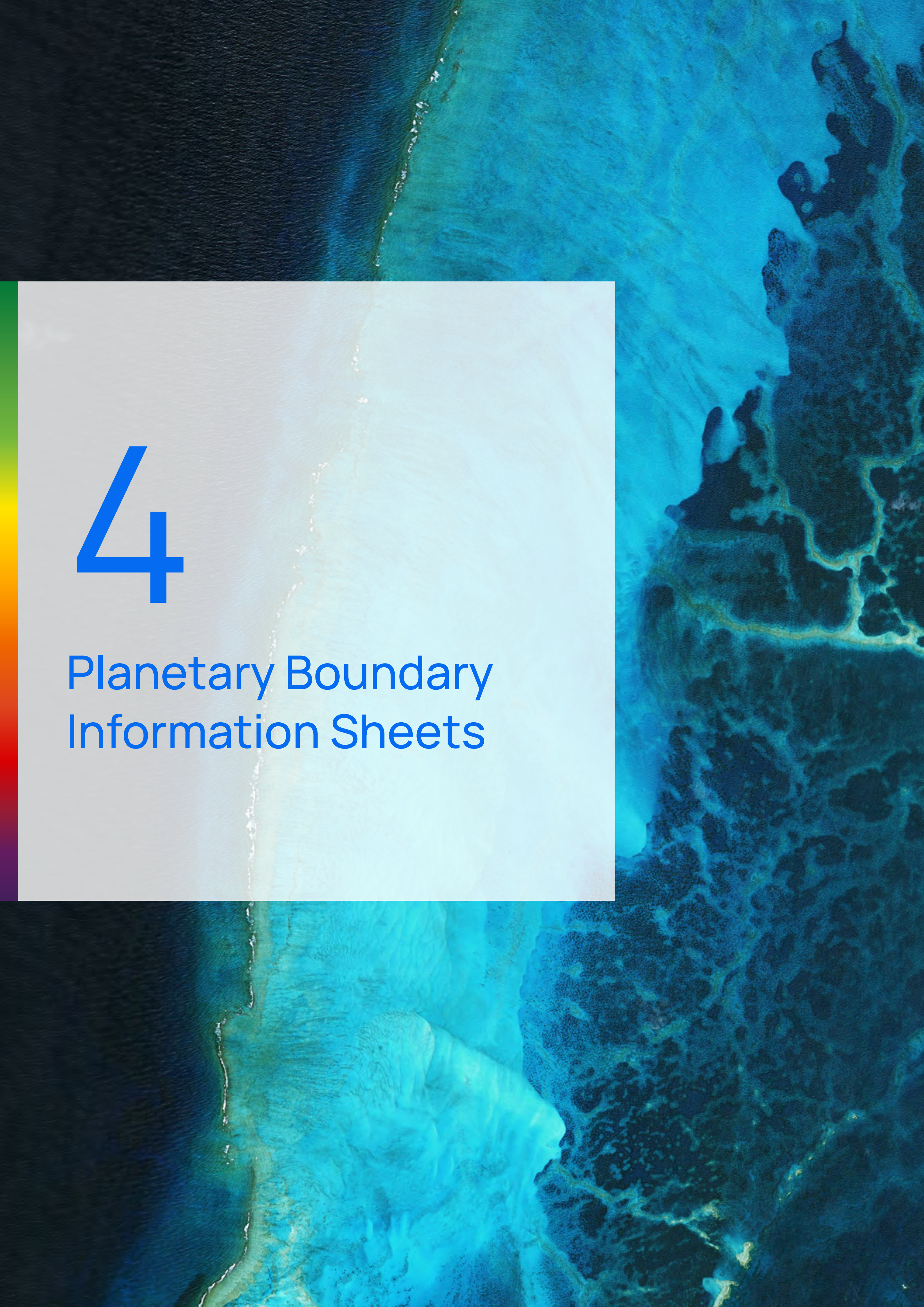
Planetary Boundaries thinking is gaining momentum across sectors and governance levels. More than just a systems approach to environmental challenges, it represents a fundamental shift in how human activities are understood and governed in the context of the entire Earth system. By framing socio-economic development within the biophysical limits of a stable and resilient planet, Planetary Boundaries thinking repositions human activity as part of – not apart from – the Earth system. This Anthropocene-adapted perspective highlights the need to operate within absolute biophysical constraints, in contrast to conventional goals of relative improvement.

Crucially, the recognition of absolute boundaries raises unresolved but essential questions of fairness, equity, and ethics: How should the remaining environmental space be equitably shared among nations, communities, and economic actors? These are not technical questions alone, but political and moral ones that demand inclusive societal deliberation.

By framing socio-economic development within the biophysical limits of a stable and resilient planet, Planetary Boundaries thinking repositions human activity as part of – not apart from – the Earth system.

The Planetary Boundaries framework also provides a much-needed organizing logic for integrating environmental governance across scales – from local to global – and across sectors. This integration can enable more coherent and effective responses to escalating environmental pressures, reducing fragmentation and aligning actions with the biophysical reality of a shared planet.

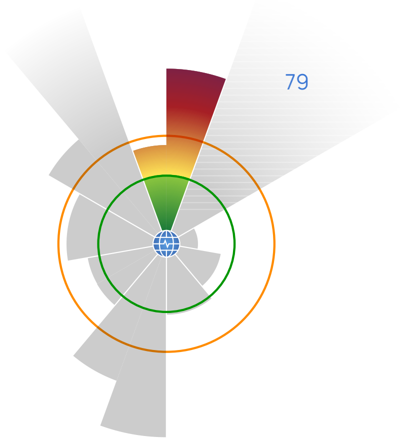
To fully realise the potential of Planetary Boundaries, further scientific, policy, and societal efforts are needed to operationalise the framework at multiple scales. This includes developing methodologies for cross-scale translation, building accountability mechanisms, and supporting context-specific pathways for transformation. Ultimately, adopting a Planetary Boundaries lens compels a societal dialogue about the deep changes needed in our economies, governance, and lifestyles to ensure sustainable and just futures.



4

Planetary Boundary Information Sheets

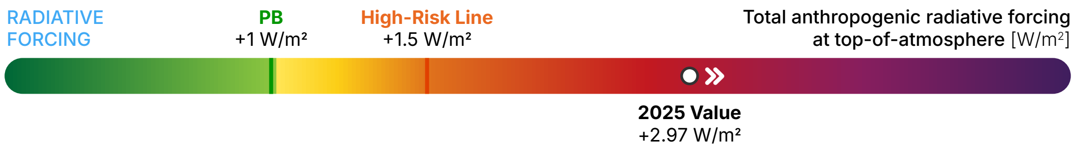
4.1 Climate Change



Main Takeaways

Climate change is disrupting the Earth's climate system in ways that threaten the foundations of human wellbeing. 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 stabilize the Earth's energy balance, which is a necessary condition for the overall stability of the climate system. A stable climate is in turn also vital for the reliable functioning of most Earth system processes. Today, human activities that disrupt the Earth's energy balance are the primary driver of climate change. This disruption is most notably through the accumulation of greenhouse gases, such as CO_2, which trap heat in the atmosphere and thereby destabilize the climate system.

2025 Status

Both the atmospheric concentration of CO_2 (423 ppm) and the total anthropogenic radiative forcing at the top of the atmosphere (+ 2.97 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 Variables

#1 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.[3] 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. [234]
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.[52,235,236,237] 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.[4]

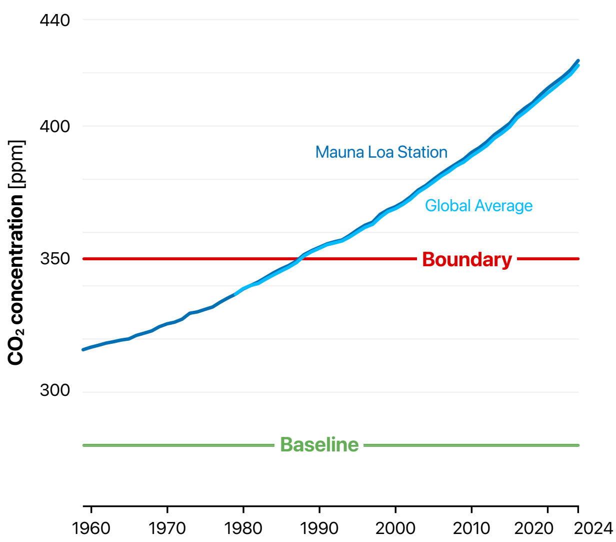


FIGURE 17 - Atmospheric CO_2 concentration far exceeds the safe level. This figure illustrates the steady increase in the atmospheric CO_2 concentration, as one of the **Climate Change** boundary's control variables. The dark blue line represents annual mean values from 1959 to 2024 at the Mauna Loa Observatory in Hawaii, operated by the National Oceanic and Atmospheric Administration (NOAA).[238] The light blue line shows globally averaged CO_2 concentrations from multiple international monitoring sites,[238] 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.

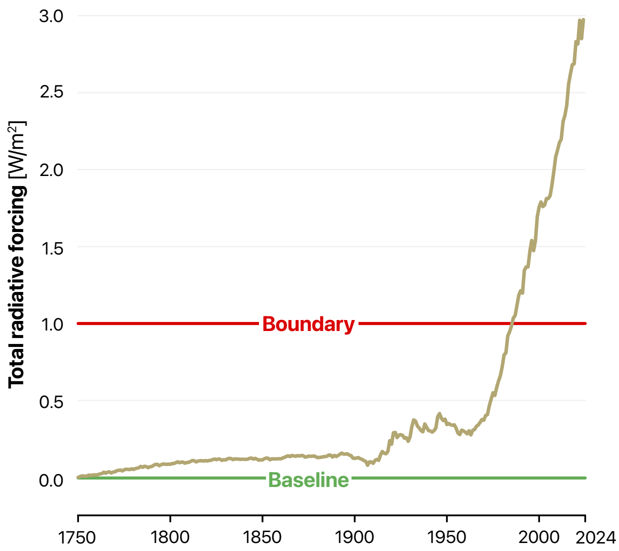
Key takeaway: *CO_2 continues to rise and remains the dominant driver of climate change, with current levels approximately 50% above pre-industrial concentrations.*

#2 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.[3] While direct 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,[239,240] 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.[241]
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.[1] Exceeding this boundary increases the risk of irreversible climate impacts and long-term 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 2024.[242] 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.[243] 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 in the atmosphere. 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).[244,245] These gases stay in the atmosphere for years or even centuries, steadily warming the planet.[246] Water vapor is also a powerful greenhouse gas, although it mostly increases as a feedback when the planet gets warmer, primarily due to the increase in CO_2.[247]

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.[248] 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.[249]

These changes are closely linked to major sectors of the economy. Energy production, transportation, and agriculture are among the largest sources of greenhouse gases.[249] Decisions that societies make in areas such as electricity production, food production, and transportation therefore have a major impact on the climate.

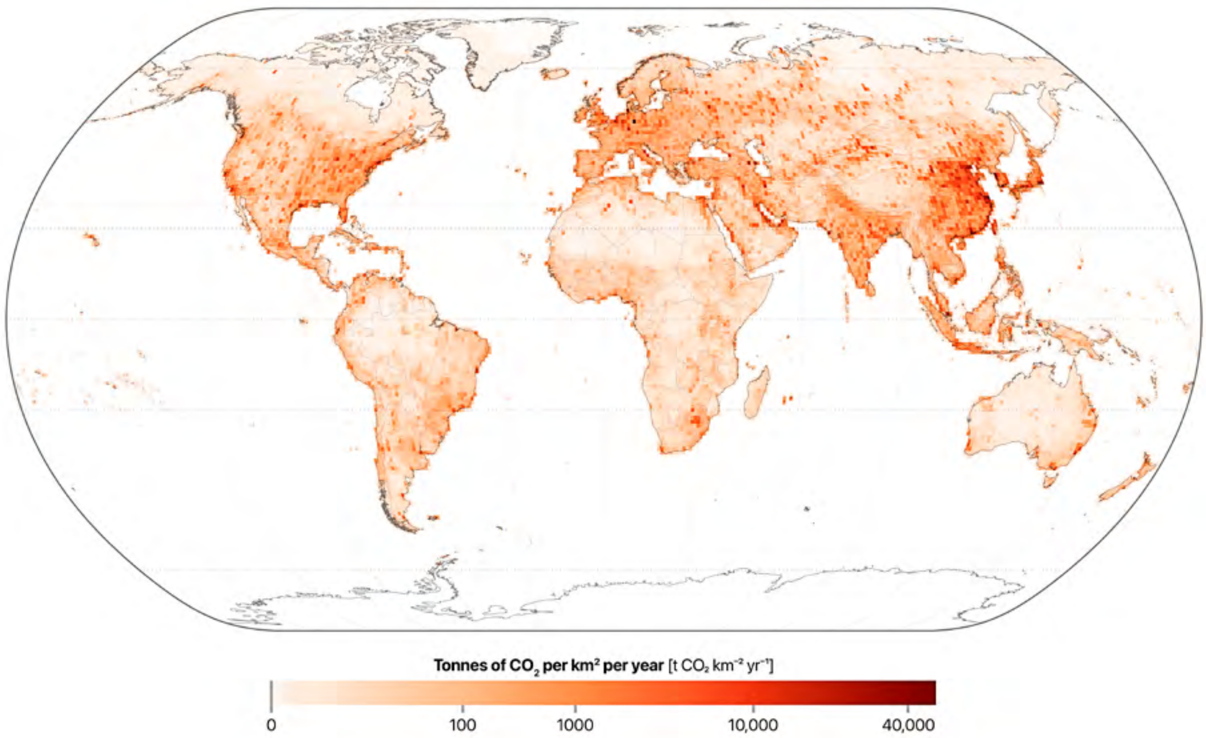


FIGURE 19 - Where climate change begins – Global patterns of fossil CO_2 emissions. The map shows fossil CO_2 emissions intensity in 2024, expressed as tonnes of CO_2 per square kilometer per year on a 1° × 1° grid. This data from Climate TRACE combines satellite observations with AI models to measure emissions from thousands of individual facilities worldwide.[250] 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 fires.*

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.[251] Human-driven climate change now far exceeds natural variability.[252]

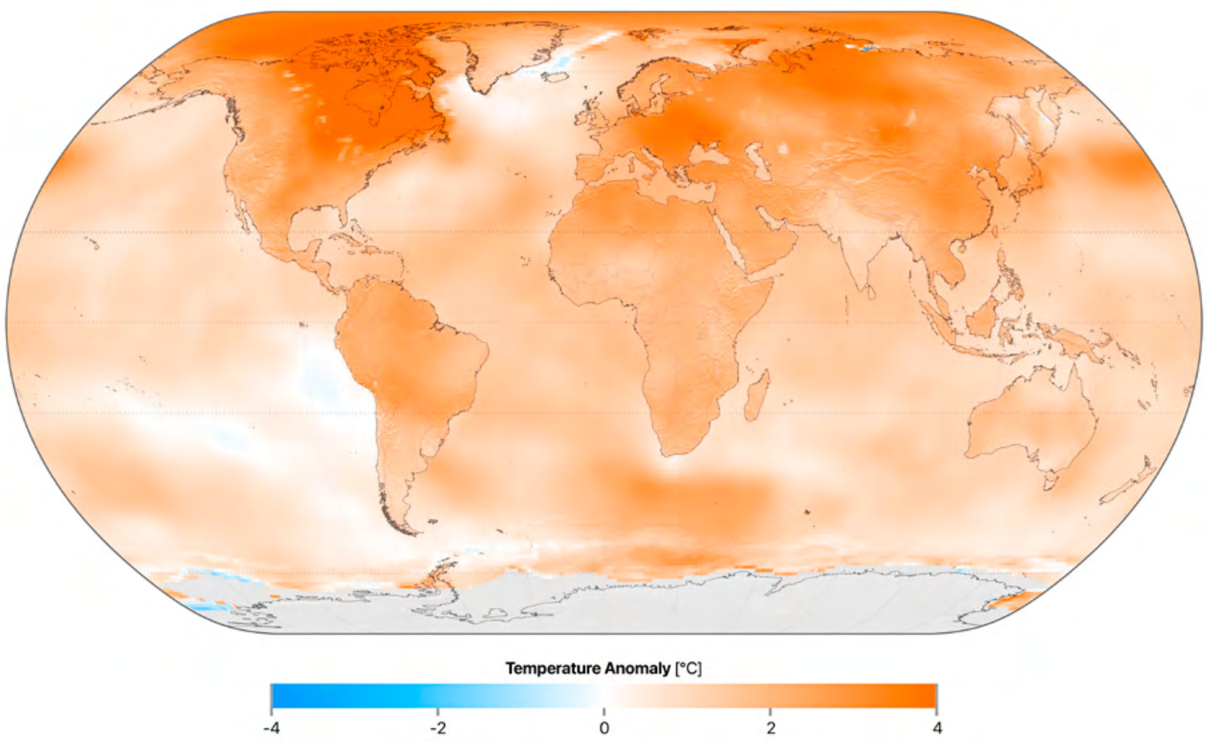


FIGURE 20 - How Earth's temperature has changed since the late 19th century. This map shows how the Earth's surface temperature[253] changed in 2024 compared to the average from 1880 to 1899, before modern climate change began. Red areas are warmer, while blue areas are cooler.

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.

Ecosystems are under growing pressure. In the oceans, warming and acidification disrupt food webs and force species to migrate.[139] On land, ecosystems are degrading, and species are struggling to adapt.[254] Agriculture and food security are increasingly vulnerable. Shifting rainfall patterns and rising temperatures affect crop yields and water availability, threatening livelihoods and regional stability.[255,256] 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.[252]

Climate change also impacts human health, increasing exposure to heat stress, air pollution, and disease.[257] 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, crossing 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.

