Planetary Health Check

A Scientific Assessment of the State of the Planet

FIRST EDITION

2024

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Acknowledgments

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Planetary Boundaries Science is an international scientific partnership established at the end of 2023 to provide annual *Planetary Health Checks*, while steadily advancing the underlying science and ensuring contemporary and efficient science communication. *PBScience* will improve Planetary Boundaries assessments by a) applying cutting-edge data analysis techniques, b) utilizing the latest available data sets, c) enhancing Earth system modeling, and d) using modern, comprehensive communication tools to convey its messages to a broad audience. Collaborating closely with the *Planetary Guardians*, *PBScience* strives to elevate global awareness and drive action towards maintaining planetary stability.

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Disclaimer: It is not our intention in this first report to encompass all relevant literature on recent Planetary Boundaries (PBs) research in order to produce a full review. Rather, we aim to provide an updated PBs assessment, offer a thorough explanation of the PBs framework and methods, and identify potential initial advancements. We 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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Foreword

It is with great passion and commitment that I introduce this inaugural *Planetary Health Check*. This report marks a significant step forward in our collective mission to understand and protect the stability, resilience and life-support systems. This is the first of many annual editions to come and represents a solid starting point for the journey ahead.

Our dedicated team has worked tirelessly to bring this initial version to life, and will continue to improve it by advancing and synthesizing our ongoing Planetary Boundaries research. Recognizing the importance of timely and comprehensive updates, we aim to make a massive step-change in the frequency, synthesis, and depth of advancing Planetary Boundaries science – from updates every 6-8 years to annual reports. This will allow us to integrate the latest Earth Observation data and provide the most current insights.

As this research and its communication is of outstanding importance, we recently initiated *Planetary Boundaries Science (PBScience)*. This growing international partnership is committed to deepening our understanding and assessment of the Earth system and providing pathways of how we can navigate our future on Earth. Critical to this endeavor is science-based communications of why and how we now need to become stewards of the entire Earth system.

A unique feature of *PBScience* is that it serves as the foundation for the *Planetary Guardians*: global leaders from all walks of life mobilized to be ambassadors for our planet, with a focus on protecting and managing Earth's life support within the Safe Operating Space of Planetary Boundaries. In the future, our goal is to translate science into action, ranging from governance of Planetary Boundaries to guiding investments in finance and business. We are on a scientific mission to develop a *Planetary Boundaries Monitor* – a control room for Planet Earth. We envision a world where Planetary Boundaries are respected, ensuring a safe and sustainable future for all.

We invite new partners to join us in this critical endeavor. Your involvement can make a significant difference in helping us provide the most up-to-date information possible and in driving the global response needed to safeguard our planet.

I want to highlight that this report is written to be accessible to a broad audience. While we have firmly based it on rigorous scientific publications – recommended for further reading – to ensure scientific integrity, we have also made some simplifications to make the information easier to understand.

Thank you for your interest in this pivotal topic. Your engagement and support are vital as we work together to protect our planet for future generations. Let's embrace this journey with enthusiasm and a shared commitment to positive change.

Yours sincerely,

JOHAN ROCKSTRÖM
Director, *Potsdam Institute for Climate Impact Research (PIK)*

Professor of Earth and Environmental Sciences, *University of Potsdam*

Glossary

1. **PLANETARY HEALTH:** A term that refers to the state of the Earth system in terms of its ability to maintain stability, resilience, and life-support functions. It reflects how well the planet sustains the conditions necessary for human and ecological well-being. The concept of Planetary Health is central to understanding and maintaining the Safe Operating Space.

2. **SAFE OPERATING SPACE:** An Earth system state that enables humanity to develop and thrive for generations to come. It encompasses environmental conditions akin to, but not identical to, those of the Holocene epoch, which began around 11,700 years ago. The Holocene was characterized by relatively stable and warm conditions (compared to the colder and more variable conditions before), allowing for the development of agriculture and modern civilizations. The Safe Operating Space ensures that crucial Earth system processes remain within boundaries that support global stability, resilience and life-support functions.

3. **PLANETARY BOUNDARY (PB):** The outer bounds of the Holocene-like Safe Operating Space that define the limits within which humanity can safely operate without causing significant disruption to the environment. The Planetary Boundaries framework identifies the nine Earth system processes essential for maintaining global stability, resilience and life-support functions. These boundaries represent the safe operating limits for each process, beyond which the risk of causing severe and potentially irreversible environmental changes increases. Staying within these boundaries helps ensure that the Earth system remains stable and capable of supporting life and human development.

4. **ZONE OF INCREASING RISK:** Transgressing boundaries pushes our planet into a "Zone of Increasing Risk" where the likelihood for damage increases as the boundary transgression continues. As conditions worsen, the risk of crossing into more severe impacts, destabilizing specific PB processes, and undermining PB functions across various scales increases.

5. **HIGH RISK ZONE:** This zone lies farther out and represents a higher risk of triggering both the loss of systemic life support functions and irreversible changes to the functions that regulate Earth's livability. Conditions here have significantly deviated from safe levels, making severe, potentially irreversible environmental impacts more likely. Immediate action is necessary to prevent losing a Holocene-like Earth system state or substantially eroding Earth system resilience.

6. **TIPPING POINT:** A critical threshold in a system beyond which change becomes self-perpetuating, leading to substantial, widespread, frequently abrupt and often irreversible impacts. This occurs when positive feedback processes amplify initial changes, leading to a rapid and substantial transition from one stable condition to another. Identifying tipping points can be difficult as they may develop over various timescales and result in responses with impacts that might be disproportionately large compared to their causes.