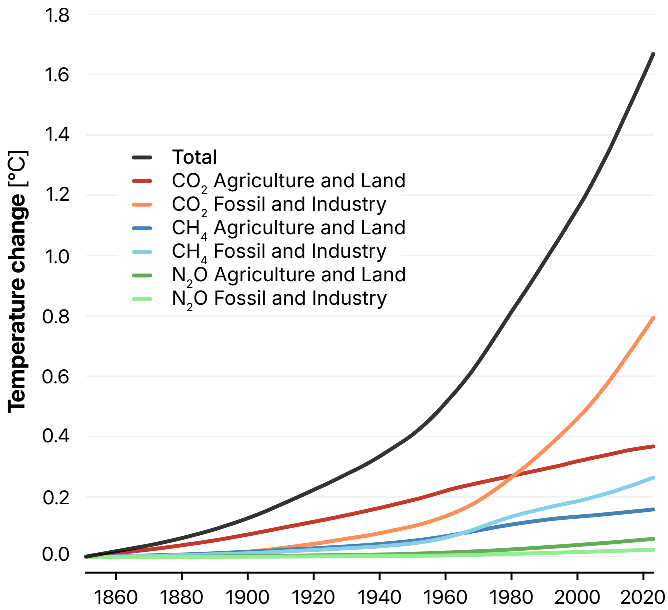
Current and Future Research

CO_2 concentration and new 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: CH_4 is ~28 times more potent over a 100-year period, and N_2O is ~265 times more potent.[258] 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,[259] which are widely used in policy contexts and underpins 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.

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) [260,261]. 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.*



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.[52] 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 measurable 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

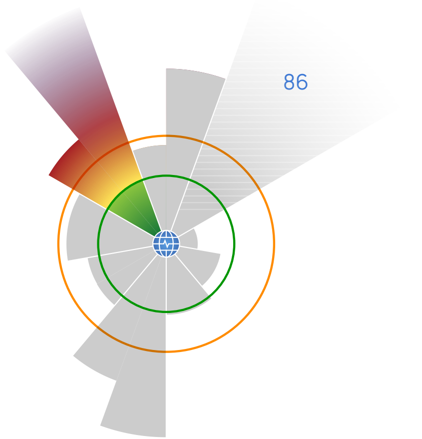
CO_2 Emissions data from Climate TRACE (2025), accessed 16-Jun-2025.

Data on global temperatures from Berkeley Earth.[253,262]

Data on CO_2 concentrations from Lan et al. (2025),[238] accessed 05-Jun-2025.

Data on anthropogenic TOA radiative forcing: Forster et al. (2025).[242].

Other Greenhouse gases: Data adopted from Jones et al. (2023)[260] and Jones et al. (2024).[261]

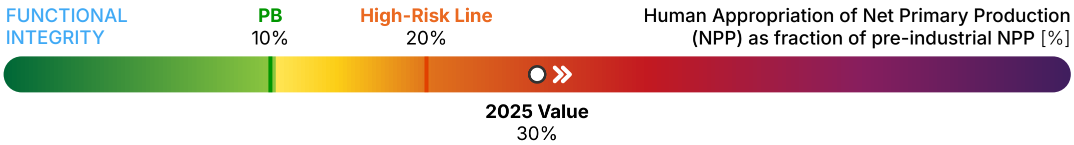


4.2 Change in Biosphere Integrity

Main Takeaways

Biosphere Integrity refers to the capacity of ecosystems across the planet to support life and maintain the overall health and stability of the Earth system. This depends on the health, diversity, and interactions of the organisms that make up these ecosystems. Human activities are putting increasing pressure on Biosphere Integrity: through land-use change (such as expanding agriculture, livestock, cities, and industry), 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 and changes in nutrient cycles. Today, the Planetary Boundary for Biosphere Integrity is strongly transgressed. When Biosphere Integrity is compromised, the resilience of the Earth system is weakened, threatening the essential conditions that support 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, and water flows within and across interconnected, healthy ecosystems. Alarmingly high extinction rates along with the loss of habitats manifest in the decline in genetic diversity and functional intactness of ecosystems and organisms. This threatens the biosphere's ability to co-regulate and stabilize the state of the planet.

2025 Status

Both the control variables for genetic diversity and the decline in the functional integrity of the biosphere have **exceeded their safe levels**. Globally, species are going extinct at an alarming rate of above 100 extinctions per million species-years (Fig. 22, PB: 10 E/MSY), and humans are using 30% of the available energy from nature (Fig 23 and 24, PB: 10%). There have been no new estimates for both control variables since the last Planetary Health Check. Additional datasets have been published that report varying values for the biosphere's functional integrity.[263,264,265] These studies differ methodologically in e.g. reconstructing reference conditions and selecting land use components. Therefore updating the control variables based on their findings awaits more comprehensive evaluation. Nevertheless, all available studies consistently place the level of transgression within the high-risk zone for biosphere integrity.

Control Variables

#1 Genetic Diversity: Species Extinctions Rate

Definition	The decline in genetic diversity and functional intactness of ecosystems and organisms, 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 Extinctions Rate** describes the speed at which species disappear. High species extinction rates indicate a loss of species diversity, which is critical for maintaining ecosystem resilience and functionality. The Species Extinction Rates is used provisionally as a proxy for loss in genetic diversity and may be refined as more data become 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.[266]
Planetary Boundary (PB)	The PB is set at 10 E/MSY.[3] This is set in relation to the background extinction rate, with 10x faster rate of loss of species compared to the natural background rate being the best expert judgment of 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.

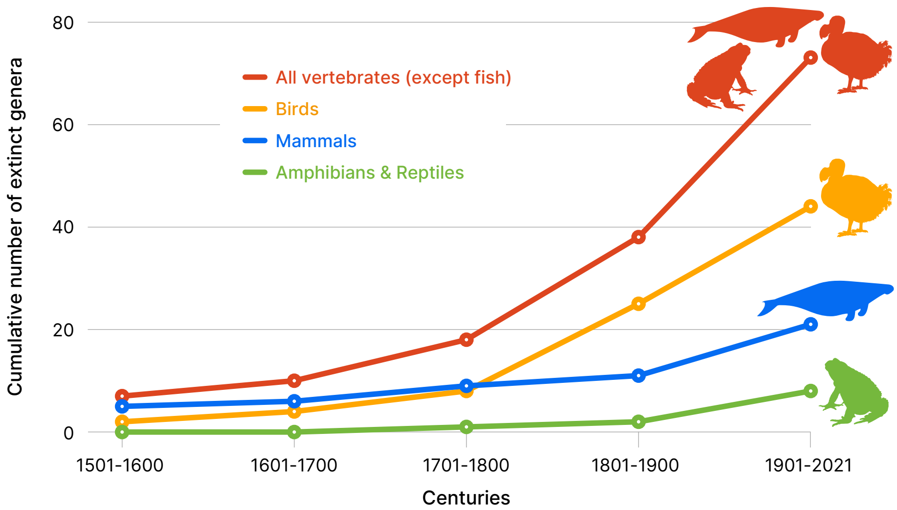


FIGURE 22 - Species extinctions accelerating globally. Cumulative number of extinctions of genera (closely related species with likely common ancestors) per century in different classes of vertebrates. This graph shows that at least 73 genera became extinct over the last 500 years. Similar estimates for mammals, birds and fish indicate a total extinction rate of up to 100 E/MSY. Data from Ceballos & Ehrlich (2023)[267].

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 PB transgressions.*

#2 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 organic matter (biomass) in an ecosystem, after accounting for the organic matter they use for respiration. NPP is a fundamental measure of ecosystem productivity and health and serves as a proxy for the energy flow into the biosphere, which all life processes depend on. HANPP measures the extent to which human activities, such as agriculture, forestry, and urbanization, 1) inhibit net primary production and 2) withdraw energy by harvesting products for human use and consumption.
Unit	HANPP is measured in petagrams of carbon appropriated per year. In the context of PB, HANPP is measured as a fraction of the natural Holocene reference NPP (i.e. the natural state of exergy flow into the biosphere).
Historical Range	In the absence of 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 pre-industrial NPP shifting into the zone of high risk at 20%. Those thresholds are based on observational data and ecological modeling, which reveal negative trends in several critical metrics of biosphere functioning.[4] As NPP is the basis for the energy and materials flow that underpins the biosphere's functioning,[268] today's impact of HANPP reflects the significant declines seen across major indicators of ecosystem health.

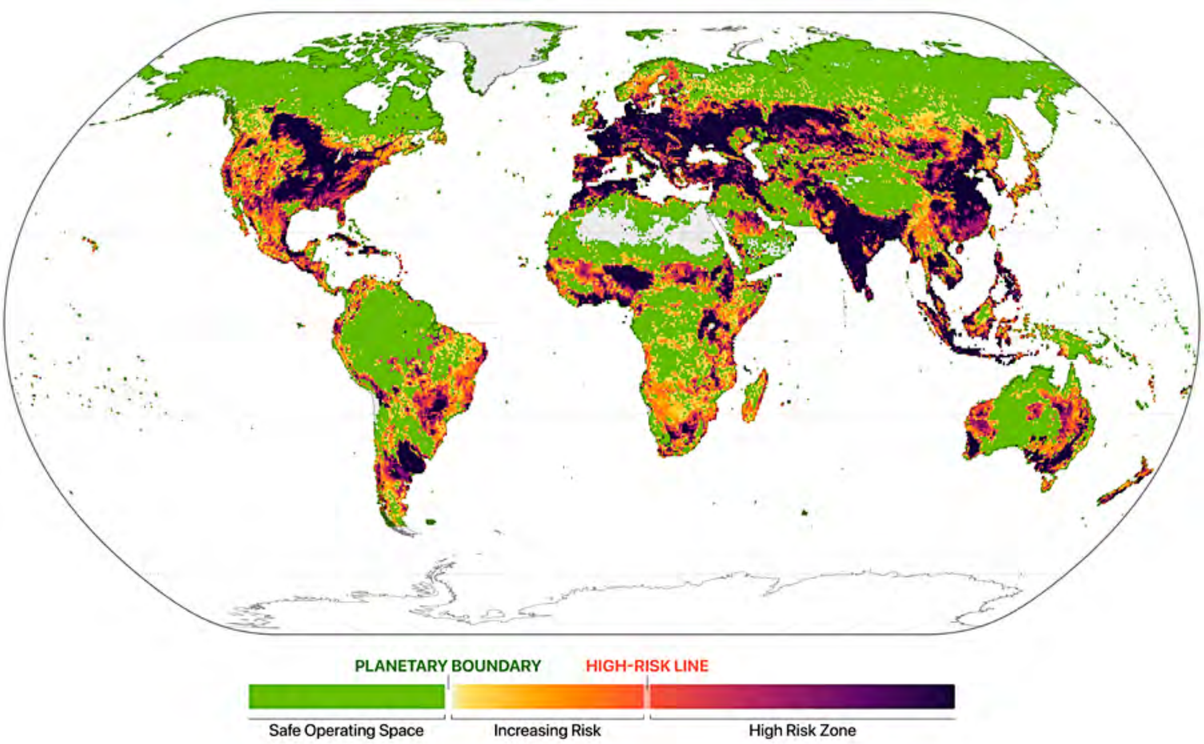
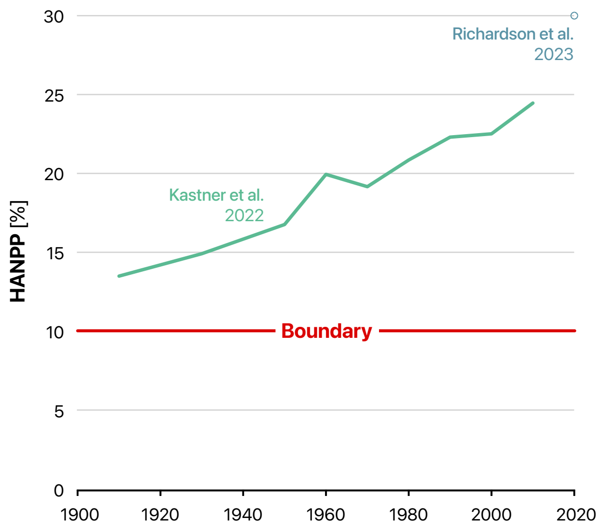


FIGURE 23 - Global risk map of Change in Biosphere Integrity – HANPP. Transgression is based on the HANPP control variable. All values shown on the map refer to the year 2010. Based on data from Kastner et al. 2022.[269]

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.*

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) of the year 1910. The time series is presented as 10-20 year means and covers the period from 1910 to 2010. The 2020 estimate of 30% is based on an analysis from Richardson et al., 2023[4]. The red line shows the Planetary Boundary of about 10% based on Richardson et al., 2023.[4] Different estimates have been published, and the measurement is associated with significant uncertainties.[263,264,265] However, all measurements agree that HANPP is currently in the High-Risk Zone.

Key takeaway: *The current HANPP has exceeded the Planetary Boundary 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 rapid expansions in agricultural and livestock farming lands, as well as direct exploitation of ecosystems through human activities such as fishing and logging.[270] Climate change, pollution, and the introduction of invasive species further exacerbate these pressures.[270] These stressors often interact in complex ways, introducing significant uncertainty into predictions of future biodiversity loss.[271,272]

Human appropriation of net primary production (HANPP) for human consumption such as food, fuel, fodder, and fiber has historically exceeded sustainable levels for over a century (Fig. 24).[4] This extraction of energy from the biosphere varies across different biomes (Fig. 23); on land, it involves harvesting plant materials and conversion of natural ecosystems into less productive managed lands.[273] 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.[274,4]

Impacts

The impacts of losing the integrity and functioning of the biosphere are hard to overstate. The biosphere co-regulates the overall state of the Earth on many levels, as it is closely tied into our planet's biogeochemical cycles and energy balance. The loss of vital services provided by ecosystems also has the potential to deprive our societies of irreplaceable sources of food and feed, energy, materials and medicines, while destabilizing the entire Earth system.[270] Examples are the loss of pollinators, which are needed for more than 75% of food crop species,[275] and the loss of CO_2 uptake sequestration capacity, which could significantly accelerate climate change.[270,276]

Current and Future Research

Current assessments of biosphere integrity do not include the oceans. In addition, to fully measure the biosphere in its different facets, we need better control variable indicators that reflect the variety of life and its roles (functional diversity), along with a deeper understanding of how organisms interact within ecosystems to provide resilience, adaptability, and regulatory capacity – what scientists call biocomplexity.[277,278,279,280,281] Here we outline ideas for how current shortcomings could be addressed in the future.

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, or disruptions of the biogeochemical cycles of water, carbon, and nitrogen. To address this, the novel biosphere integrity metric **EcoRisk** was developed by Stenzel et al. to quantify these changes as a proxy for the risk of ecosystem destabilization, based on simulations with the Dynamic Global Vegetation Model LPJmL5.[265] **EcoRisk** indicates that many ecosystems have significantly degraded compared to the pre-industrial state. High-risk regions include areas of intense land use and deforestation, as well as climate-sensitive zones such as deserts (Fig. 25). A comparison with other biosphere integrity metrics yields local thresholds for **HANPP** and **EcoRisk** as local boundary control variables. Globally aggregated, 60% of the ice free land surface is currently transgressing these local boundaries, with 38% already being at high risk of degradation.[264]

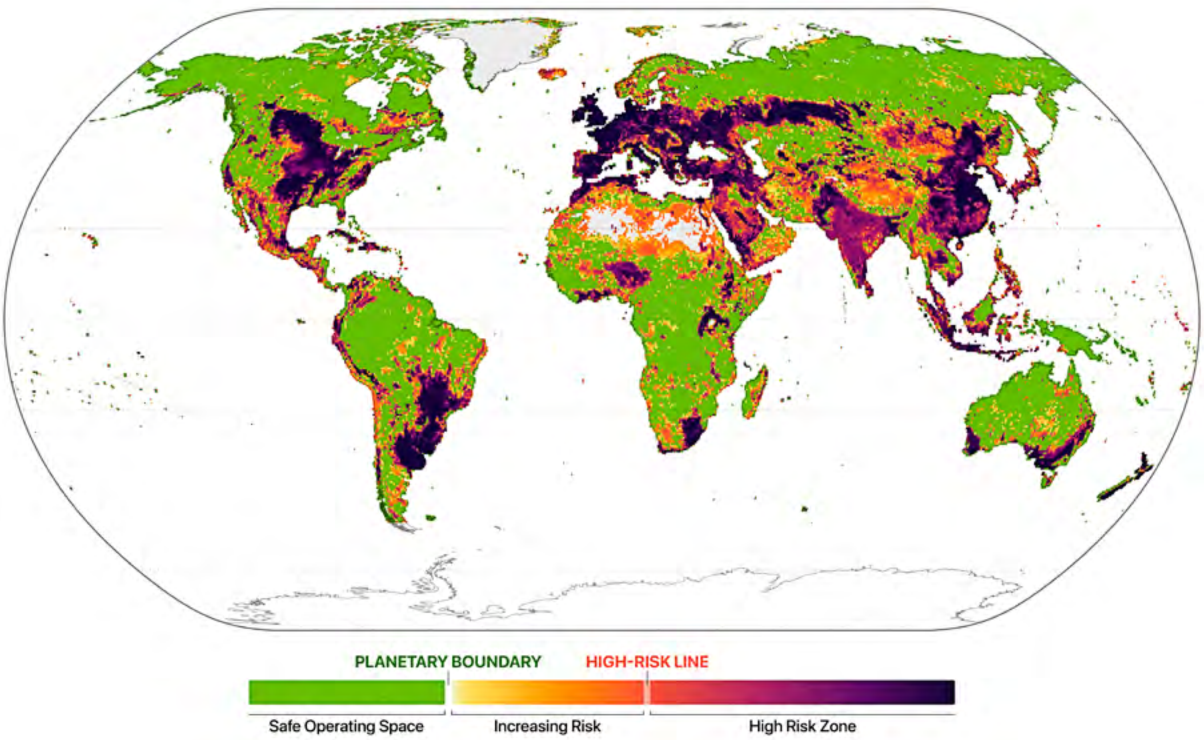


FIGURE 25 - Global map of ecosystem destabilization risk based on the biosphere integrity indicator EcoRisk (status average 1987-2016 based on LPJmL model simulations). Regions with zero NPP are colored grey. Replotted from Stenzel et al. (2025)[264].

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.*

The Role of Biocomplexity for Planetary Functioning

Understanding the integrity of the biosphere requires attention to its multiple levels of biological organization. The biosphere is structured across nested levels of organization, from genes and individuals to populations, ecosystems, up to the entire Earth system. Key functions of the biosphere such as resilience, adaptability, and regulation emerge from interactions across these layers, which is described by the concept of biocomplexity.[282] Losses at any level could erode this interactive structure, potentially triggering cascades that undermine the stability of the broader Earth system.[283,284]

Current assessments of biosphere integrity focus on only two levels of biological organization: the genetic level, using extinction rates as a proxy for the loss of genetic diversity, and the ecosystem level, based on HANPP. While these indicators provide valuable insights into key aspects of biosphere integrity, they reflect only parts of the biosphere's broad complexity.

Efforts to develop more comprehensive biodiversity metrics are expanding,[285] with indices now assessing genetic, species, and ecosystem levels in tandem.[286,287] In the future they may help capture dimensions of ecological change that current indicators overlook. Building on this, recent initiatives such as the SEED index (Sustainable Ecology and Economic Development index,[287] Fig. 26) and the Ecosystem Integrity Index[286] (EII) aim to explicitly integrate data across multiple levels of biological organization. The first assessment of the SEED Index, carried out in 2024, identifies especially losses of biocomplexity in regions with intensive human activity, such as North America, Europe, China and India (Fig. 26). These patterns are broadly consistent with areas identified as high-risk by other indicators, including EcoRisk and HANPP, highlighting intensive human activity as a primary driver of ecological degradation (Fig. 23 and Fig. 25).

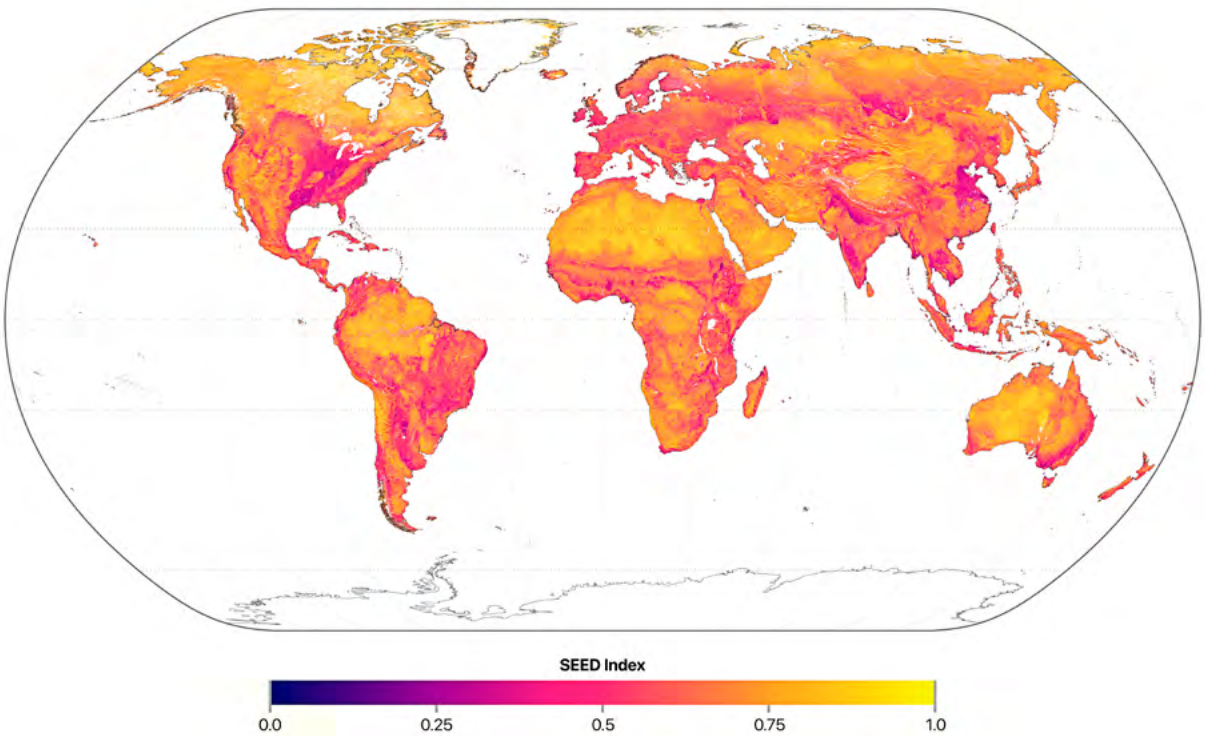


FIGURE 26 - Global biocomplexity measured by the SEED index. The index reflects integrated biocomplexity across genetic, species, and ecosystem levels.[287] Lower SEED values indicate regions with less intact biocomplexity, and vice versa. Patterns are broadly consistent with other indicators such as HANPP and EcoRisk (Fig. 23 and Fig. 25).

Key takeaway: *Regions with intensive human activity show notably lower SEED values, indicating significant losses in biocomplexity. Unlike HANPP or EcoRisk, the SEED index integrates genetic, species, and ecosystem-level information, providing a more comprehensive measure of biocomplexity loss across multiple biological scales.*

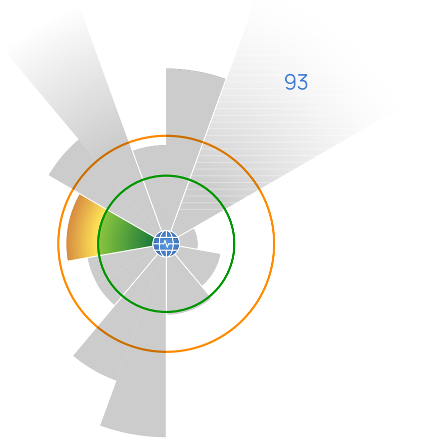
Despite these advances to better capture biocomplexity, key challenges remain. In the current available indices – including SEED and EII – critical thresholds at which biocomplexity loss threatens biosphere integrity are still poorly defined. To address this issue, Earth System Models with improved biocomplexity could play a key role.[288,289,290,291] Earth System Models are complex computer simulations that represent interactions between the atmosphere, oceans, land, and biosphere. With improved representation of biocomplexity, these models could be used to better understand how changes in biological diversity and interactions affect Earth system stability.[291]

The Role of the Ocean

Ocean warming, oxygen loss, acidification, overfishing, nutrient input, pollution, habitat destruction, and invasive species threaten marine ecosystems.[292,293] These disturbances also undermine functions like biological carbon uptake and storage. While the Planetary Boundaries framework includes marine life in the assessment of global genetic diversity, the functional integrity of marine life is not yet represented. Ongoing efforts by members of the PBScience Initiative and collaborating ocean scientists aim to integrate a specific control variable that reflects marine functional biosphere integrity, acknowledging its role in keeping the Earth system in a Holocene-like state.

Data Sources

Cumulative (1500-2022) extinctions from Ceballos & Ehrlich (2023).[267] HANPP data from Kastner et al. (2022)[269] and Richardson et al. (2023).[4]



4.3 Land System Change

Main Takeaways

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

Agriculture – especially livestock grazing and cropland expansion – is the leading direct cause, but deeper forces like illegal logging, infrastructure expansion, weak governance, and climate change also play major roles. In the Amazon, for example, deforestation often begins with illegal timber extraction before land is converted to pasture.

The impacts of forest loss are profound. It disrupts biodiversity, increases carbon emissions, alters rainfall patterns, and weakens soil and water systems. It also affects human health, for example by increasing malaria risk in deforested areas. Climate change and water stress are further amplifying damage through heatwaves, fires, and bark beetle outbreaks. If land degradation continues, it will weaken our chances of stabilizing the climate, securing water, and protecting biodiversity. To stay within safe limits, we must urgently protect and restore healthy ecosystems – keeping the land resilient, and Earth livable, for generations to come.

Definition

The Planetary Boundary for **Land System Change** defines the global threshold beyond which alterations in land use – particularly deforestation, agriculture expansion, and urbanization – compromise Earth's capacity to maintain ecological stability, biodiversity, climate regulation, and essential ecosystem services. Crossing this boundary increases risks of irreversible shifts in ecosystem structure and functioning, disrupting Earth's resilience and potentially triggering adverse feedback loops across multiple planetary systems.

2025 Status

Globally, only 59% of the potential forest cover remains, significantly below the safe threshold of 75%. This means that the remaining forest areas are globally **outside of the Safe Operating Space**. Even when considered individually, all major forest biomes around the world have breached their boundaries to varying degrees (see Fig. 27, Fig. 28).

Control Variable

Forest Area

Definition	Forest area is an accessible quantity and represents the area most responsible for maintaining major global ecological functions. 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'). It is determined for boreal, temperate, and tropical forest biomes (as contiguous area per continent) and globally aggregated. Although different land types have distinct functions in the Earth system, forests are most important for the climate system.[294]
Unit	Percentage (%) of potential forest cover.
Historical Range	The value of relative forest cover ranges from 100% (no difference between current and potential forest cover) to 0%.
Planetary Boundary (PB)	The PB for land-system change is set at 75% of the original forest cover, with safe levels specified for different biomes: 85% for boreal and tropical forests, and 50% for temperate forests.[3] These thresholds are based on studies indicating that tropical and boreal forests have a stronger influence on regional and remote climatic conditions than temperate forests.[294,295]

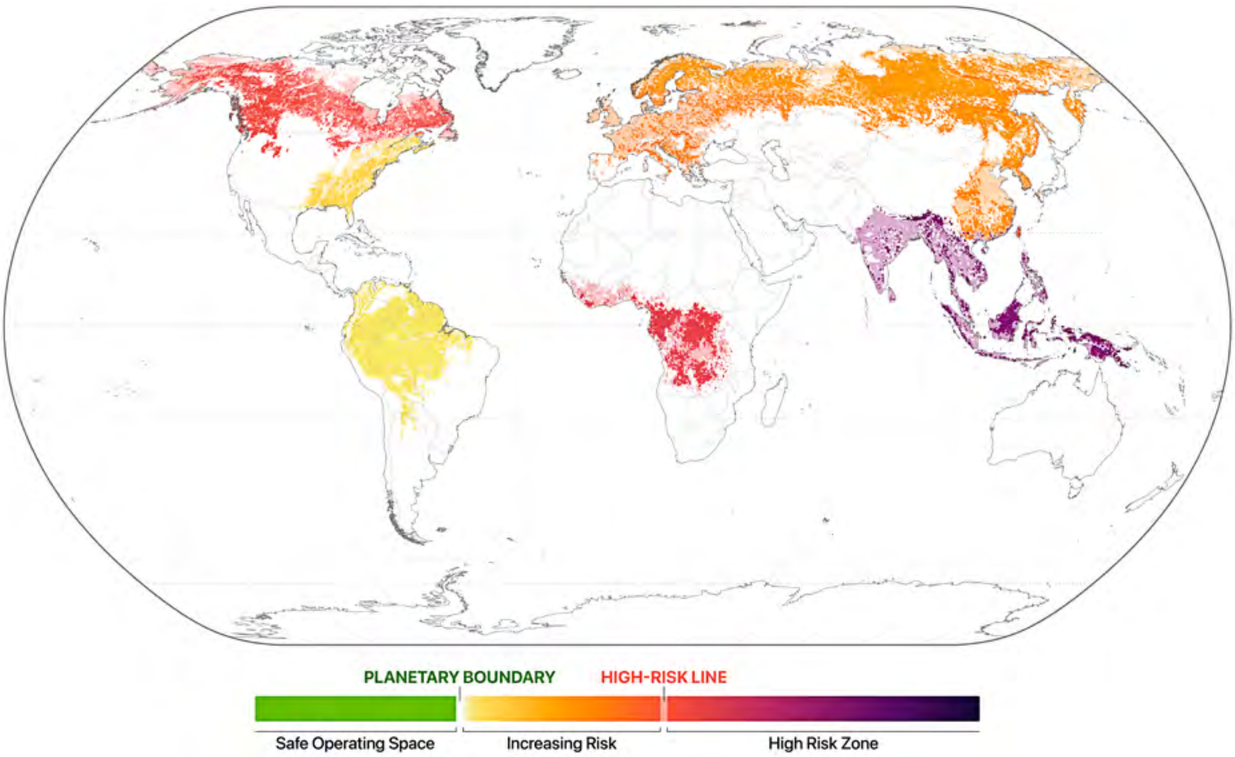


FIGURE 27 - Global risk map of the Land System Change boundary transgression – Forest area. Transgression is shown for the major continuous forest biomes as defined in Steffen et al. 2015.[3] Transgression is based on the control variable, remaining forest area. Lighter shades of a color indicate areas that were originally covered with forest but are now predominantly deforested. Areas without continuous potential forest cover are shown in grey. Based on data from Copernicus (2024) and Ramankutty & Foley (1999).[296,297]

Key takeaway: *The large continuous forest biomes of the Earth have all transgressed the Planetary Boundary, although with varying degrees of transgression.*

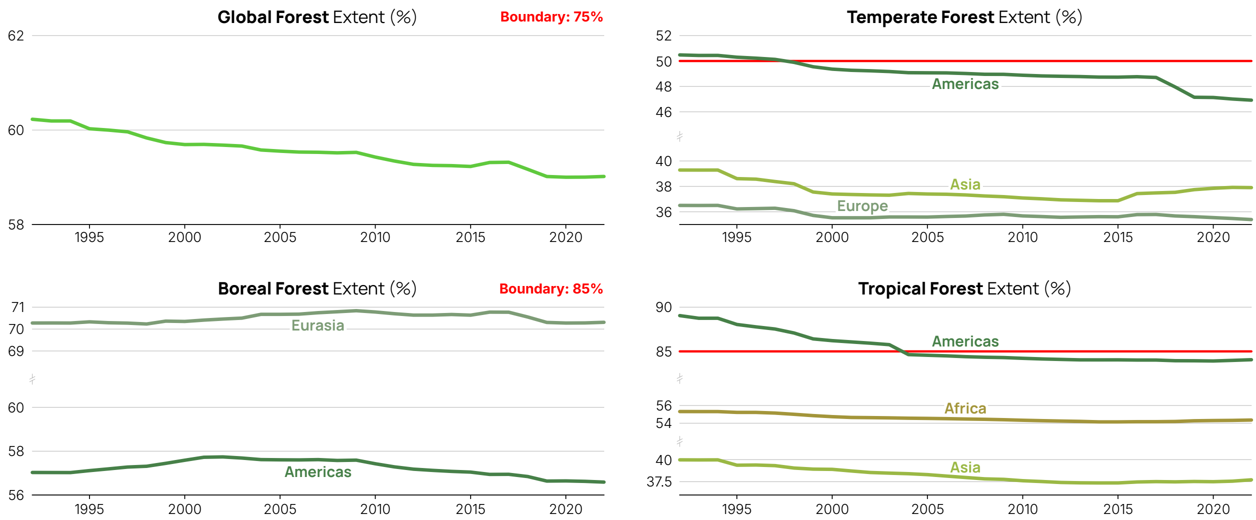


FIGURE 28 - Global recent forest decline. Annual mean forest cover, expressed as a percentage of potential forest cover, globally and for three different biomes (temperate, boreal and tropical) between 1992 and 2022. Red lines show the Planetary Boundaries of 75%, 50%, 85% and 85% for global, temperate, boreal and tropical forests, respectively, while the light green line always represents the baseline of 100% potential forest cover. Data from Copernicus (2024) and Ramankutty & Foley (1999).[296,297]

Key takeaway: *As a result of land use and, increasingly, climate change, global and regional forests have been steadily declining over the last few decades across all major forest biomes. Most regions are already significantly below their biome-scale boundaries, while some areas, such as temperate and tropical Americas, have just recently surpassed them.*

Key Drivers

The drivers of forest loss are deeply intertwined and vary greatly from place to place. Often, the reason a forest is initially cleared is different from what the land is ultimately used for. While agriculture – especially livestock grazing and cropland expansion[152] – is a major direct cause of deforestation, the full picture is much more complex. Historically, forests have been cleared not only for farming, but also for timber, settlements, and to create open landscapes for hunting.[298,299,300] Modern data from satellites shows that between 2000 and 2018, nearly 90% of direct deforestation came from the spread of agriculture – around 52% for crops and 38% for grazing.[152] But these numbers don't tell the whole story.

In many places, especially the Amazon, deforestation begins with illegal logging, often tied to criminal networks involved in land grabbing and the black-market timber trade.[301] 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 one of the final steps in a longer chain of destructive actions. Blaming it alone would overlook the broader dynamics at play.

Regional patterns also differ: Cropland expansion is the leading cause of forest loss in Africa and Southeast Asia, while livestock plays a bigger role in South America and Oceania.[152,302] In tropical conservation areas, infrastructure projects and small-scale or subsistence farming also play a major role. In Europe and parts of the tropics, forest degradation is often driven by timber, paper, and pulp industries.[303,302] And behind many of these drivers are deeper systemic issues – such as weak governance, poverty, unclear land rights, and political instability.[304,305]

Moreover, **Climate Change** and **Freshwater Change** are increasingly acting as indirect but powerful drivers of land-system change. Rising temperatures and shifting rainfall patterns – particularly reduced moisture transport in the atmosphere – can stress forest ecosystems and weaken their resilience.[306] In extreme cases, this can lead to large-scale forest dieback through drought, flooding, or increased fire risk. In temperate forests, warming and water stress have also been linked to an increase in disease outbreaks, most notably bark beetle infestations. These outbreaks, often triggered or amplified by heat and drought, can devastate large forest areas and interact with other disturbances like windthrow, creating cascading forest degradation.[307,308]

Forest loss does not always result from direct human intervention. Wildfires, now more frequent and severe due to climate change, are a growing cause of forest degradation, especially in North America and Oceania.[309] This kind of forest loss can happen even without direct human land use. At the same time, some areas are seeing forest cover increase – through reforestation programs, natural regrowth, or because climate change is making new regions suitable for trees. One example is the northward shift of forests into areas that used to be too cold.[310] While this may seem like a positive development, such shifts can disrupt local ecosystems, negatively affect albedo and surface energy balance, and reshape the distribution of species and ecological functions.

Altogether, forest loss and land-system change are the result of complex chains of events, shaped by both local pressures and global processes – 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 just what is happening to forests, but why, where, and how different drivers interact over time.

Impacts

Forests and land systems play a vital role in maintaining crucial Earth system functions and closely interact with several other Planetary Boundaries, while also serving as primary habitats for terrestrial life and supporting biodiversity at the genetic, species, and ecosystem levels.[311,312] Forest loss diminishes this biodiversity and weakens the integrity of ecosystems.[313] Forests are also an essential carbon sink. Living and non-living biomass above and below ground take up and store a significant share of atmospheric CO_2, making terrestrial ecosystems a major component in regulating climate change.[35] When forests are removed, this function is lost, and the stored carbon is released, contributing to further warming. Deforestation increases both mean and maximum air temperatures and amplifies temperature extremes.[314]

Forests and other land systems also interact with the atmosphere in regulating local climate, for instance by modulating surface temperatures via latent heat fluxes and albedo, and by transporting moisture to other regions via evapotranspiration.[205] The land system plays a key role in the freshwater cycle, regulating water quality and quantity in aquifers, soils, and surface water bodies.[311] Forest loss can therefore contribute to altered rainfall patterns, reduced water availability, and increased runoff and erosion.