7. **TIPPING ELEMENT:** A component of the Earth system that can pass a tipping point, leading to a major and often irreversible shift in its state. Tipping elements are critical subsystems, such as ice sheets, ocean currents, or large-scale ecosystems, that have the potential to trigger significant changes in the overall Earth system if their thresholds are crossed. These elements can be sensitive to changes and their destabilization can lead to cascading effects across interconnected systems.

8. **CONTROL VARIABLE:** A variable used as a representative indicator to estimate the state or condition of a PB process. Typically, 1-2 control variables are utilized per PB to monitor and assess the boundary's status.

9. **DRIVERS OF TRANSGRESSION:** Human activities that contribute to exceeding or breaching Planetary Boundaries (PBs), resulting in the Earth system being pushed out of its Safe Operating Space. These activities, such as burning fossil fuels or deforestation, directly impact control variables (e.g., atmospheric CO_2 levels) and lead to environmental changes that destabilize critical Earth system processes. Understanding these drivers is crucial for addressing the root causes of environmental challenges and exploring effective solutions.

This inaugural annual report represents a crucial step in monitoring and safeguarding Earth's stability, resilience, and life-support functions – what we refer to as "Planetary Health". Our recently established and fast-growing international science partnership, called *Planetary Boundaries Science (PBScience)*, will work on advancing the Planetary Boundary (PBs) framework by integrating new data and methodologies while fostering innovative science communication.

The PBs framework analyses and monitors the nine PB processes and systems that scientifically are proven to regulate the health of our planet. Each of these processes, such as **Climate Change** or **Ocean Acidification**, is currently quantified by one or two different control variables. The *2024 Planetary Health Check* report reveals that six out of nine PB processes have breached the safe PB levels, with all six showing trends of increasing pressure in all control variables, suggesting further boundary transgression in the near future (Fig. 1).

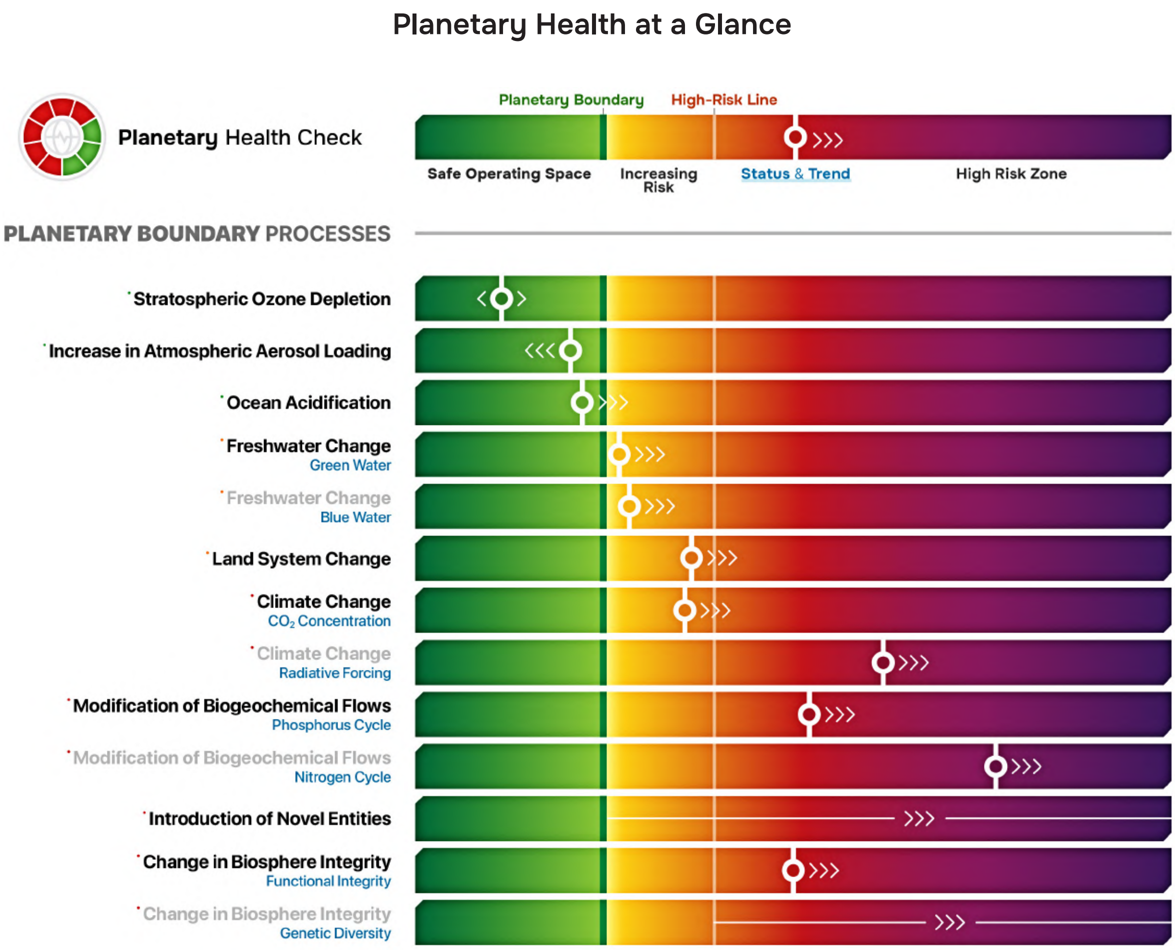

FIGURE 1 Planetary Health at a Glance. Just as a blood test provides insights into a human body's health and identifies areas of concern, this *Planetary Health Check* evaluates the 13 control variables across the 9 Planetary Boundary (PB) processes to report on Earth's stability, resilience, and life-support functions – the overall health of our planet. The 2024 assessment shows that six of the nine PBs have been transgressed: Climate Change, Biosphere Integrity, Land System Change, Freshwater Change, Biogeochemical Flows, and the Introduction of Novel Entities. All of these show increasing trends, suggesting further transgression in the near future. Three PB processes remain within the Safe Operating Space: Ocean Acidification (increasing trend and close to PB), Atmospheric Aerosol Loading (decreasing global trend), and Stratospheric Ozone Depletion (no trend).