Furthermore, the vegetation root zone provides erosion protection and supports nutrient cycling.[315] The loss or degradation of this root structure can therefore accelerate soil degradation and reduce nutrient retention in ecosystems. Additionally, several potential tipping elements lie at the interface between the land system and the atmosphere (see Ch. 2.3). 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 further fuel **Climate Change**.[52]

Beyond these direct environmental impacts, land system change also has serious implications for human well-being. For example, forest loss has been associated with higher malaria incidence in children in some regions, likely due to altered habitats for mosquitoes.[316] In tropical regions, forests provide critical ecosystem services such as weather regulation, freshwater supply, and biodiversity support, all of which underpin livelihoods and food security.[317]

Current and Future Research

The current control variable for land system change within the Planetary Boundaries framework is based on the global percentage of remaining forest cover, aggregated from the biome level. Biomes are large geographic regions characterized by specific climate conditions, plant life, and animal communities. This measure was originally selected for its simplicity, scientific grounding, and data availability. In Steffen et al. (2015),[3] maintaining biome-level forest cover above critical thresholds was proposed as a way to preserve the functioning of large-scale Earth System processes, including carbon cycling, hydrological regulation, and biodiversity support. Forest cover thus served 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 forest 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.[318,319,320] Forests may be expanding in some areas, but this does not necessarily signal recovery of ecological function – especially when new forests are monocultures, poorly connected, or under ongoing stress. Compounding this, a recently identified issue in the biome area extents from Snyder, Delire, and Foley (2004)[294] – used for aggregating biome-level values into a global percentage – may affect the Planetary Boundary threshold by 1–2 percentage points. If confirmed, this would slightly shift the global boundary value due to revised biome weights.

In parallel, ongoing research is exploring whether new or complementary control variables could provide a more nuanced and functionally meaningful assessment of land-system change. These efforts aim to better reflect the actual state and function of terrestrial ecosystems, including indicators of forest fragmentation, ecological integrity, or land-use intensity. However, any such improvements must balance scientific robustness with global applicability, consistency across time, and feasibility of data collection and monitoring. Looking ahead, the scientific community continues to work toward refining the land-system boundary, improving data sources, and evaluating the potential of alternative or additional control variables that better reflect the quality, not just the quantity, of forests and land-use systems.

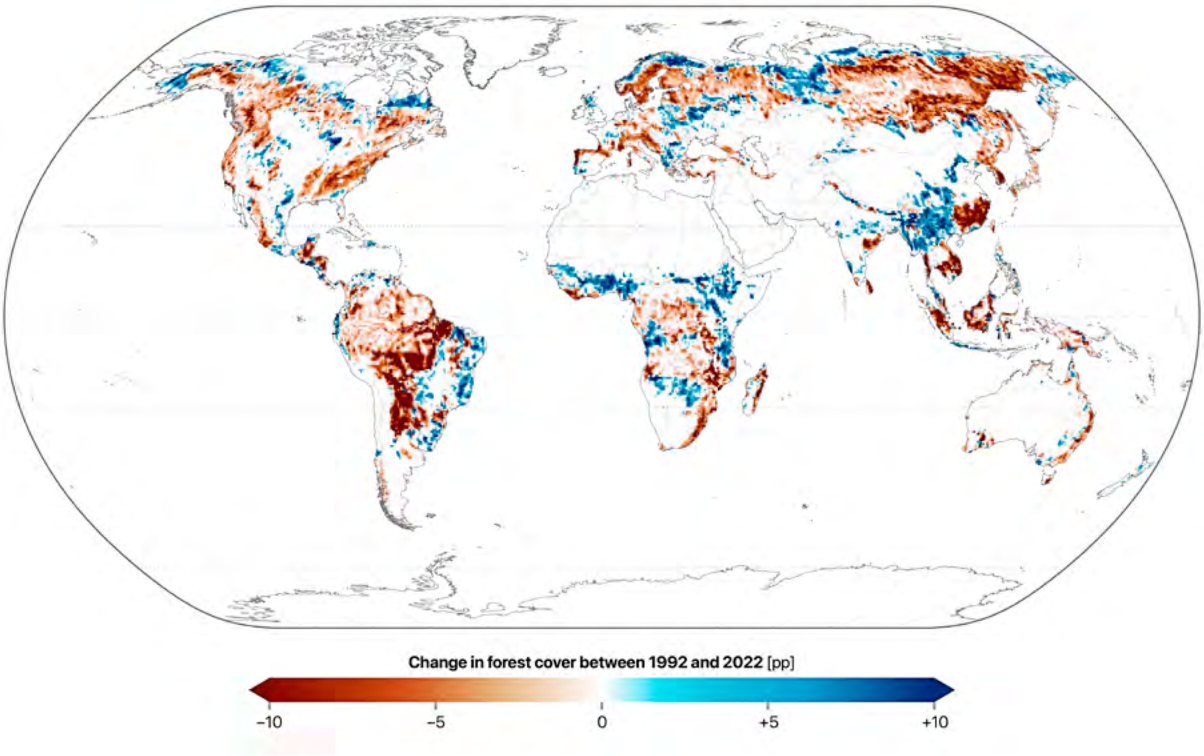


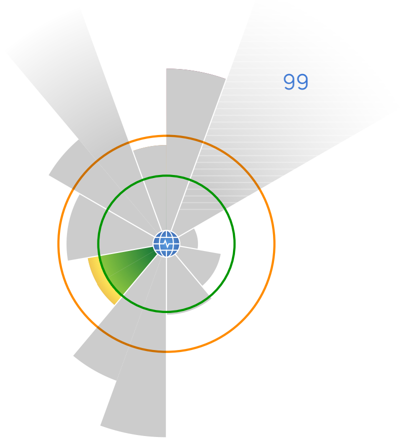
FIGURE 29 - Global map of recent forest cover changes. Colors indicate absolute changes in the percentage of forest cover between 1992 and 2022, with shades of blue representing an increase in forest cover and shades of red a decrease in forest cover (e.g. a change from 60% to 50% forest cover would be indicated by a value of -10%). Areas that had either no forest cover in both 1992 and 2022, or show no change in forest cover, are shown in white. Data from Copernicus (2024).[296]

Key takeaway: *Patterns of forest loss and gain have been heterogeneous, with prevailing net losses at the biome scale (see Fig. 28). Continuous 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.*

Data Sources

Observed forest cover data Copernicus (2024),[296] accessed on 15-May-2024.

Potential forest cover data from Ramankutty and Foley (1999).[296,297]



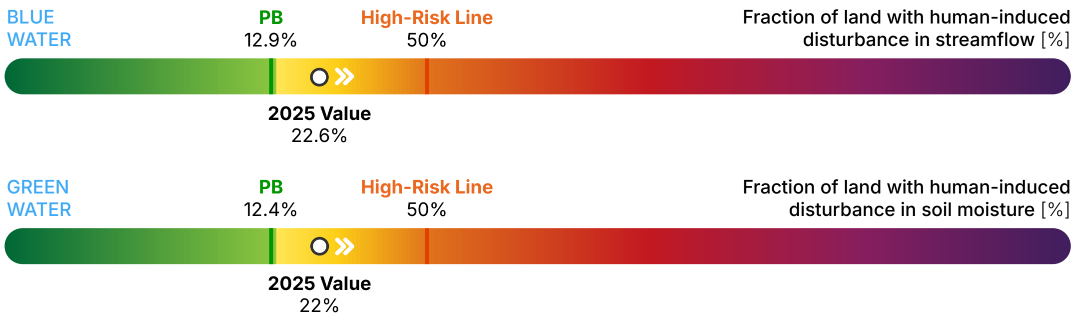
4.4 Freshwater Change

Main Takeaways

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 on freshwater resources; the occurrence of droughts and storms has increased, while groundwater stocks are under depletion and river flows to the ocean are widely disrupted. The Planetary Boundary for freshwater change measures how far streamflow and soil moisture conditions have deviated 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 double as large land areas than under pre-industrial-like conditions, due to extensive human impacts on the freshwater 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 undermine terrestrial and aquatic ecosystem integrity and modify land carbon balance. They also critically change water availability for human uses.



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.

2025 Status

Human-induced disturbances of freshwater change have exceeded the safe level. Currently, more than a fifth of the global land area experiences dry or wet deviations for both blue water (22.6%) and 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 most current year in the hydrological model ensemble[321] used for freshwater boundary analysis[322] is 2019, therefore, 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 the current state to a 119-year long pre-industrial-like baseline state that is largely unaffected by human-induced disturbances.[322]

Control Variables

#1 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 and terrestrial ecosystems.
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%. The baseline conditions reflect a hypothetical unaffected Earth system state, based on a 119-year long pre-industrial-like scenario with no climate change and 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 strong wet or dry 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.

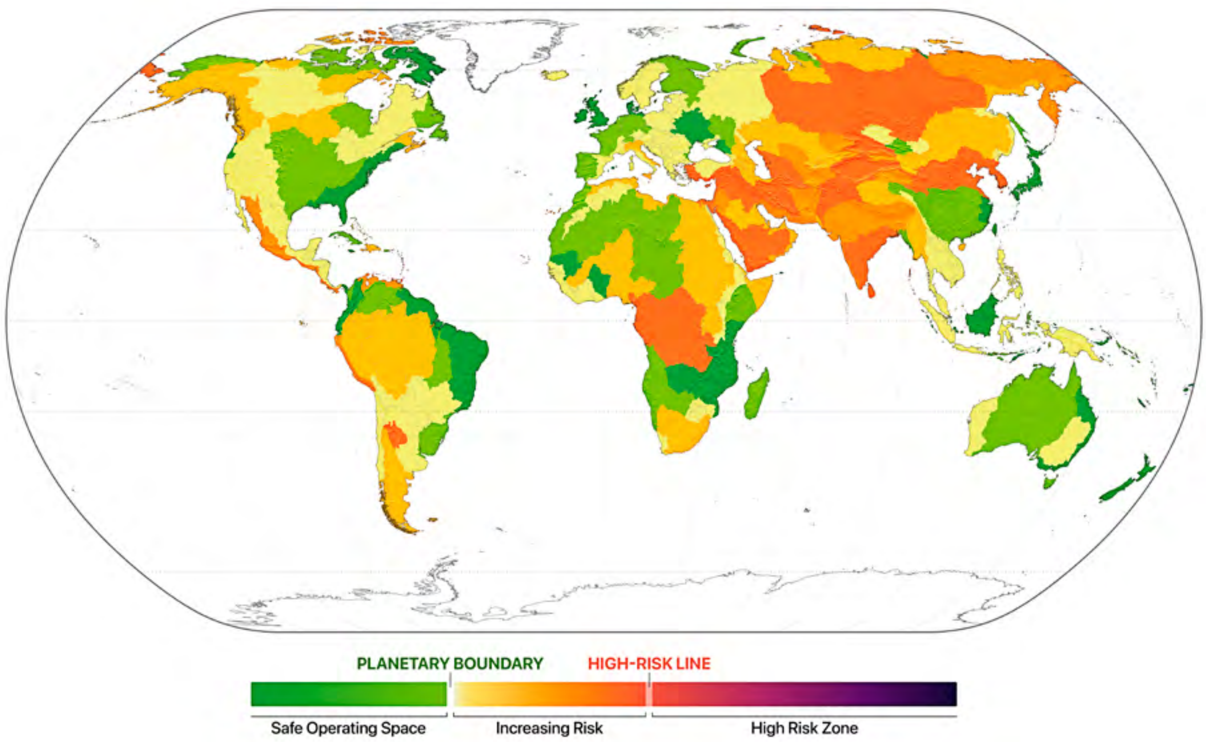
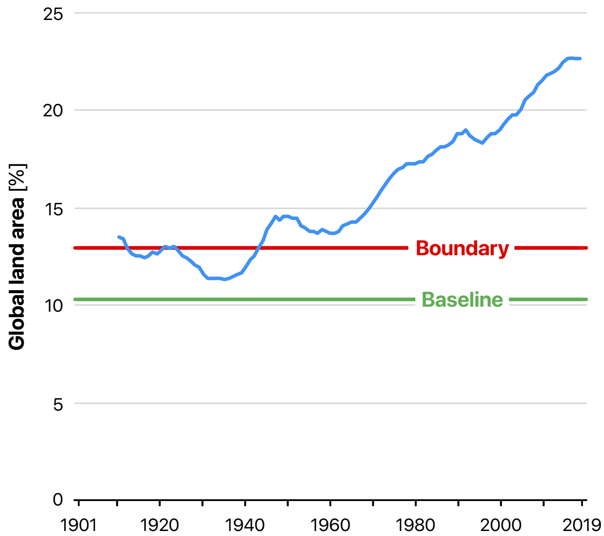


FIGURE 30 - Global risk map of Earth's freshwater systems (I) – Blue water. This map shows boundary transgression at river basin scale for major basins[323] of the world (n = 268). Transgression is based on the control variable streamflow. For details on this figure, please see the Supplementary Materials. Based on data from Virkki et al. (2025).[322]

Key takeaway: *The increase in both wet and dry streamflow deviations across large parts of the world suggests increasing variability and instability in global freshwater systems.*

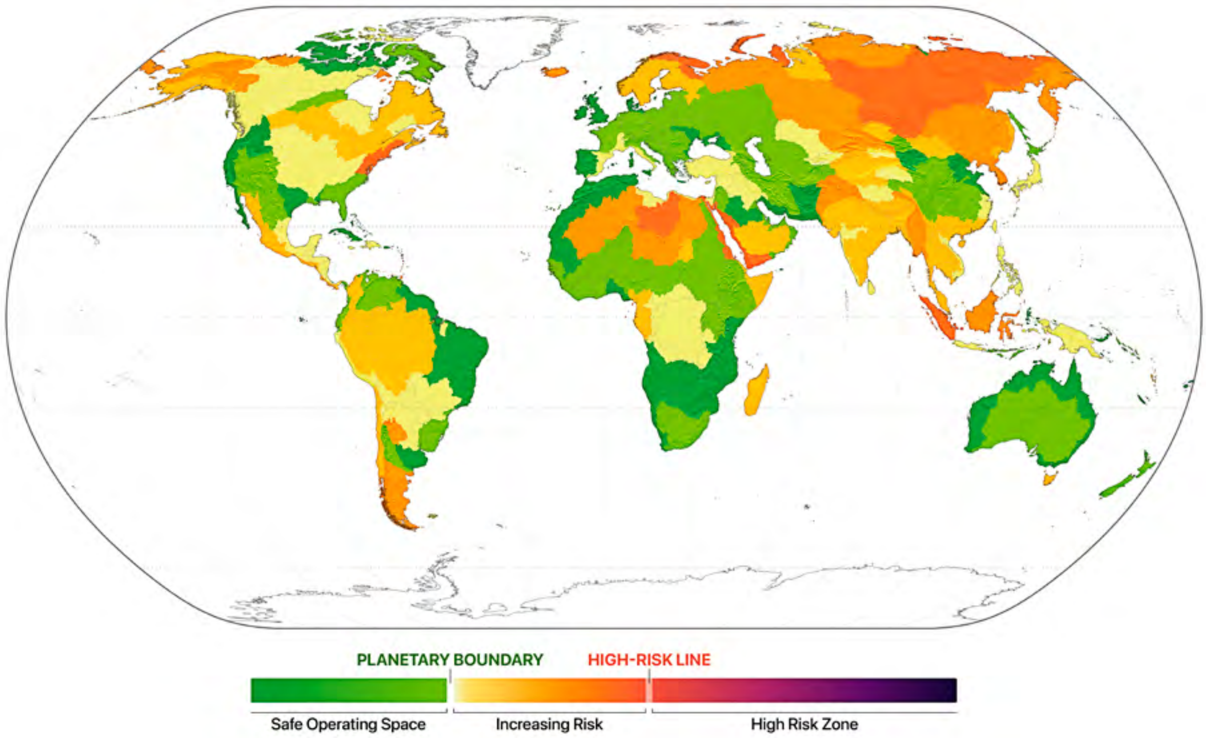
FIGURE 31 - Disturbance of Earth's freshwater systems (I) – Blue water. This figure shows the percentage of land area with significant alteration of blue water flows (streamflow) from 1901 to 2019 compared to the baseline state. The blue line shows the percentage of land area exhibiting local deviations in blue water (10-year moving average of streamflow deviations). The red line shows the Planetary Boundary of 12.9% land area affected, while the green line represents the baseline median of 10.3% land area. Data from Virkki et al. (2025).[322]

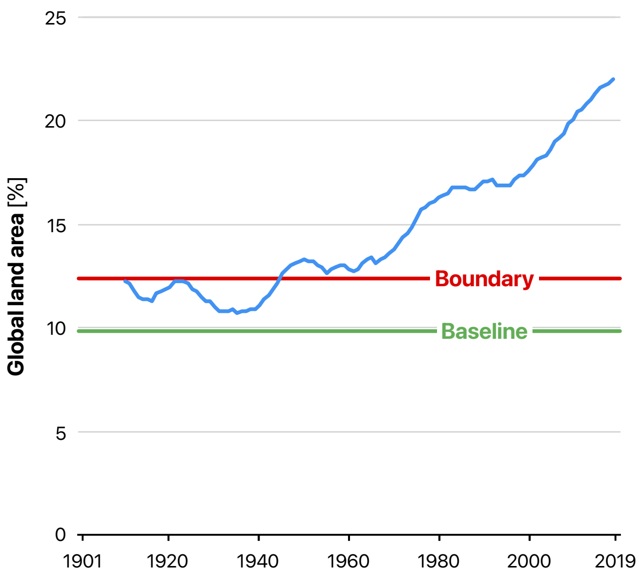
Key takeaway: *Local streamflow deviations have significantly increased since the early 20th century, surpassing the Planetary Boundary around 1940 and continuing to rise since then.*



#2 Green Water

Definition	Human-induced disturbance of green water, which refers to the stock of soil moisture available to plants, is approximated by the annual global area with significant deviations in root zone 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%. The baseline conditions reflect a hypothetical unaffected Earth system state, based on a 119-year long pre-industrial-like scenario with no climate change and 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 strong wet or dry deviations in soil moisture. This corresponds to the 95th percentile of 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 32 - Global risk map of Earth's freshwater systems (II) – Green water**. This map shows boundary transgression at river basin scale for major basins[323] of the world (n = 268). Transgression is based on the control variable root zone soil moisture. For details on this figure, please see the Supplementary Materials. Based on data from Virkki et al. (2025).[322]

Key takeaway: *The increase in both wet and dry soil moisture deviations indicates growing variability and instability within global green water systems, which affects water stored in soils and thus available for use by plants.*

← **FIGURE 33 - 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 blue line shows the percentage of land area exhibiting local deviations in green water (10-year moving average of soil moisture). The red line shows the PB of 12.4% land area affected, while the green line represents the baseline median of 9.8%. Data from Virkki et al. (2025).[322]

Key takeaway: *Local soil moisture deviations have significantly increased since the early 20th century, surpassing the PB 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.[322] Climate change intensifies and redistributes branches of the water cycle, which manifests as increasing deviations and novel hydrological regimes across water cycle elements.[324,53] On top of that, freshwater withdrawals, river diversions, dam constructions, and land use changes have exacerbated exceedances of the blue and green water boundaries.[322]

Such direct human activities are regionally strong drivers of change in water boundary transgressions.[322] Freshwater withdrawals from rivers, reservoirs, and groundwater significantly affect water levels and aquatic and surrounding ecosystems. The main driver of these withdrawals is irrigation, which globally accounts for approximately 70% of freshwater withdrawals and 90% of consumptive use (water not returned to the source).[325,326] Industry and household use account for around 20% and 12%, respectively.[327]

The **Freshwater Change** boundary is closely intertwined with activities impacting other Planetary Boundaries. For instance, Climate Change influences droughts and floods by altering atmospheric water-holding capacity, cloud formation, and circulation patterns (see also Ch. 2.4).[328,329,330] Additionally, Land-System Change related to deforestation, agriculture, and urbanization affect soil water-holding capacity, streamflow, and evaporation rates. This can intensify droughts and alter large-scale precipitation patterns like monsoons, thereby creating feedback loops that further impact Climate Change.[330]

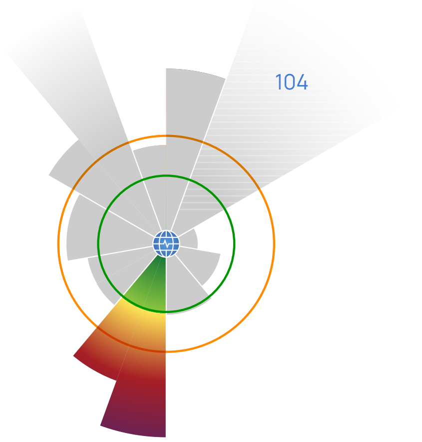
Impacts

Transgressing the Freshwater Change PB has significant impacts on the functioning of the Earth system, as well as on human societies. Disrupting the water cycle threatens the viability of entire ecosystems, such as the Amazon, which degrades biosphere integrity and ecosystem services.[306] Furthermore, dry deviations in blue water flows can lead to loss of wetlands, depletion of lakes and reservoirs, and violations of in-stream environmental flow requirements, resulting in considerable aquatic ecosystem degradation and regional climate change impacts.[331] 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 collapse, and bursts of CO_2 emissions affecting the climate.[332] 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 flow regimes.[333] Wet deviations in green water can drive waterlogging in the soil and permafrost thawing, which may release vast quantities of CO_2 and CH_4 into the atmosphere.[334]

Global food security, via human food and fodder production, is especially threatened by reduced freshwater availability or overconsumption of 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.[326,335]

Data Sources

Blue and green water deviations based on an analysis from Virkki et al. (2025)[322] utilising the ISIMIP3a global hydrological model ensemble[321] and following the methodological approach of Porkka et al. (2024)[331] and conceptual framing of Wang-Erlandsson et al (2022).[330]

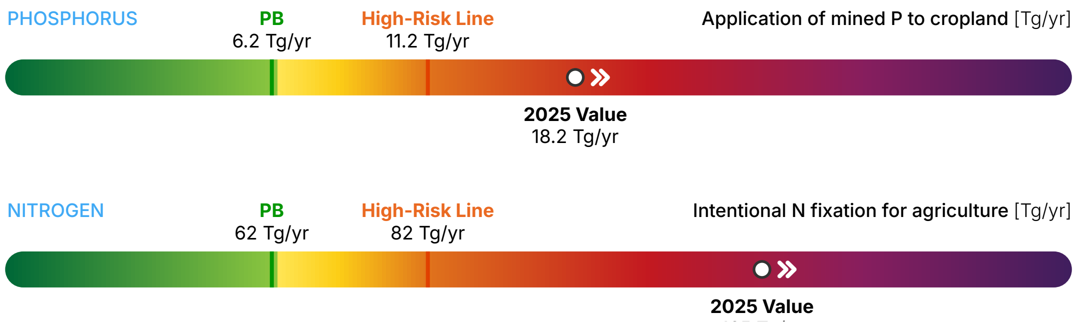


4.5 Modification of Biogeochemical Flows

Main Takeaways

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 fertilisers. Combined with the mining of phosphate rock, this led to a drastic increase in fertilizer application on agricultural land.[336] Because only a part of the fertilizer is actually taken up by crops, large quantities of both nutrients remain in the environment.[337,338]

Nitrogen is released into the air and stored in groundwater and surface waters. Phosphorus accumulates in soils and is released into surface waters via soil erosion and surface runoff. Excess nutrients can have negative effects on biodiversity and the resilience of ecosystems on land, in freshwater and in the ocean, which are adapted to specific nutrient levels. Currently, losses of both nutrients to the environment are disrupting ecosystems beyond the safe level.



Definition

The Planetary Boundary for biogeochemical flows relates to 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, freshwaters and the ocean used to be a major limiting factor for biological productivity on Earth.[339]

2025 Status

Both the application of mined phosphorus to cropland (~18.2 Tg P year^{-1}) and the anthropogenic fixation of nitrogen for agriculture (extracting nitrogen from the atmosphere, ~165 Tg N year^{-1}) are disrupting the corresponding nutrient cycles **beyond the safe levels** of 6.2 Tg P year^{-1} and 62 Tg N year^{-1}, respectively.

Control Variables

#1 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. 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 $year^{-1}$). 1 teragram equals 1 million metric tons.
Historical Range	Before human intervention, phosphorus flows were low (~2.5 Tg P $year^{-1}$ from land to freshwater and ~1.3 Tg P $year^{-1}$ of export to the ocean).[340] Human activities have increased flows from land to freshwater systems through a global application of mined phosphorus to cropland of around 18.2 Tg P $year^{-1}$ (regional, aggregated) and have increased phosphorus flows to the ocean to around 4.4 Tg P $year^{-1}$ (global), largely due to fertilizer use.[340,341]
Planetary Boundary (PB)	The regional boundary is set to an application of 6.2 Tg P per year,[3] while the global boundary is established at a flow of 11 Tg P per year, which is roughly ten times the natural flow rate.[342] Here, we focus on the regional boundary, as it is more limiting than the ocean boundary.

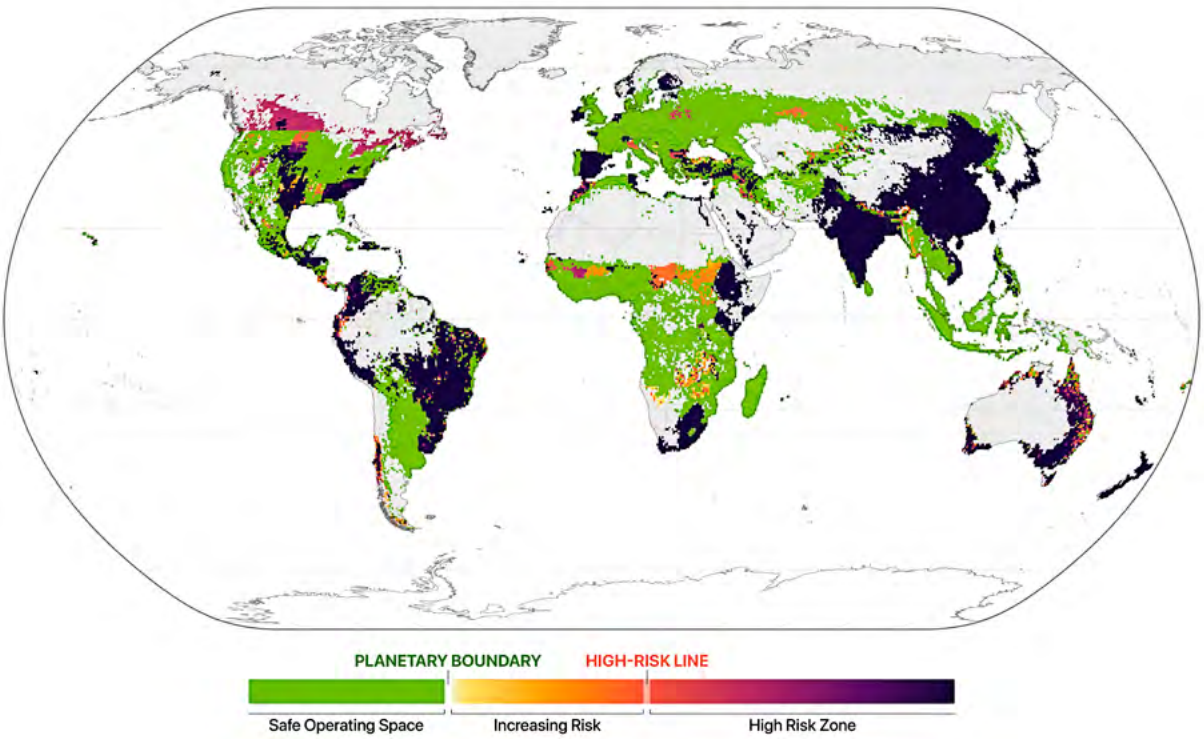


FIGURE 34 - Global risk map for the transgression of the Modification of Biogeochemical Flows boundary – Phosphorus cycle. The regional boundary status is calculated based on agricultural phosphorus surplus in the year 2020. This graphic aligns with the suggestion for a control variable definition that is more closely related to phosphorus losses to the environment (phosphorus surplus instead of input).[103] The regional boundaries were preliminarily derived from the global boundaries, assuming a uniform rate of fertilizer surplus on cropland. Regional pollution limits may deviate significantly from these boundaries.[3] Based on data from model runs with IMAGE-GNM, using the methodology of van Vuuren et al. (2025).[103]

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.*

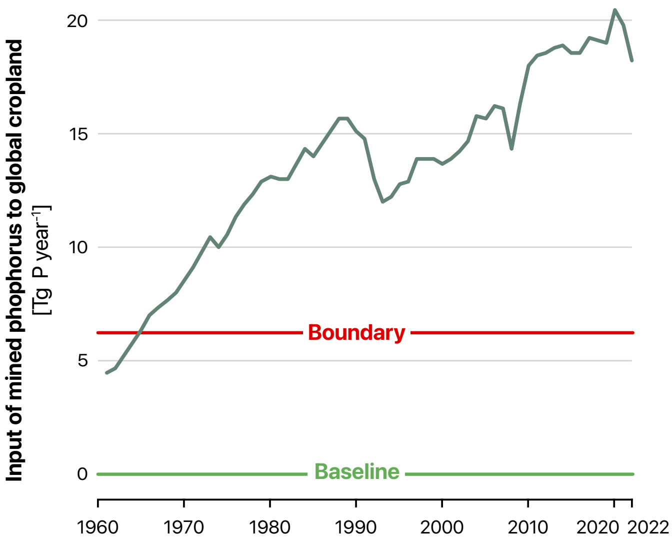


FIGURE 35 - Phosphorus inputs to global cropland. This graph shows the estimated global application of mineral phosphorus on all croplands (in Tg P year-1, i.e. million tons per year) from 1961 until 2022. Data from Ludemann et al. (2024).[341]

Key takeaway: *The significant increase over time in phosphorus application highlights the growing reliance on phosphorus in agriculture over the decades.*

#2 Nitrogen (N) Fixation

Definition	The nitrogen boundary sets a threshold for anthropogenic nitrogen fixation in agriculture. It is the total amount 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}). 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^{-1} 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.[343]
Planetary Boundary (PB)	The nitrogen PB targets industrial and intentional biological nitrogen fixation, setting a threshold at 62 Tg N year-1. This boundary is established based on empirical data, environmental considerations, and the precautionary principle to uphold biogeochemical balance and safeguard ecosystem health.[3]

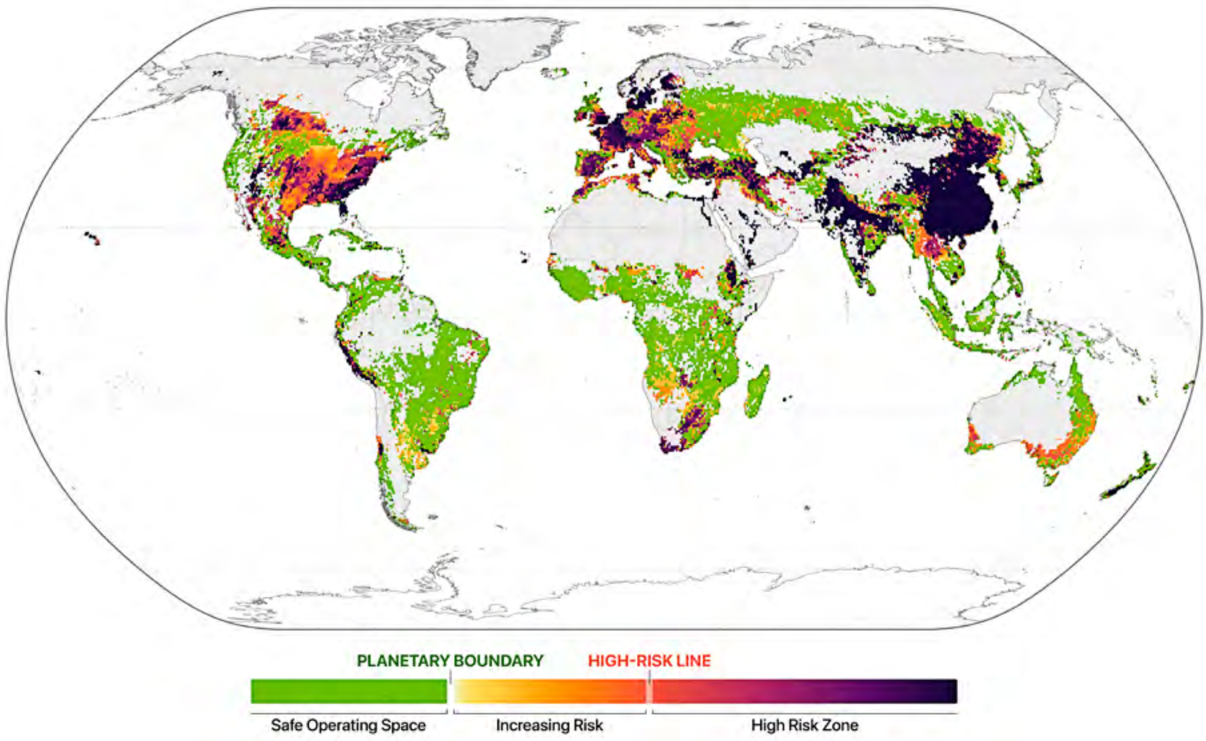
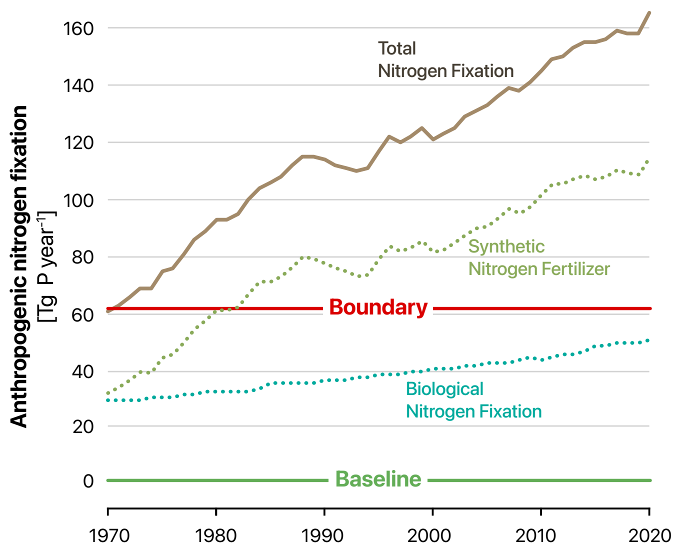


FIGURE 36 - Global risk map for the transgression of the Modification of Biogeochemical Flows boundary – Nitrogen cycle. The regional boundary status is calculated based on agricultural nitrogen surplus in the year 2020 and estimates of regional surplus boundaries. The assessment aligns with the suggestion for an enhanced control variable definition[344] 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), as illustrated in Fig. 1. Note that the threshold between the Zone of Increasing Risk and the High-Risk Zone is a preliminary estimate and needs further refinement. Based on data from model runs with IMAGE-GNM, using the methodology of Schulte-Uebbing et al. (2022).[344]

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.*

FIGURE 37 - Nitrogen inputs to agriculture. This graph shows the estimated global anthropogenic nitrogen fixation, through fertilizer application and biological fixation, on all croplands (in Tg N year^{-1}, i.e. million tons per year) from 1961 until 2022. Data from the IMAGE-GNM model[103] and FAO.[345]

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 in much the same way they affect climate change.[4,346] 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.[343] Similarly, agricultural activities have accelerated the phosphorus cycle two to three times beyond natural rates.[315,347] 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.

Besides the introduction of new nitrogen and phosphorus, internal factors are also responsible for the disruption of the respective nutrient cycles. This includes the 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.[348] It is also important to note that the effects of accumulated soil phosphorus and groundwater nitrogen loadings can persist long after initial inputs have been reduced.[346]

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.[349,346]

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, fisheries, and tourism. Once released into the environment, reactive forms of nitrogen contribute substantially to aerosol loading, ozone depletion and global warming.[350] 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.[351,352]

Besides their individual impacts, shifts in the ratio of nitrogen and phosphorus can pose an additional threat to ecosystem integrity. 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, Stratospheric Ozone Depletion, Atmospheric Aerosol Loading and Land System Change.**

Current and Future Research

The additional fixation and release of reactive nitrogen that enters the nitrogen cycle through the combustion of fossil fuels and the depletion of soil reservoirs is not yet included in the control variable, but should be considered in future assessments. In addition, several studies suggest using agricultural nitrogen surplus as a control variable.[259,344,353] Nitrogen surplus describes the amount of nitrogen remaining in the environment after harvest, which is more closely related to nitrogen losses to the environment and the resulting adverse effects.