The six PB processes that have breached safe PB levels are:

Climate Change (6.1): Atmospheric CO_2 levels are at a 15-million-year high, and global radiative forcing continues to rise, with a persistent warming trend that has accelerated since the late 20th century. Global mean temperatures are now higher than at any point since human civilizations emerged on Earth.

Change in Biosphere Integrity (6.2): The global loss of genetic diversity and the loss of functional integrity (measured as energy available to ecosystems) are both exceeding safe levels and accelerating, particularly in regions experiencing intensive land use. The vast decrease in biosphere integrity raises concerns that Earth's biosphere is losing resilience, adaptability, and its capacity to mitigate various pressures, including those from transgressing other PBs.

Land System Change (6.3): As a result of land use and increasingly due to climate change, global and regional forests have been steadily declining over the last few decades across all major forest biomes. Most regions are already in the High Risk Zone, well beyond their safe boundaries, while some areas have only recently breached safe levels (e.g., temperate and tropical America).

Freshwater Change (6.4): Local streamflow and soil moisture deviations have significantly increased since the late 19th century, surpassing their respective PBs in the early 20th century. The increasing variability and instability in global freshwater and terrestrial water systems signal growing concerns for water resource management and environmental stability.

Modification of Biogeochemical Flows (6.5): The use of phosphorus and nitrogen in agriculture has exceeded safe boundary levels, driving significant ecological change. Breaching this boundary has led to severe environmental impacts such as water pollution, eutrophication, harmful algal blooms, and "dead zones" in freshwater and marine ecosystems. This issue has been prevalent in industrialized countries for a long time and is increasingly becoming a concern in developing regions as well.

Introduction of Novel Entities (6.9): The global introduction of novel entities — such as synthetic chemicals, plastics, and genetically modified organisms — is vast, yet a significant portion of these substances remains untested for their environmental impacts. This indicates that the boundary is likely exceeded, although exact figures are uncertain. Novel entities can disrupt critical Earth system processes (e.g., CFCs notably damaged the ozone layer), harm ecosystems (e.g., pesticides have caused significant declines in insect and pollinator populations), and lead to long-term, possibly irreversible changes in the environment, including the contamination of soil and water bodies and the alteration of natural habitats.

Even though **Ocean Acidification** is close to transgressing its PB, the three PB processes that remain within the **Safe Operating Space (2)** are:

Ocean Acidification (6.6): Ocean acidification is approaching a critical threshold, with significant declines in surface aragonite saturation, particularly in high-latitude regions like the Arctic and Southern Ocean. These areas are vital for the marine carbon pump and global nutrient cycles, which support marine productivity, biodiversity, and global fisheries. The growing acidification poses an increasing threat to marine ecosystems, especially those reliant on calcium carbonate for shell formation.

Atmospheric Aerosol Loading (6.7): The difference in aerosol optical depth between hemispheres is decreasing, indicating progress toward safer levels, though some regional patterns show opposing trends. Aerosols influence the Earth's energy balance by reflecting sunlight back into space and altering cloud formation. This impacts global and regional climate systems, including temperature regulation, precipitation patterns, and the distribution of solar energy. Managing aerosol levels is crucial for maintaining the stability of the Earth's climate system and preventing shifts that could disrupt weather patterns and ecosystems.

Stratospheric Ozone Depletion (6.8): Ozone recovery has plateaued, with mixed trends and ongoing challenges in addressing the Antarctic ozone hole. The stratospheric ozone layer plays a vital role in shielding the Earth from excessive ultraviolet (UV) radiation. This protection is essential for maintaining the integrity of the Earth's biological systems, as UV radiation can harm phytoplankton, disrupt marine ecosystems, and alter terrestrial plant growth – elements that are foundational to the global food web and carbon cycle. Stabilizing and restoring the ozone layer is critical for preserving these interconnected Earth system processes.

A New Era

Humanity has thrived for over 10,000 years within a period of climatic stability and a resilient Earth system, which has allowed the development of advanced technologies and cultures. However, as the 2024 PHC report shows, we are now entering a dangerous new era marked by increasing symptoms of PB transgressions, such as more frequent extreme weather events, wildfires, reduced plant productivity, and water scarcity. These challenges are compounded by a still-growing global population that must navigate unprecedented difficulties. Beyond these immediate concerns, a more profound threat lies in the gradual weakening of Earth system resilience. As we approach – and potentially cross – critical **tipping points (5)**, these slow changes may not result in abrupt shifts but could lead to irreversible trends, such as accelerated sea-level rise and self-reinforcing pathways that move us further from the stable, Holocene-like conditions crucial for human life.

The interconnectedness of PB processes **(Interconnections & Drivers, 3)** means that addressing one issue, such as limiting global warming to 1.5°C, requires tackling all of them collectively. This holistic approach, though daunting, offers the potential to transform what seems like a burden into an opportunity for sustainable progress. Reversing the multiple drivers currently pushing systems toward tipping points can yield synergistic effects of conservation and resilience. Immediate and coordinated global action, involving governments, businesses, and civil society, is essential to return to the **Safe Operating Space (2)** across all PBs and secure a prosperous future for both people and the planet **(Solution Space, 9)**.

A Path Forward

In the near future, *PBScience* plans to establish a broader *Planetary Boundaries Initiative (PBI)* in collaboration with a growing network of partners. PBI aims to provide decision support to guide global development back into the Safe Operating Space by using the PBs framework as a scientific accounting system that guides policy, stimulates innovation, and drives transformative change.