Future assessments of the regional boundary for phosphorus could similarly build on assessments of phosphorus surplus in crop production, or on current efforts to quantify the input of phosphorus to freshwater systems directly.

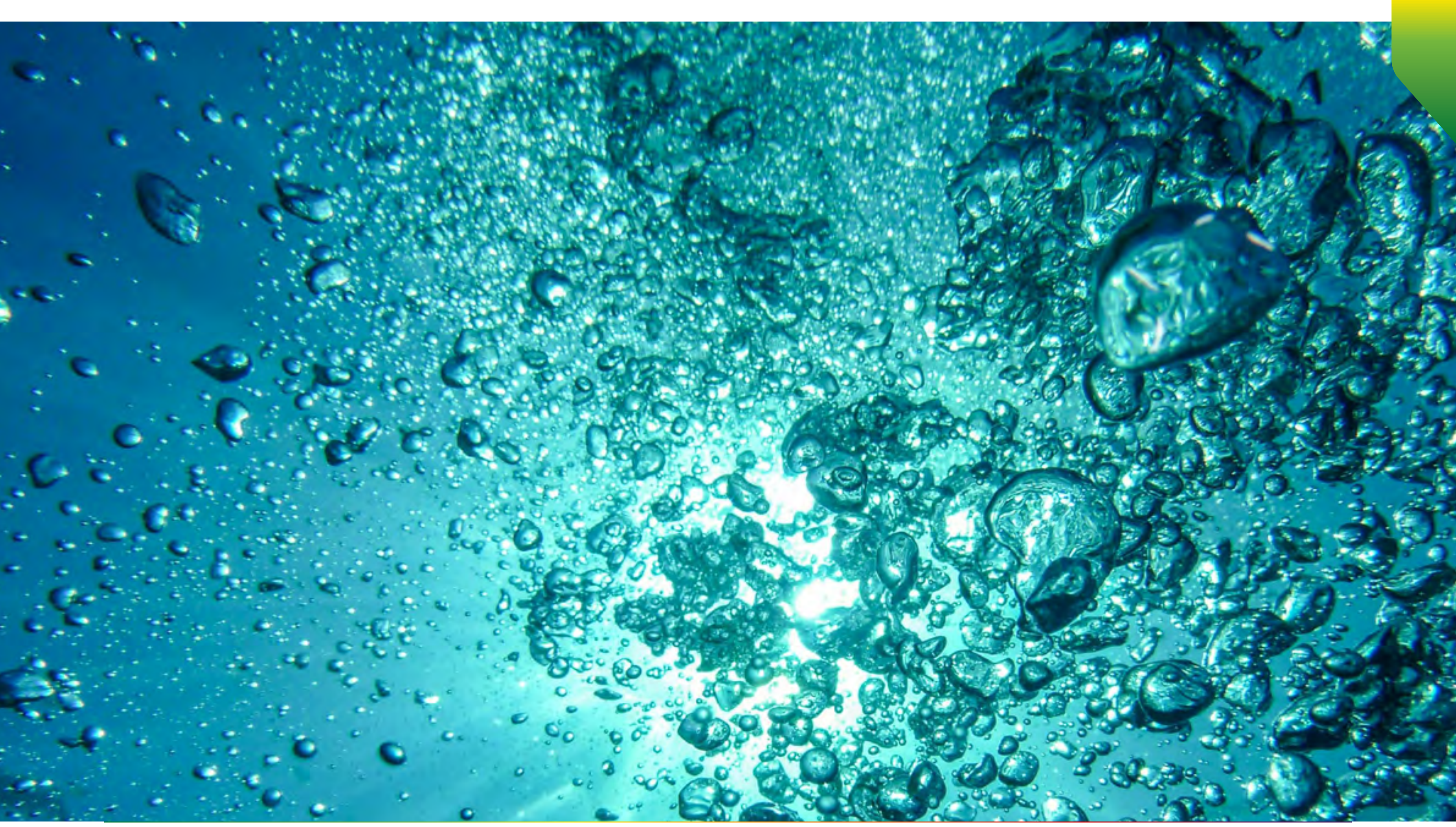
Data Sources

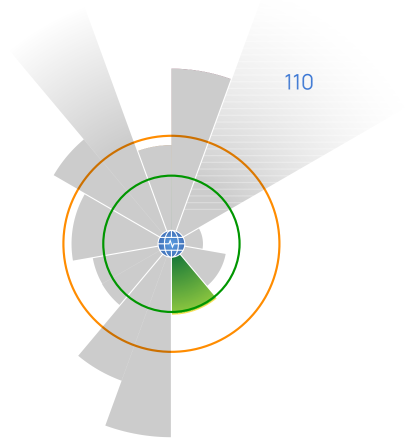
Phosphorus fertilizer input data from Ludemann et al. (2024).[341]

Global Phosphorus flow into the ocean from model runs with IMAGE-GNM, based on the methodology of Beusen et al. (2022).[340]

Exceedance of critical P surplus data from model runs with IMAGE-GNM, based on the methodology of van Vuuren et al. (2025).[103]

Exceedance of critical N surplus data from model runs with IMAGE-GNM, based on the methodology of Schulte-Uebbing et al. (2022).[344]



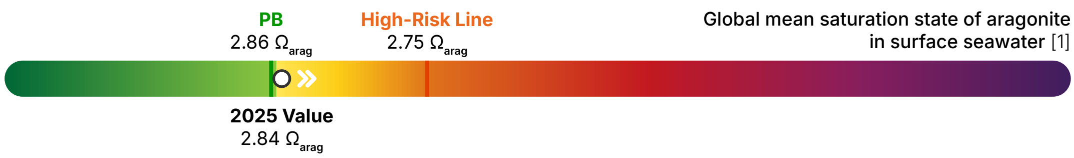


4.6 Ocean Acidification

Main Takeaways

The ocean absorbs a substantial proportion 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. This makes it harder for these organisms to grow and survive. Marine ecosystems are already feeling the effects. Cold-water corals, tropical coral reefs, and Arctic marine life 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 atmospheric CO_2. This process poses a risk to many calcifying organisms, disrupts marine ecosystems, and reduces the ocean's efficiency to function as a carbon sink.

2025 Status

The Planetary Boundary for **Ocean Acidification** is **now assessed as transgressed**. This conclusion is based on a high-quality global observational dataset of surface ocean acidification variables, combined with a revised estimate of pre-industrial conditions. Recent model simulations from CMIP6 suggest that the pre-industrial aragonite saturation state (Ω) in the year 1750 was higher than previously thought, with a value of 3.57.[354] This indicates that current ocean conditions have diverged more significantly from the pre-industrial state than earlier assessments suggested.

The Planetary Boundary for **Ocean Acidification** defines a "safe operating space" as 80% of the pre-industrial Ω value – a 20% decline. Applying this threshold to the revised pre-industrial estimate of 3.57 yields a boundary value of 2.86. The observed global surface aragonite saturation state in 2024 was 2.84,[355] which is below the revised Planetary Boundary threshold. This is supported by an independent study published earlier this year, which also found that the Planetary Boundary for ocean acidification has been transgressed.[356]

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 in seawater relative to the amount needed for stable aragonite formation, 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 4.0 in tropical regions to 1 to 2 in polar regions.
Planetary Boundary (PB)	The PB for global mean surface Ω is set at 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, thereby limiting harmful impacts on marine calcifiers.

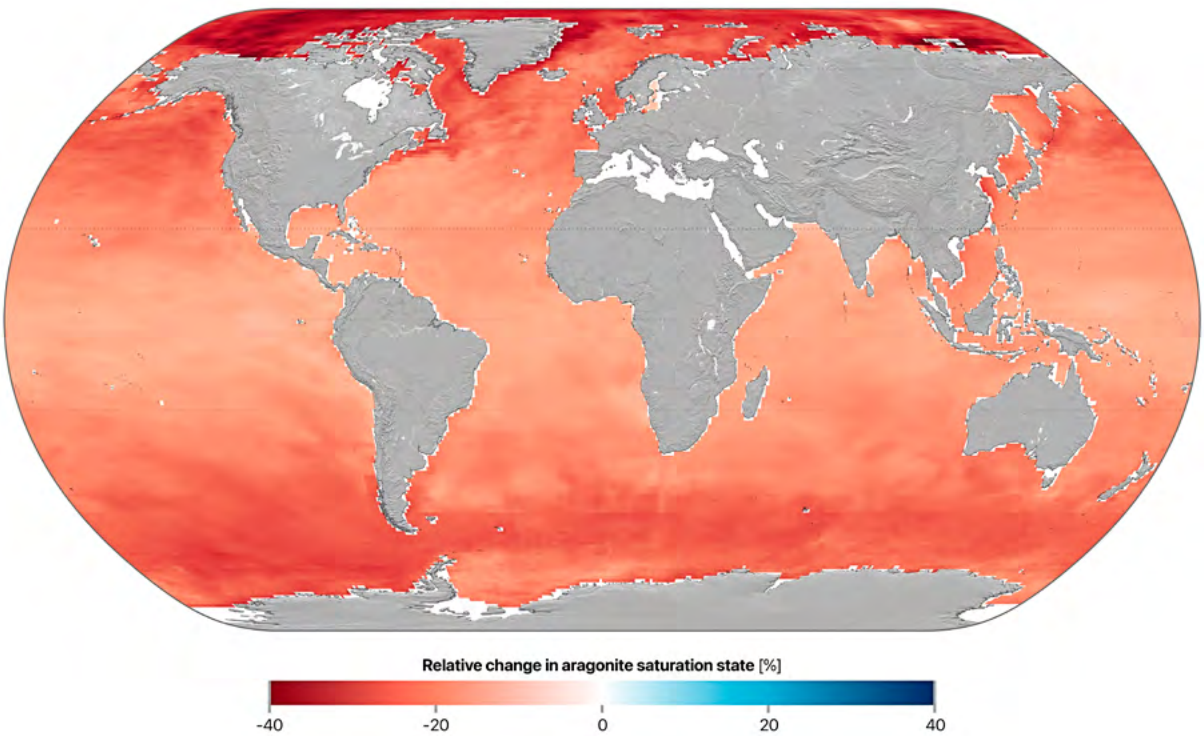


FIGURE 38 - Global map of Ocean Acidification, as indicated by aragonite saturation state. This map shows anomalies in surface aragonite saturation state for the decadal mean of 2015-2024 with respect to year 1750, based on CMIP6 model results for the CO_2 emission scenario SSP2-4.5.[354]

Key takeaway: *The Ocean has significantly acidified globally, particularly in the Arctic and Southern Ocean regions.*

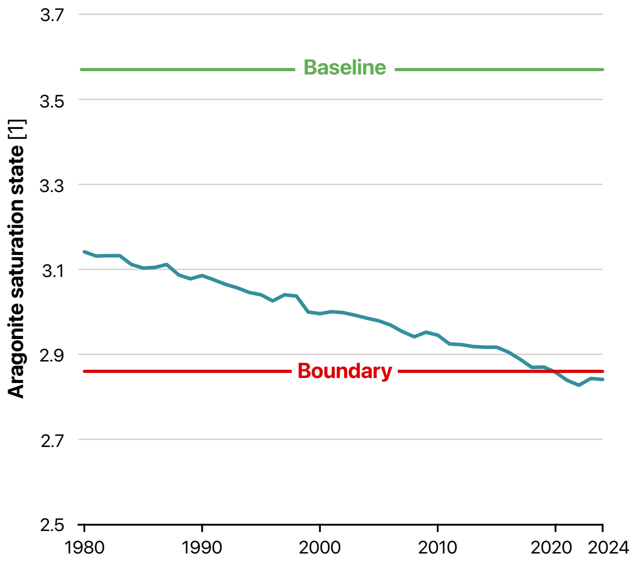


FIGURE 39 - Ocean Acidification has transgressed its Planetary Boundary. This figure shows how the global surface aragonite saturation state has changed over time (based on UExP-FNN-U data).[355] It has declined significantly in recent decades and has now breached the Planetary Boundary. The baseline (green line) is a revised estimate of the pre-industrial aragonite saturation state around the year 1750, based on Jiang et al. (2023)[354]. Because it is higher than previous estimates, the revised Planetary Boundary (set at 80% of the pre-industrial state; red line) is also higher – meaning today's ocean is even further from its pre-industrial state than previously thought.

Key takeaway: *Ocean acidification has gone beyond safe limits, increasingly endangering marine ecosystems.*

Key Drivers

The control variable for the **Ocean Acidification** Planetary Boundary is the global mean aragonite saturation state of the surface ocean. 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.[357] As the ocean absorbs more CO_2, it forms carbonic acid, which breaks apart and releases hydrogen ions. These hydrogen ions bind with carbonate, making less of it available. This lowers the aragonite saturation state, making 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 main driver of ocean acidification, causing a long-term decline in aragonite saturation state (Fig. 39).

Impacts

Biological Impacts of Ocean Acidification

Ocean acidification affects marine life in multiple ways. Calcifying organisms – such as corals, shelled mollusks, and some crustaceans – require more energy to build and maintain their calcium carbonate structures, a requirement that can hinder their growth and survival. High-latitude pteropods, tiny drifting snails also known as sea butterflies, are already showing signs of shell damage.[358,359] Since these snails play an important role in the marine food web, their decline could cause ripple effects that impact other species, including those without shells, and potentially harm the wider marine ecosystem.

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. These reefs are facing increased loss of suitable environmental conditions, including favorable pH levels.[4] While increasingly frequent marine heatwaves are the main cause of shallow-water coral reef degradation in tropical regions, ocean acidification adds further pressure by impairing the recovery of bleached reefs.

Deep-water corals are particularly vulnerable to ocean acidification because they live near the aragonite saturation horizon – the depth where aragonite, the mineral that forms their skeletons, begins to dissolve. Acidification progresses faster in deep waters due to lower buffering capacity, causing this aragonite saturation horizon to rise closer to the surface.[149] As a result, deep-water corals face increasing difficulty building and maintaining their skeletons, making acidification one of their greatest threats.

Changes in Ocean Chemistry and CO_2 Uptake

In addition to harming marine life, ocean acidification also reduces the ocean's ability to absorb CO_2 from the atmosphere. This effect is linked to acidification's reduction of carbonate ion availability in seawater. Since these ions are crucial to the ocean's buffering capacity – the system that helps neutralize acidity – their decline weakens this natural buffer. Recent observations show that the ocean's ability to absorb CO_2 has slightly declined, likely due to a combination of reduced buffer capacity and changes in ocean circulation linked to climate change.[149] Despite this observed decline, the ocean still absorbs about 25% of human-caused CO_2 emissions[35] and is expected to continue playing a major role in removing human-caused CO_2 from the atmosphere and moderating climate change.[107]

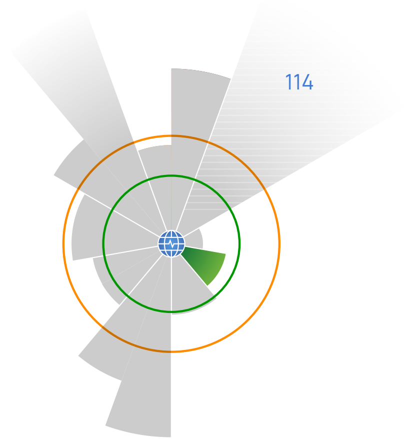
Regional Differences in Ocean Acidification

The Arctic Ocean has experienced the most severe acidification to date (Fig. 38), 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.[356,322] 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. These processes contribute to strong regional and seasonal variability in acidification levels.

Data Sources

Data from Ford et al. (2025),[355] version v2025-1.

We acknowledge support and data from the European Space Agency (ESA) projects Ocean Carbon for Climate (OC4C; grant no. 3-18399/24/I-NB) and Satellite-based observations of Carbon in the Ocean: Pools, Fluxes and Exchanges (SCOPE; grant no. 4000142532/23/I-DT).



4.7 Increase in Atmospheric Aerosol Loading

Main Takeaways

Aerosol loading refers to the concentration of small particles suspended in the atmosphere, originating 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 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 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 reducing them 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 dynamics, and hydrological cycles. Human-driven transgression of this 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.

2025 Status

The difference in atmospheric aerosol loading (0.063) between the hemispheres (interhemispheric) is below the Planetary Boundary of 0.1, and thus **within the Safe Operating Space**. It is trending towards safer values, but strong regional differences remain.

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. Regionally, local AOD correlates with PM2.5 (fine particulate matter with diameters ≤2.5 micrometers, a health-hazardous air pollutant) concentration, which is particularly important in the context of justice considerations regarding human health.[259] 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).
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 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. In addition, a provisional regional boundary is set at 0.25, as higher AOD values in monsoon regions likely lead to significantly lower rainfall, ultimately affecting biosphere integrity.[3] This threshold is also relevant in the context of justice considerations related to human health.[259]

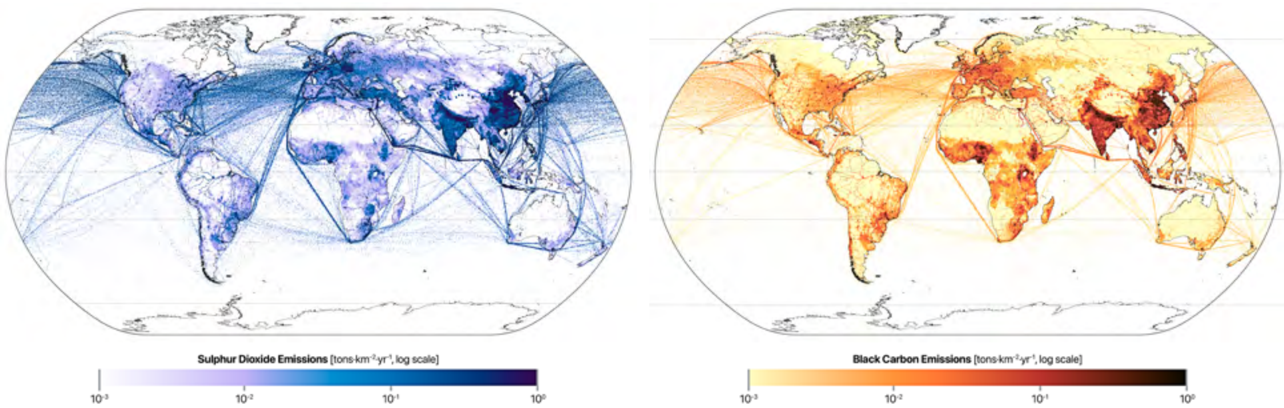


FIGURE 40 - Global aerosol emissions, averaged annually over 2010–2020. The Copernicus Atmosphere Monitoring Service (CAMS) aerosol emission dataset combines multiple sources, including bottom-up inventories, satellite observations, and reported data. Its goal is to generate consistent, spatially and temporally resolved global estimates of key atmospheric pollutants. The emissions are chemically differentiated and assimilated within atmospheric models. (a) Sulfur dioxide (SO_2) emissions, a major precursor to sulfate aerosols, and (b) black carbon (BC) emissions, a light-absorbing component of particulate matter, are shown over the period 2010–2020.

Key takeaway: *Aerosol emissions are centered on population and industrial centers, as well as transportation corridors.*

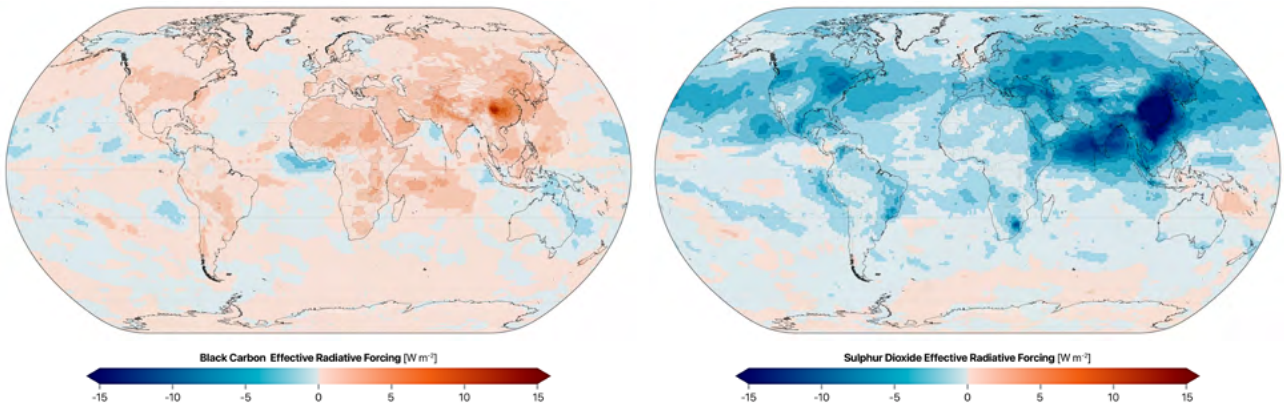


FIGURE 41 - Effective radiative forcing (W m^{-2}) of sulfur dioxide and black carbon, averaged annually over 2010–2020. Effective radiative forcing (ERF) estimates for (a) sulfur dioxide (SO_2) and (b) black carbon (BC) are shown, based on simulations from CMIP6 models participating in AerChemMIP. ERF 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.*

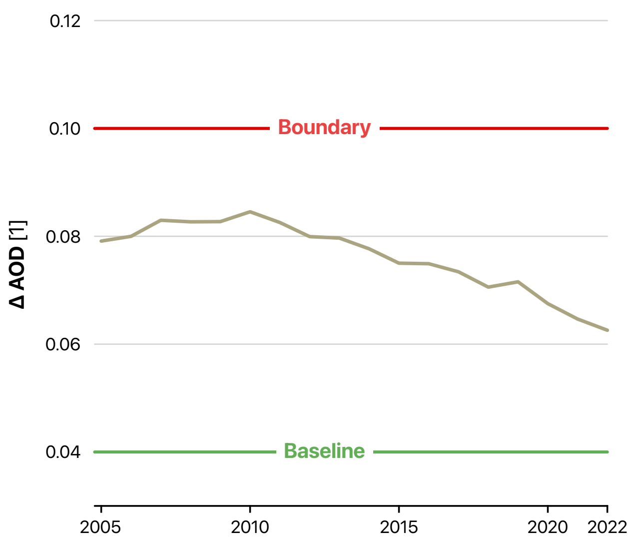


FIGURE 42 - Bridging the divide: Declining interhemispheric difference in Aerosol Loading. This chart shows the 5-year running mean of the difference in the aerosol optical depth (AOD) between the Northern and Southern Hemispheres, calculated by averaging data from 60° north to 60° south for the period from 2003-2024. The red line shows the Planetary Boundary of 0.1, while the green line represents the baseline of 0.04. Data from CAMS EAC4.[360]

Key takeaway: *The difference in aerosol optical depth between the Northern and Southern Hemispheres has been decreasing from 2010 to 2024, indicating that we are moving further into the Safe Operating Space.*

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.[361,362] Sulfur dioxide (SO_2) and black carbon are among the most important aerosol precursors (gases that react in the atmosphere to form aerosol particles) and are primarily emitted through industrial activity, power generation and transportation.[363,364] 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.[363,364] The CAMS reanalysis, averaged over 2010–2020 (Fig. 40), highlights substantial differences in emission levels between the Northern and Southern Hemispheres, which drive the observed interhemispheric AOD contrast used as the control variable.

While the global control variable remains within the safe operating space of the Planetary Boundary, it does not fully capture regional risks. In some areas, aerosol emissions and thus AOD levels exceed safe thresholds, 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.[365] 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.[366] These changes can alter global monsoon systems, including the South Asian, West African, and East Asian monsoons, potentially shifting them toward drier or delayed states.[367]

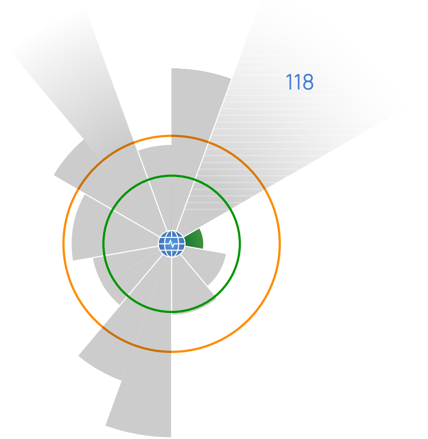
Aerosols also modify Earth's energy balance through effective radiative forcing (ERF).[368] Scattering aerosols (like sulfate, formed from sulfur dioxide) tend to cool the atmosphere by reflecting incoming sunlight, while absorbing aerosols (like black carbon) warm the atmosphere by trapping solar radiation (Fig. 41).[368] These opposing effects complicate the overall climate response and can lead to regionally contrasting impacts on temperature, precipitation, and cloud dynamics.

While interhemispheric difference in AOD is a globally averaged indicator, many significant aerosol related effects are regional. For example, elevated aerosol concentrations over the Indian subcontinent have been linked to a weakening of the South Asian monsoon, increasing the risk of prolonged droughts and reduced agricultural productivity.[3]

Data Sources

AOD data (total AOD for light at 550 nm wavelength) is the ECMWF Atmospheric Composition Reanalysis 4 product from the Copernicus Atmosphere Monitoring Service (CAMS).[360,369]

Effective radiative forcing estimates 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.[370] 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.[371]



4.8 Stratospheric Ozone Depletion

Main Takeaways

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. Transgression 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.

2025 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.[1]
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.

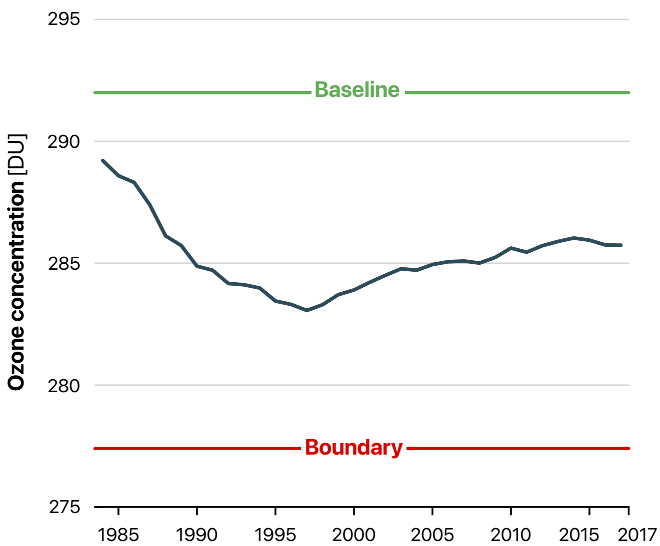


FIGURE 43 - Ozone layer revival: A success story. This chart displays the 11-year mean of the control variable "global mean stratospheric ozone concentration" measured in Dobson Units (DU) for the data from 1979-2022. The red line shows the Planetary Boundary of about 277, while the green line represents the baseline of 292 (values updated [4,372]). Data from Copernicus (2020).[373]

Key takeaway: *While the global stratospheric ozone layer has recovered since the mid-1990s following a significant decline, this recovery may have plateaued in recent years.*

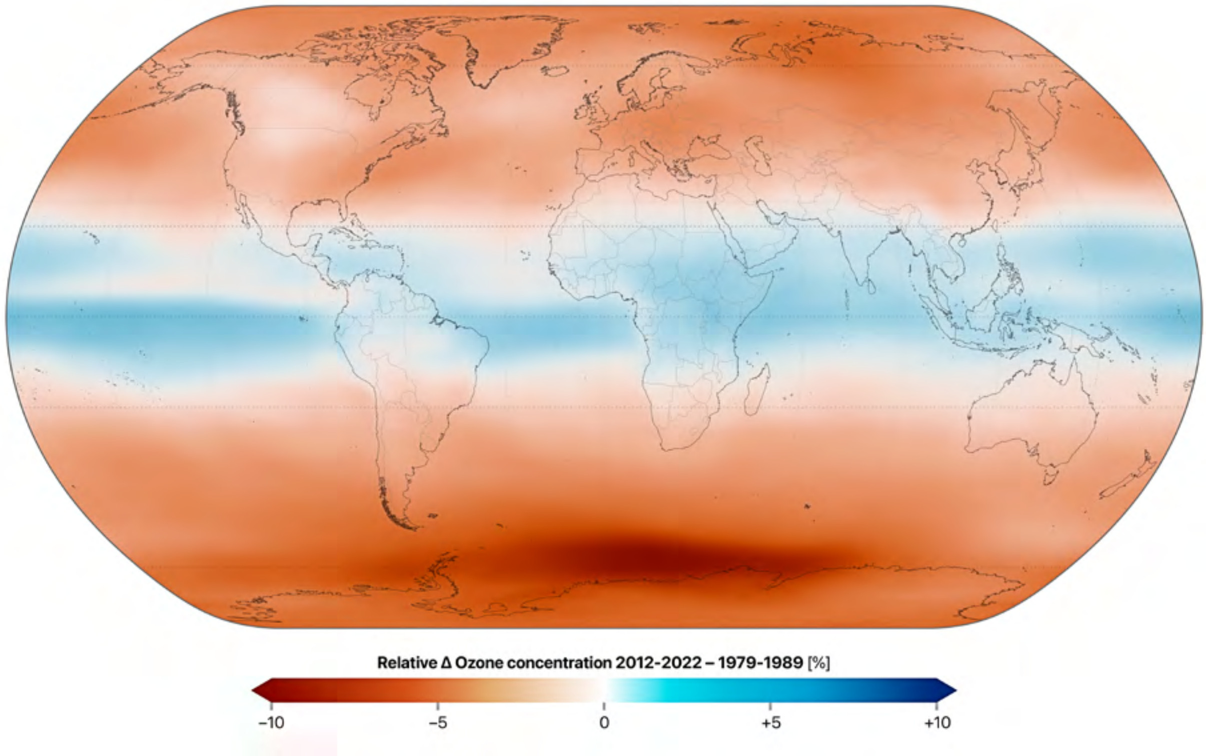


FIGURE 44 - Global map of recent ozone layer changes. This map shows the relative change of the control variable "global mean stratospheric ozone concentration" between 1979-1989 (first 11-year cycle of this data set) and 2012-2022 (last 11-year cycle of this data set, e.g. a change from 260 DU to 273 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).[373]

Key takeaway: *Global changes in stratospheric ozone concentration between 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.*

Key Drivers

UV radiation reaching Earth's surface poses a threat to biological 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 is a catalytic cycle within the stratosphere involving 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.[374] The Montreal Protocol has successfully controlled CFC emissions; today, the most significant remaining source of ozone-depleting substances is nitrous oxide (N_2O).[375] Agricultural activities are a major source of N_2O, contributing to its presence in the atmosphere through various pathways.[376]

Impacts

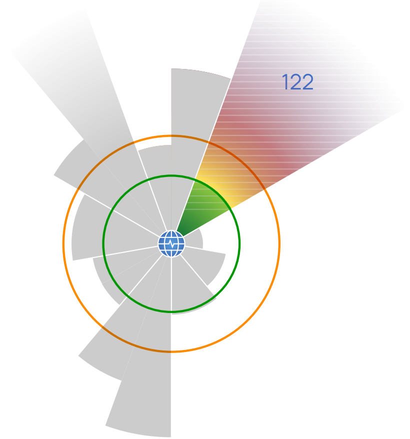
Depletion of stratospheric ozone allows more harmful ultraviolet (UV) radiation to reach the Earth's surface, significantly increasing the risk of skin cancer, cataracts, and other health problems in humans. This increased UV radiation also adversely affects terrestrial and aquatic ecosystems. In the 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.[377] 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.

The depletion of Antarctic stratospheric ozone in the period from 1960 to 2000 resulted in the cooling of 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.[378] This led to changes in the Southern Hemisphere tropospheric circulation, including the poleward shift of the mid-latitude tropospheric wind jet and the poleward expansion of the equatorial tropospheric convection cell, which also had an impact on rain precipitation in the Southern Hemisphere.[379] After the year 2000, the Antarctic ozone recovery led to a weakening of the Antarctic polar vortex and to earlier polar vortex breakup dates.[378] Recent studies[380] 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 multiple evidence of Antarctic ozone depletion- and recovery-related changes in the Southern Hemisphere, influencing tropospheric circulation and surface climate, no robust evidence of such linkage was found in the Northern Hemisphere.[378]

The increasing amount of space debris at the low-Earth orbit ultimately leads to ozone depletion due to the production of nitrogen monoxide in the middle atmosphere by reentering space debris. Additionally, a growing amount of rocket launches and reentering 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.[378]

Data Sources

Ozone data from Copernicus (2020),[373] accessed on 17-Jun-2024.

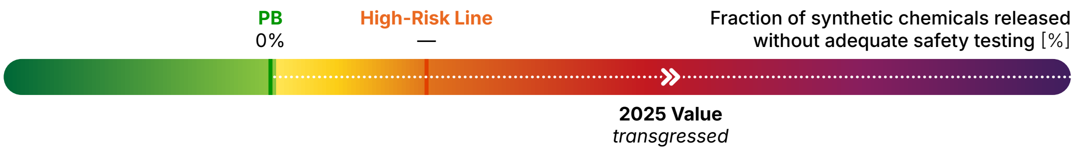


4.9 Introduction of Novel Entities

Main Takeaways

Novel entities comprise human-made chemicals, naturally occurring chemicals that are mobilized by humans, human-made particles like plastics and human-modified life forms. Produced and released in myriad forms and huge quantities, they can interact and accumulate in ways that threaten Earth-system processes. For example, many harmful chemicals (such as banned pollutants and plastics) are still widespread globally, accumulating in animals like marine mammals and causing adverse effects on wildlife and humans.

However, our understanding of planetary scale exposure and impacts is still fragmented due to the amount and tremendous diversity of novel entities. To track this planetary risk, we use a practical proxy: the proportion of novel entities that undergo rigorous safety assessment before widespread use. That share is currently low, and on this basis the Planetary Boundary for Introduction of Novel Entities is considered transgressed – the creation of new substances far outpaces our capacity to evaluate them. Future assessments may incorporate additional metrics, such as production volume, environmental release, and mixture effects, to refine our understanding of this planetary risk.



Definition

Novel entities are novel anthropogenic introductions to the Earth system. These include synthetic chemicals and substances (e.g., microplastics, endocrine-disrupting chemicals, and organic pollutants); anthropogenically mobilized radioactive materials, including nuclear waste and nuclear weapons; and human modification of evolution, genetically modified organisms and other direct human interventions in evolutionary processes.[4]

They can disrupt Earth system processes and pose risks of irreversible harm to other PBs, e.g., via impacts on life in the biosphere and the carbon cycle. Since the Planetary Boundaries framework focuses on Earth system stability rather than human or individual ecosystem health, a key scientific challenge is to determine how much novel entity loading the system can tolerate before it shifts irreversibly into a less habitable state.[4]

2025 Status

The amount of human-made chemicals and particles as well as human-modified life forms introduced into the environment without adequate testing is **beyond safe levels**. Following the precautionary principle, no human-made entities should be released without adequate safety testing.

Control Variables

Percentage of synthetic chemicals released to the environment without adequate safety testing

Definition	The share of human-made chemicals released into the environment without adequate safety testing. This control variable is a critical indicator of how effective regulations are and our understanding of chemical risks, and it is essential for managing the potential impacts these substances may have on human health and the environment.
Unit	Percentage, i.e. the fraction of synthetic chemicals released without adequate safety testing.
Historical Range	This percentage can vary from 0% (all chemicals undergo sufficient testing before release) to 100% (none are tested).
Planetary Boundary (PB)	Following the precautionary principle, the PB is set at 0 % – no human-made chemicals should be released without adequate safety testing. Historical examples like Dichlorodiphenyltrichloroethane (DDT, which harmed bird populations and entered food chains), Chlorofluorocarbons (CFCs, which depleted the ozone layer) and Polychlorinated Biphenyls (PCBs, which partly exceed effect thresholds in marine mammals) underscore the need for strict testing. Legacy contamination has persisted for decades and will continue to be present in the Earth system, emphasizing the need to follow the precautionary principle to avoid the release of harmful substances. Currently, a significant portion of chemicals remains untested or is not adequately tested (i.e. how they interact in mixtures), indicating that the PB is exceeded. In addition to the scientific limitations in testing such large numbers of chemicals and their diverse modes of action, many legal bodies and regulators lack the capacity to assess these chemicals, regulate their use, and to ensure compliance with existing regulation.

Key Drivers

The control variable for the **Introduction of Novel Entities** Planetary Boundary, which measures the percentage of untested human-made chemicals, is directly driven by human activities. It has been transgressed due to a rapid increase in chemical production in the last decades, 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 insufficient monitoring covering all components.

In addition to these gaps, the limited capacity to translate scientific testing results into effective regulatory actions, and to enforce them and ensure monitoring of their compliance, undermines compliance with regulations. As Persson et al. (2022)[74] emphasized, "the rapid increase in the production and release of large volumes and diverse types of novel entities exceeds society's capacity to conduct safety assessments and monitoring."