To achieve this, the PHC will play a central role, beginning with annual reports that update on PB science and human progress toward reaching safe boundary levels. The approach includes introducing new control variables that focus on human-system interfaces, advancing Earth system simulation models with AI-powered analysis, and developing a near-real-time dashboard with data to guide investments and paths to safety. The PBI also emphasizes the importance of public awareness and scientific understanding, with a communications team working to make these insights widely accessible.

1. Planetary Boundaries

Why Planetary Boundaries?

In the current era, which is characterized by significant and rapid environmental changes,[1] there is an urgent need to establish comprehensive frameworks that help to understand how to ensure the stability, resilience, and life-support functions of our planet.

The "Planetary Boundaries (PBs)" framework is specifically designed to address this knowledge gap, focusing on maintaining a liveable planet for humans by using the Holocene period as a reference point for a stable environment.

While the framework provides critical global-level boundaries, it complements rather than replaces existing environmental assessment and policy measures, such as ecological footprints, chemical tolerability, air and water quality standards, and species protection lists. These measures are crucial, particularly at local levels, and collectively contribute to the safe space within which humanity can thrive.

The PBs framework fills a critical gap in the current Anthropocene by offering much-needed "health metrics" for our planet. With ample evidence now that humans are destabilizing the Earth system, it is essential to integrate local and global efforts to ensure a sustainable future. The PBs framework provides the capacity to achieve this integration.

Planetary Boundaries Framework

The biophysical Earth system consists of all 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 better care for 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 sustain life on our planet by, for example, maintaining temperature ranges suitable for abundant life in many regions and sustaining the cycles of water between soils, plants, and the atmosphere.

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 (2)**. Scientists have delineated this space by setting boundaries for critical processes that regulate stability, resilience, and life-support functions.

Introduction

Rooted in Earth system science, Planetary Boundaries (PBs) have been defined for the nine Earth system processes identified as crucial for maintaining the Earth system's stability and resilience. The PBs framework also identifies zones of increasing and high risk. Gradual changes, interactions, or **tipping points (5)** may occur within these zones, becoming more likely the further we enter them.

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.[2]

However, the PB processes are significantly influenced by human activities, which have proliferated since the mid-20th century, causing Earth to transgress six out of the nine PBs. This **Great Acceleration (2.1)**[1] 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 PBs framework was introduced in 2009[2] and refined in 2015[3] and 2023[4] following significant scientific advancements across all disciplines involved. However, at present, the global scientific community only has the resources to measure, analyze, and synthesize our planet's vital signs every 6-8 years.

To address this gap, advance the science, and avoid delays in reporting scientific progress, *Planetary Boundaries Science (PBScience)* will publish 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 PBs annually for the first time. Its primary purpose is to maintain ongoing dialogue and awareness about our planet's health.

1.1 **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. PB assessments use representative variables, called 'control variables,' to describe the state of all nine crucial Earth system processes (the colors – red for "High Risk Zone", green for within **Safe Operating Space (2)**, and yellow for "Zone of Increasing Risk" – refer to the state of boundary transgression; see Fig. 2). To date, the PBs framework uses 1-2 control variables per PB process (**Tables 1, 2; pg. 79-81**).

1

Climate Change

The alteration of the Earth's radiative balance – for example, through the accumulation of greenhouse gasses in the atmosphere – increases global temperatures and alters climate patterns.

2

Change in **Biosphere** Integrity

The decline in the diversity, extent, and health of living organisms and ecosystems threatens the biosphere's ability to co-regulate the state of the planet by impacting the energy balance and chemical cycles on Earth.

3

Land System Change

The transformation of natural landscapes, such as through deforestation and urbanization, diminishes ecological functions like carbon sequestration, moisture recycling, and habitats for wildlife – all crucial for Planetary health.

4

Freshwater Change

The alteration of the global hydrological cycle impacts all natural functions on land, including carbon sequestration and biodiversity, and can lead to large ecological shifts undermining Earth's resilience.

5

Modification of **Biogeochemical** Flows

The disruption of global nutrient cycles of nitrogen and phosphorus negatively affects soil health, water quality, and biodiversity and triggers dead zones in freshwater and marine systems.

6

Ocean Acidification

Ocean acidification is the phenomenon of increasing acidity (decreasing pH) in ocean water due to the absorption of atmospheric CO_2. This process harms calcifying organisms, impacting marine ecosystems, and reduces the ocean's efficiency in acting as a carbon sink.

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, allows more harmful UV radiation to reach Earth's surface.

9

Introduction of **Novel Entities**

The introduction of novel entities includes synthetic chemicals and substances, anthropogenically mobilized radioactive materials, and human interventions in evolutionary processes, such as genetically modified organisms (GMOs) and other direct modifications of evolution.

*For more detailed information on each PB, please refer to their respective **Information Sheets (6)** included later in this report.*

1.2 **Planetary Boundaries Diagram**

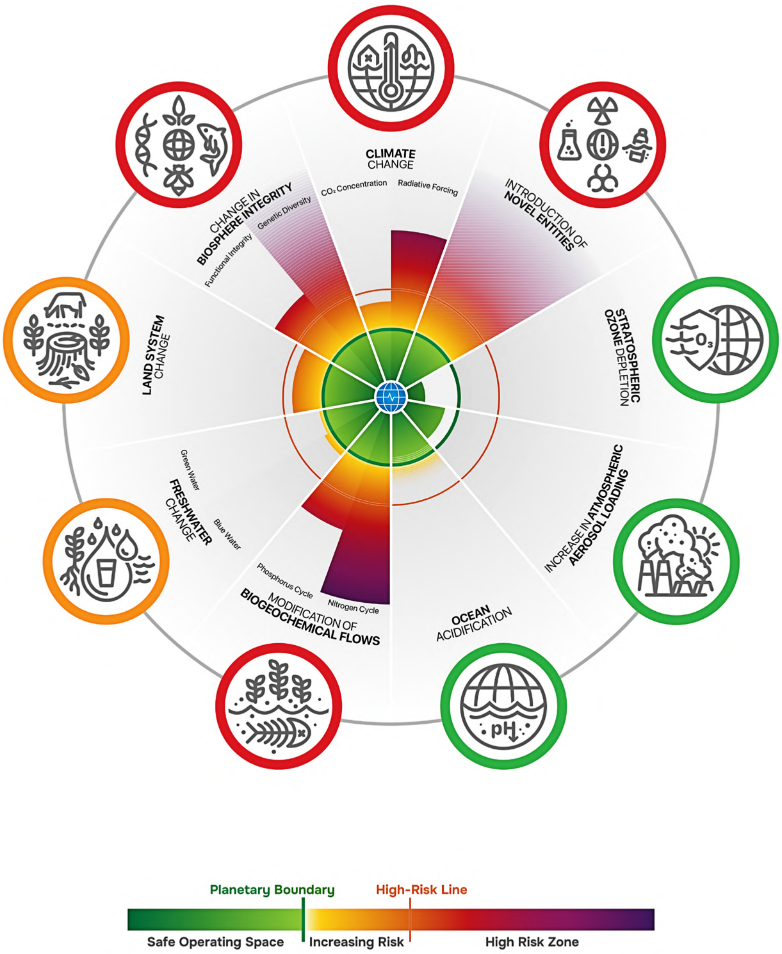

FIGURE 2 State of the Planet. The Planetary Boundaries (PBs) diagram visually represents the current status of the nine PB processes that define the safe limits for our planet's health. Each process is quantified by one or more control variables based on observational data, model simulations and expert opinions.

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 (2)** or beyond its PB (indicating PB transgression). Key visual markers are the PB (dark green circle) and the high-risk line (thin orange circle).

The **GREEN** area represents the Safe Operating Space that provides a high chance of keeping the 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 PB 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 Zone, for example, a high probability of destabilizing the Earth system due to a very large 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 (5)**. At a lower level, this damage involves destabilizing 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**), current values remain uncertain (**Change in Biosphere Integrity**), or current "safe" conditions may have to be re-evaluated considering the latest scientific insights (**Ocean Acidification**). 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]

1.3 **Planetary Health - Latest Assessment (2024)**

Six out of the nine Planetary Boundary (PB) processes have breached their PBs, meaning that the values of the corresponding control variables have exceeded their safe levels. This breach indicates significant environmental stress and the potential for irreversible changes. The transgressed boundaries are:

1. **Climate Change (6.1):** Both the atmospheric concentration of CO_2 and the total anthropogenic radiative forcing at the top of the atmosphere have exceeded their safe levels.

2. **Change in Biosphere Integrity (6.2):** Both the loss of genetic diversity and the functional integrity of the biosphere have exceeded their safe levels.

3. **Land System Change (6.3):** The globally remaining forest areas for all major forest biomes (tropical, boreal and temperate) have fallen below the safe levels.

4. **Freshwater Change (6.4):** Human-induced disturbances of both the blue and the green water flows have exceeded the safe levels.

5. **Modification of Biogeochemical Flows (6.5):** Both the global phosphorus flow into the ocean and the industrial fixation of nitrogen (the extraction of nitrogen from the atmosphere) are disrupting the corresponding nutrient cycles beyond the safe level.

6. **Introduction of Novel Entities (6.9):** The amount of human-made substances that are released into the environment without prior adequate testing is above the safe level.

Three PB processes remain within the **Safe Operating Space (2)**. However, **Ocean Acidification** is found on the verge of boundary transgression:

7. **Ocean Acidification (6.6):** While the global surface ocean aragonite saturation state is within its Safe Operating Space, it is close to breaching its safe level. New studies suggest that even the current conditions may be problematic for multiple marine organisms, indicating an urgent need to re-evaluate the safe boundary.

8. **Atmospheric Aerosol Loading (6.7):** The difference in aerosol optical depth between hemispheres is decreasing, indicating progress toward safer levels, though some regional patterns show opposing trends.

9. **Stratospheric Ozone Depletion (6.8):** The current total amount of stratospheric ozone is within the Safe Operating Space, but values are still below the mid-20th century levels.

1.4 **Planetary Boundaries Assessments Over Time**

The Planetary Boundaries (PBs) framework helps scientists and decision-makers assess where and how strongly human activities are pushing the Earth system beyond safe levels. It underscores the need for further research as well as targeted efforts to better understand and manage these critical processes.

While some of the obvious larger differences between past diagrams are due to changes in the methodologies and visualization techniques used for data assessment, there remains a clear trend: Humanity has increased its pressures on almost all PB processes since the first assessment in 2009. Future updates to this report will continue to track the evolving scientific understanding and visual representation of PBs, and will include an assessment of the actual state of each PB process over time using the most up-to-date methodology.