Impacts

The introduction of new components of novel entities, adding to legacy contamination, can disrupt critical Earth system processes. For instance, fluorinated gases contribute to climate change by trapping heat, and Polycyclic Aromatic Hydrocarbons (PAHs, emitted from vehicles and industry) are involved in aerosol formation, which impacts air quality. These novel entities also harm ecosystems by eliciting adverse effects by themselves or in chemical mixtures with compounds of the same mode of toxic action, hence affecting the health of wildlife and potentially humans. Pesticides, for example, have caused substantial declines in insect and pollinator populations. Persistent organic pollutants like PAHs, along with anthropogenic particles including microplastics, inflict harm and adverse effects on marine and terrestrial life. PFAS – a group of highly persistent human-made chemicals – exemplify the long-term risks posed by novel entities. Widely used in industrial processes and consumer products, PFAS have now been detected across the globe in water, soil, wildlife, and human blood.

The accumulation and persistence of some novel entities can lead to long-term, possibly irreversible changes in the environment including the contamination of soil and sediments, air and water bodies as well as the alteration of natural habitats. Radioactive elements which also form part of novel entities can cause immediate and long-term health effects, including mutations and cancer.

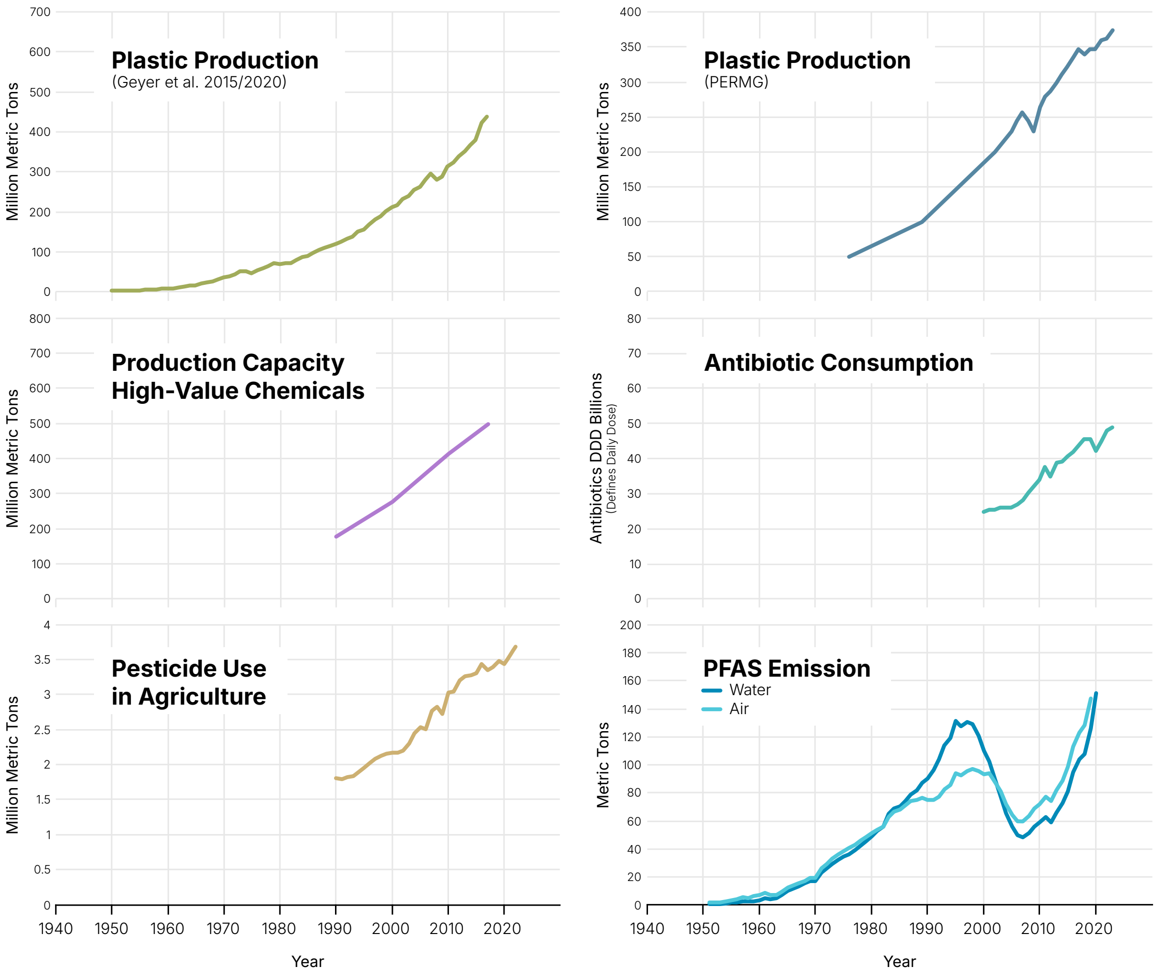


FIGURE 45 - From conception to contamination: The rise of novel entities. This figure exemplifies the trends of production (Plastics, High-Value Chemicals), application (Antibiotics, Pesticides) and release (PFAS) of different novel entities.

Key takeaway: *Production of many human-made substances such as plastics, antibiotics, pesticides and harmful chemicals is steadily rising, posing significant threats to the Earth system – as well as human health.*

"Current and Future Research

The currently used control variable for the **Introduction of Novel Entities** is the percentage of untested chemicals released into the environment, which so far is challenging to assess accurately and comprehensively. Large-scale safety testing of novel entities is important, but those tests are only useful if they follow rigorous scientific protocols. However, even high-quality safety tests cannot assess all possible environmental interactions and rule-out long-term, low probability, high impact side effects of novel entities.

An effective control variable should meet three criteria: It must be (1) measurable, (2) robust and directly linked to effects on the Earth system, and (3) able to capture the global scope of the problem. Persson et al. (2022)[74] proposed to employ a set of control variables for novel entities that comprise the main stages of the impact pathway. This includes production and use, release, fate and Earth system impacts (e.g., trends in the production volume and use, trends in the release to the environment, and impacts of novel entities on environmental processes, on species and/or vulnerable populations and on other PBs). These control variables can then be refined for certain groups of novel entities such as plastics[381] or human-modified life forms.

Data Sources

Data for plastic production including additives from fossil resources from Geyer et al. (2017)[382] and Geyer (2020).[383]

Data for plastic production from fossil resources excluding additives compiled from Plastics Europe Market Data.[384]

Data on chemical production capacities from UNEP (2019).[385]

Data and projections on antibiotic consumption compiled from Klein et al. (2018)[386] and Klein et al. (2024).[387]

Data on pesticide use in agriculture from FAOSTAT (2024).[341]

Data on Per- and Polyfluoroalkyl Substances (PFAS) emissions from Simon et al. (2024).[388]

5

Outlook – From Insight to Actionable Intelligence

We stand at a pivotal moment: Unprecedented planetary risk coincides with the emergence of powerful tools to monitor and understand the Earth system. In 2025, PIK launched the **Planetary Boundaries Science Lab (PBScience Lab)** – a dedicated working group for advancing the core Planetary Boundaries framework, coordinating and producing the annual Planetary Health Check (PHC) and building the foundations of a global collaboration: the **Planetary Boundaries Initiative (PBI)**.

Early Momentum and Community Building

- **Workshops to advance science:** PBScience hosted its first ocean-focused expert workshop, gathering leading scientists to refine how ocean processes are represented in the Planetary Boundaries framework. Equivalent workshops are planned for additional topics in the near future.
- **Open calls to improve the PBs framework:** In 2024/2025 PBScience launched open calls for new control variables and indicators, resulting in diverse proposals from researchers, practitioners, and students. We will continue this participatory approach, and welcome any suggestions.
- **Bridging science and action:** To better connect with decision makers, PBScience is engaging with actors from policy, business, and civil society helping translate global thresholds into real-world decisions.
- **A growing transdisciplinary network:** From Earth observation and climate modeling to economics, governance, and Indigenous knowledge, the PBScience Lab is coordinating a broad coalition. **This network forms the scientific basis of the Planetary Boundaries Initiative.**

Toward a Global Planetary Boundaries Initiative

To scale our efforts globally and turn cutting-edge science into real-world impact, we are currently co-creating the **Planetary Boundaries Initiative (PBI)** – a multi-institutional platform that will track, assess, and help respond to the planetary risks identified in the PHC. The PBI is organized into three working clusters that integrate science, solutions and communication:

1. Science for Diagnostics: monitors PBs in high spatial and temporal resolution, advances the PBs framework, enhances the precision of boundary settings, assesses PB interactions, analyzes tipping risks and Earth resilience.
2. Science for Solutions: synthesizes PBs in practice, translates diagnostics into transformation pathways, tracks real-world responses, identifies positive tipping potentials, designs dynamic decision support.
3. Communication for Action: translates Planetary Boundaries science for key target groups, combines storytelling, design, and adaptive messaging, builds a global community of partners.

The clusters converge their efforts in the development of what we call the Planetary Boundaries Analyzer (**PBAnalyzer**).

The Planetary Boundaries Analyzer

The **PBAnalyzer** is a modular, semi-automated workflow that:

- **Mediates collaboration** across PBI clusters and plugs in external workflows
- **Standardizes, automates, and accelerates** PB assessments via advanced big data management and analytics
- Guarantees **full reproducibility** and broad usability through open-access principles and a shared data architecture
- **Identifies** and **fuses** suitable **datasets** from Earth observation, empirical socio-economic sources, simulation models, and literature
- Keeps results continuously updated via **near real-time links** to data providers
- Operates **across spatial and temporal scales** by handling heterogeneous resolution datasets
- Advances PBs research by applying **latest methods** of remote sensing, modelling, and artificial intelligence
- Integrates natural and socio-economic sciences to map causal relations and pinpoint **high-leverage intervention points**
- Translates insights for stakeholders by **thematic clustering** and **user data integration**

To achieve these capabilities the **PBAnalyzer** will use techniques of advanced modeling and combine them with expert feedback to ensure generated results are reliable and practically relevant. The workflow will enable actionable, interactive decision support that will be offered through an open access web platform which we call the **Planetary Mission Control Centre**.

Planetary Mission Control Centre

The **Planetary Mission Control Centre** will be a free, next-generation decision-support platform for scientists, policymakers, and civil society that gives easy access to results and capabilities of the **PBAnalyzer**. Users can test interventions, simulate scenarios, and explore strategies for staying within Earth's safe operating space. This will enable faster responses to scientific insights and more informed decisions at every level. Users pull or feed in the latest Earth system and socio-economic data, distill them into clear, boundary indicators, and produce insights directly for individual decision making.

An Open Invitation

The Planetary Boundaries Initiative is not just a project but a growing community. We invite researchers, institutions, students, Indigenous knowledge holders, practitioners and other stakeholders to help shape the next generation of diagnostics, solutions, and narratives for the planetary crisis. Together, we can transform scattered data into actionable intelligence and turn planetary insight into planetary stewardship.

Contact and Information

Email: pbscience@pik-potsdam.de

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Planetary Boundaries
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6. Tables and References

6.1 Tables

Table 3 - 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 2025 or the latest documented year), and their reference values (Holocene-like baseline or similar; see PB Info Sheets (Ch. 4) 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. 1, which delineates the Safe Operating Space (Ch. 2.1), as well as the high-risk threshold, marked by a orange circle in Fig. 1, 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. 4). For comparison, we present the results of the latest PB assessment within the 2025 Planetary Health Check (PHC) alongside the most recent PB assessment from Richardson et al. (2023).[4]

Earth system process	Control variable	Current value of control variable		Reference value*		PB value		High risk value	
Assessment		**PHC 2025**	**Richardson et al. 2023**	**PHC 2025**	**Richardson et al. 2023**	**PHC 2025**	**Richardson et al. 2023**	**PHC 2025**	**Richardson et al. 2023**
Climate Change	Atmospheric CO_2 concentration (ppm CO_2)	423 ppm	417 ppm	280 ppm	280 ppm	350 ppm	350 ppm	450 ppm	450 ppm
	Total anthropogenic radiative forcing at top-of-atmosphere ($W\ m^{-2}$)	+2.97 Wm^{-2}	+2.91 Wm^{-2}	0 Wm^{-2}	0 Wm^{-2}	+1 Wm^{-2}	+1 Wm^{-2}	+1.5 Wm^{-2}	+1.5 Wm^{-2}
Change in Biosphere integrity (extinctions/ %HANPP)	Genetic diversity: Extinctions per million species years (E/MSY)	>100 E/ MSY	>100 E/ MSY	1 E/MSY	1 E/MSY	<10 E/ MSY	<10 E/MSY	100 E/ MSY	100 E/MSY
	Functional integrity: Human appropriation of the biosphere's NPP as a percentage of pre-industrial NPP (% HANPP)	30% HANPP	30% HANPP	0% HANPP	1.9% HANPP	<10% HANPP	<10% HANPP	20% HANPP	20% HANPP
Land System Change	Global: Area of forested land as percentage of original forest cover; Biome: Area of forested land as the percentage of potential forest (% area remaining)	Global: 59%	Global: 60%	Global: 100%	Global: 100%	Global: 75%	Global: 75%	Global: 54%	Global: 54%

Earth system process	Control variable	Current value of control variable		Reference value*		PB value		High risk value	
Assessment		**PHC 2025**	**Richardson et al. 2023**	**PHC 2025**	**Richardson et al. 2023**	**PHC 2025**	**Richardson et al. 2023**	**PHC 2025**	**Richardson et al. 2023**
Freshwater Change (blue/ green)	Blue water: Human-induced disturbance of blue water flow (% land area with deviations from pre-industrial variability)	22.6%	18.2%	10.3%	9.4%	12.9%	10.2%	50%	50%
	Green water: Human-induced disturbance of water available to plants (% land area with deviations from pre-industrial variability)	22.0%	15.8%	9.8%	9.8%	12.4%	11.1%	50%	50%
Modification of Biogeo-chemical Flows (P/N)	Phosphorus (global): P flow from freshwater systems into the ocean; Phosphorus (regional): P flow from fertilizers to erodible soils (Tg of P $year^{-1}$)	Global: 4.4 Tg $year^{-1}$ Regional: 18.2 Tg $year^{-1}$	Global: 22.6 Tg $year^{-1}$ Regional: 17.5 Tg $year^{-1}$	Global: 0 Tg $year^{-1}$ Region-al: 0 Tg $year^{-1}$	Global: 0 Tg $year^{-1}$ Regional: 0 Tg $year^{-1}$	Global: 11 Tg $year^{-1}$ Regional: 6.2 Tg $year^{-1}$	Global: 11 Tg $year^{-1}$ Regional: 6.2 Tg $year^{-1}$	Global: 100 Tg $year^{-1}$ Region-al:11.2 Tg $year^{-1}$	Global: 100 Tg $year^{-1}$ Region-al:111.2 Tg $year^{-1}$
	Nitrogen global: Industrial and intentio-nal fixation of N (Tg of N $year^{-1}$)	165 Tg year-[1]	190 Tg $year^{-1}$	0 Tg $year^{-1}$	0 Tg $year^{-1}$	62 Tg $year^{-1}$	62 Tg year-[1]	82 Tg $year^{-1}$	82 Tg $year^{-1}$
Ocean Acidi-fication	Global mean saturation state of aragonite in surface seawater (Ω)	2.84	2.81	3.57	3.44	2.86	2.75	2.50	2.41
Increase in Atmospher-ic Aerosol Loading	Interhemispheric difference in AOD	0.063	0.076	0.04	0.03	0.1	0.1	0.25	0.25
Stratospheric Ozone Depletion	Stratospheric O3 concentration, (global average) (DU)	285.7	284.6	292	290	277	276	263	261
Introduction of Novel Entities	Percentage of synthetic chemicals released to the environment with-out adequate safety testing	>0	>0	0	0	0	0	-	-

*The reference value may use either a Holocene-like, pre-industrial, or alternative baseline; see the PB Info Sheets (Ch. 4) for the specific period.

Table 4 - 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	Observation method	Period covered	Resolution
Climate Change	Atmospheric CO_2 concentration	Ground-Based Observations	Jan 1979 - May 2025	Monthly
	Total anthropogenic radiative forcing at top-of-atmosphere	Observations and climate models	1750 - 2024	Annual
Change in Biosphere Integrity	Genetic Diversity: E/MSY	Ground-Based Observations	~1500 - 2025	Centennial
	Functional integrity: HANPP	Data Integration and Statistical Modeling	1910 - 2010	Decadal
Land System Change	Forest Area	Remote Sensing	1992 - 2022	Annual
Freshwater Change	Human induced disturbance of blue water flow.	Global hydrological model ensemble	1901 - 2019	Annual [evaluated per month]
	Human induced disturbance of water available to plants	Global hydrological model ensemble	1901 - 2019	Annual [evaluated per month]
Modification of Biogeochemical Flows	Phosphorus flow from freshwater systems into the ocean	Data Integration and Statistical Modeling	1961 - 2013	Annual
	Industrial and intentional fixation of Nitrogen	Data Integration and Statistical Modeling	1961 - 2013	Annual
Ocean Acidification	Global mean saturation state of aragonite in surface seawater (Ω)	Data Integration and Statistical Modeling	1980 - 2024	Monthly
Increase in Aerosol Loading	Interhemispheric difference in AOD	Data Integration and Statistical Modeling	2003 - 2024	Monthly
Stratospheric Ozone Depletion	Stratospheric O_3 concentration	Remote Sensing	1979 - 2022	Monthly
Introduction of Novel Entities	Percentage of synthetic chemicals released to the environment without adequate safety testing	Ground-Based Observations	2000 - 2017	Annual

Table 5 - Author contributions and affiliations.

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

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2.2 Planetary Stability and Resilience	**Jonathan F. Donges**[a,g,i], Max Bechthold[a,j, i], Norman J. Steinert[k,a], Nico Wunderling[l,a]
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3.1 The Ocean: The Unsung Guardian of Planetary Health	**Levke Caesar**[a], Willem Huiskamp[a], Sabine Mathesius[a]
3.2 Guest article: Extreme Weather and Disasters in 2024/25 – An Attribution-Based Perspective	**Friederike Otto**[n], Emmanuel Raju[o,p]
3.3 Guest article: Putting Planetary Boundaries to Work: Emerging Practices, Actors and Tools	**Tiina Häyhä**[g], Albert Norström[g,h]
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The Planetary Health Check is more than a measure of risk – it is a compass for action, guiding us to restore balance.


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