Scientific Updates
Planetary Boundaries Assessments Over Time

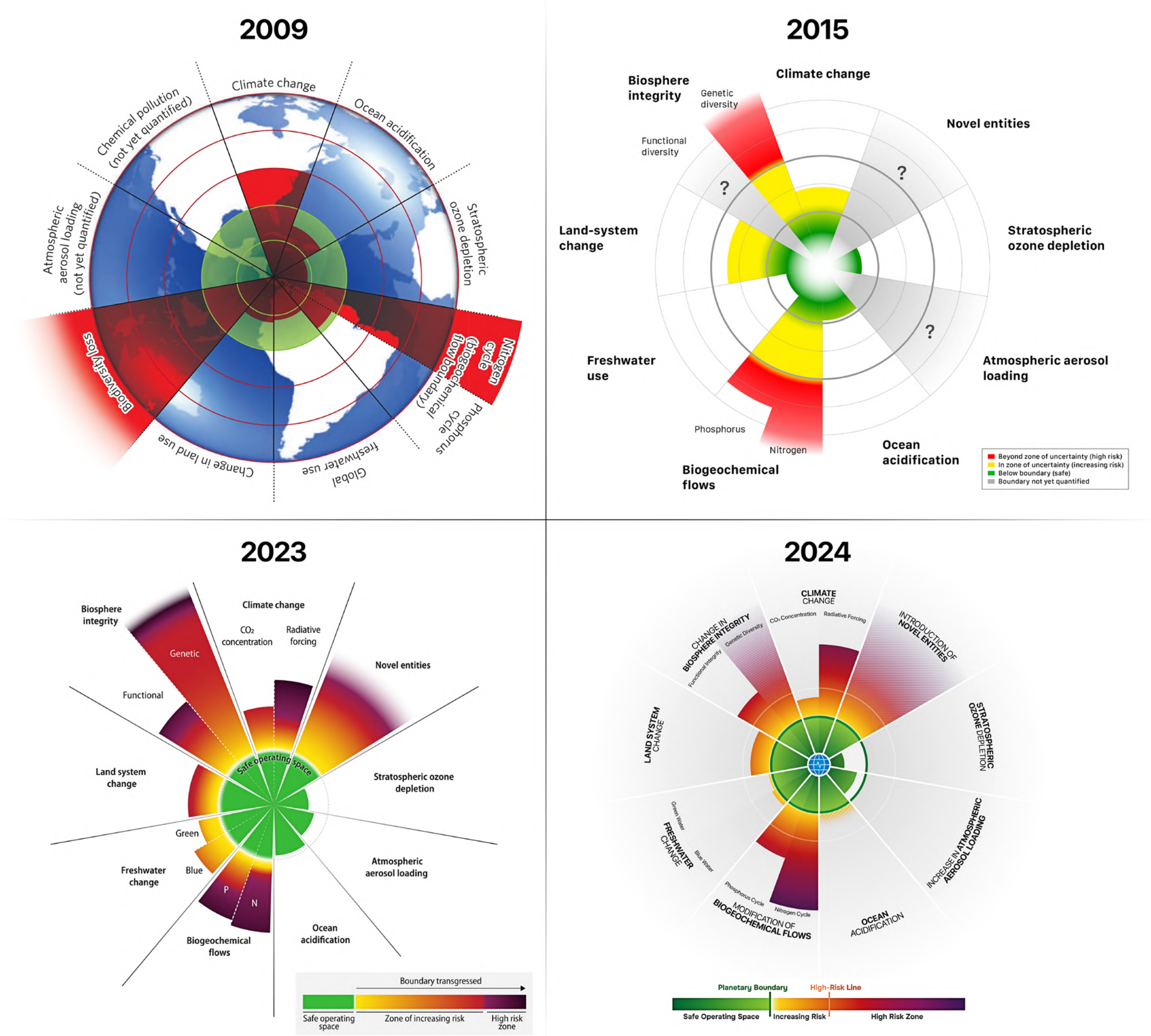

FIGURE 3 Scientific Updates - Planetary Boundaries Assessments Over Time. The evolution of the PBs diagrams from 2009 until today reflects advancements in scientific understanding, improved measurement techniques, and a deeper awareness of PBs and their implications for global sustainability efforts. (Upper left image[2]: Reproduced with permission from Springer Nature. Upper right image[3]: Reprinted with permission from AAAS. Lower left image[4]: Distributed under the terms of the Creative Commons Attribution-NonCommercial license. Lower right image: PHC, 2024.)

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2. A Safe Operating Space for Humanity

The "Safe Operating Space" is an Earth system state that allows humanity to develop and thrive for generations to come.[2–4] 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).[5]

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 (5)** – which could lead to self-amplified warming and the deterioration of life-support systems on Earth – we likely will have another 50,000 years of a Holocene-like planet, before Earth naturally moves toward the next ice age[6].

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).

Humanity's Journey on Earth
Human Population Size and Global Temperature from 500,000 Years BP Until 2100

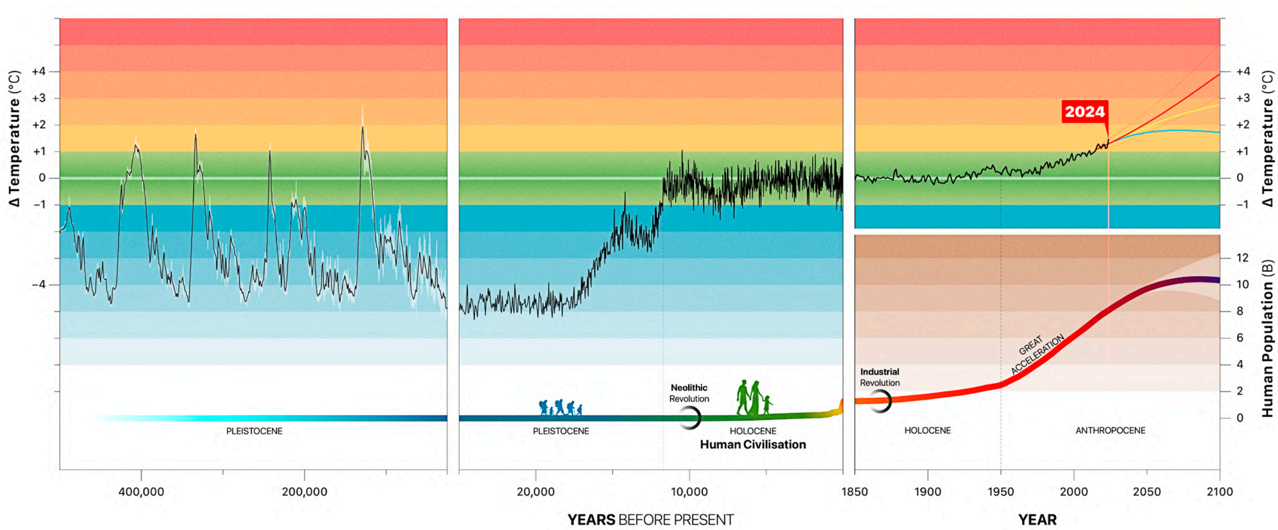
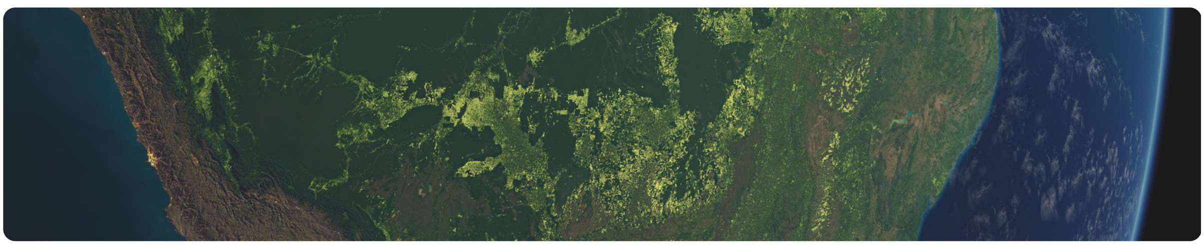


FIGURE 4 Humanity's Journey on Earth - Human Population Size and Global Temperature from 500,000 Years BP Until 2100. This figure is a composite of different data sets, including paleo data estimates, recent measurements, and future projections. For a detailed description of this figure, see **Supplementary Material**. Data from: Jouzel et al. 2007[7], Masson-Delmotte et al. 2010[8], Morice et al. 2021[9], Osborn and Jones 2014[10], CRU 2024[11], IPCC Summary for Policymakers 2021[12], Fyfe et al. 2024[13], Ritchie et al. 2024[14], Sjödin et al. 2012[15], UN World Population Prospects 2022[16]. *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 crossing 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 thrive.*



Criteria for Setting the Position of PBs

The position of PBs 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.
- Analyses of ecological resilience.
- Earth System Model (ESM) simulations.
- Expert elicitation of positive feedback mechanisms (e.g., interactions between forest decline and carbon cycle feedbacks).
- 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 Earth's systems and avoids irreversible environmental damage.

From **Holocene to Anthropocene**

During the Holocene epoch, large parts of the Earth experienced predictably moderate climates,[17–19] 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.[20,21] 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,[22] it is also considered an epoch of high biological resilience,[23] 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.[16] In recent decades, human activities have intensified,[1] potentially surpassing Earth's capacity to sustain its stability.

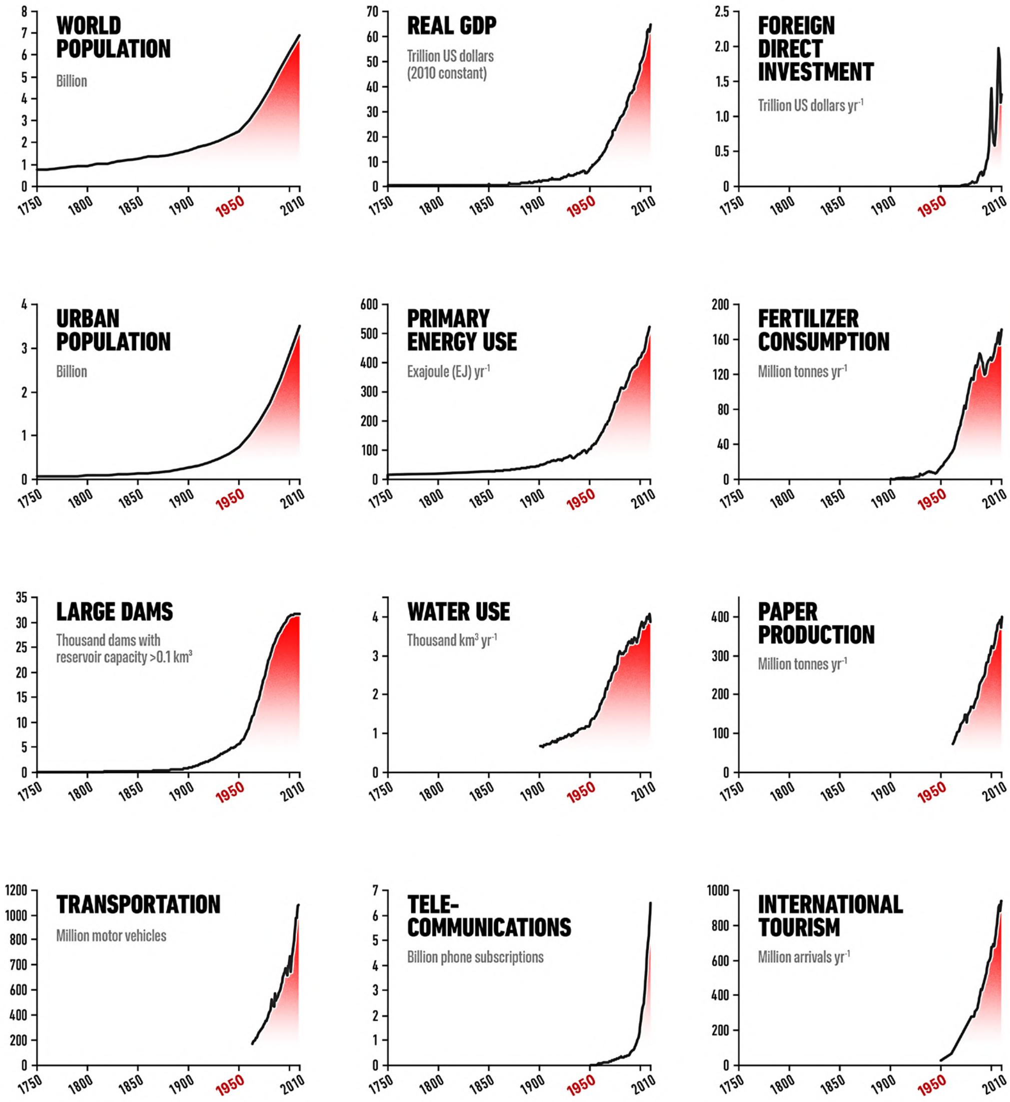
This shift marks the beginning of the Anthropocene, a period characterized by our dependence on fossil fuels, industrial agriculture, and the unsustainable use of resources, which disrupt Earth's delicate balance. This has led to rapidly increasing pressures on our planet, a phenomenon known as the "Great Acceleration" (Fig. 5).[1] Respecting PBs 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

Building on the PBs framework and its Safe Operating Space, the Earth Commission introduced the Earth System Boundaries in 2023 to delineate a "Safe and Just Operating Space" for humanity.[24] This framework adds a crucial dimension: social justice.

This innovative approach aims not only to preserve the Earth's biophysical systems but also to ensure equitable access to resources and minimize harm to humans and other living beings.[25] By integrating social thresholds, the Earth System Boundaries framework addresses the interdependence of environmental sustainability and human well-being.

Socio-Economic Trends Since 1750

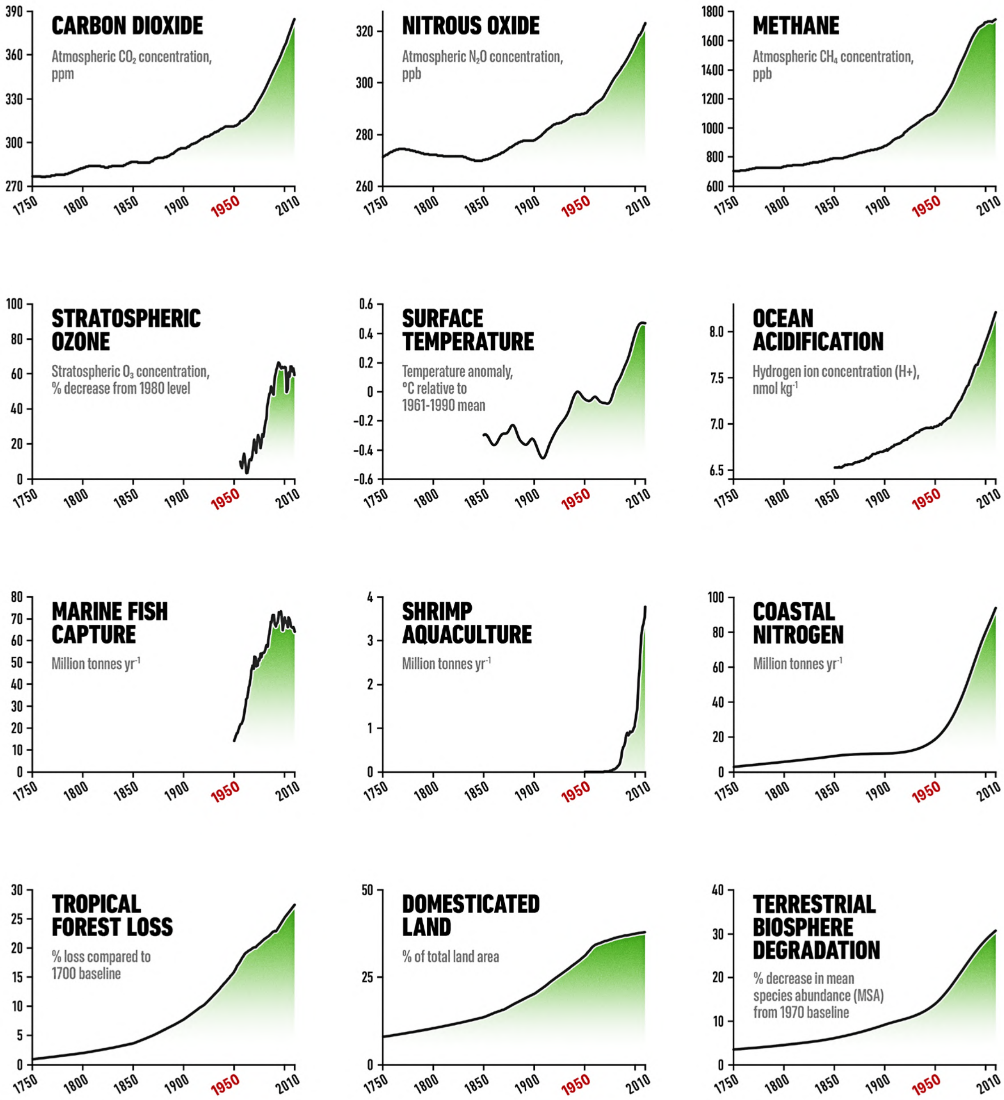


2.1 The Great Acceleration

Recent Dramatic Trends in the Earth System

FIGURE 5 These graphs[1] illustrate the dramatic socio-economic and Earth system trends in recent decades. The left-hand side highlights the exponential rise in human activities, including population growth, real GDP, and energy use. The right-hand side reveals the corresponding impact on Earth system indicators such as carbon dioxide levels, surface temperature, and ocean acidification.

Earth System Trends Since 1750

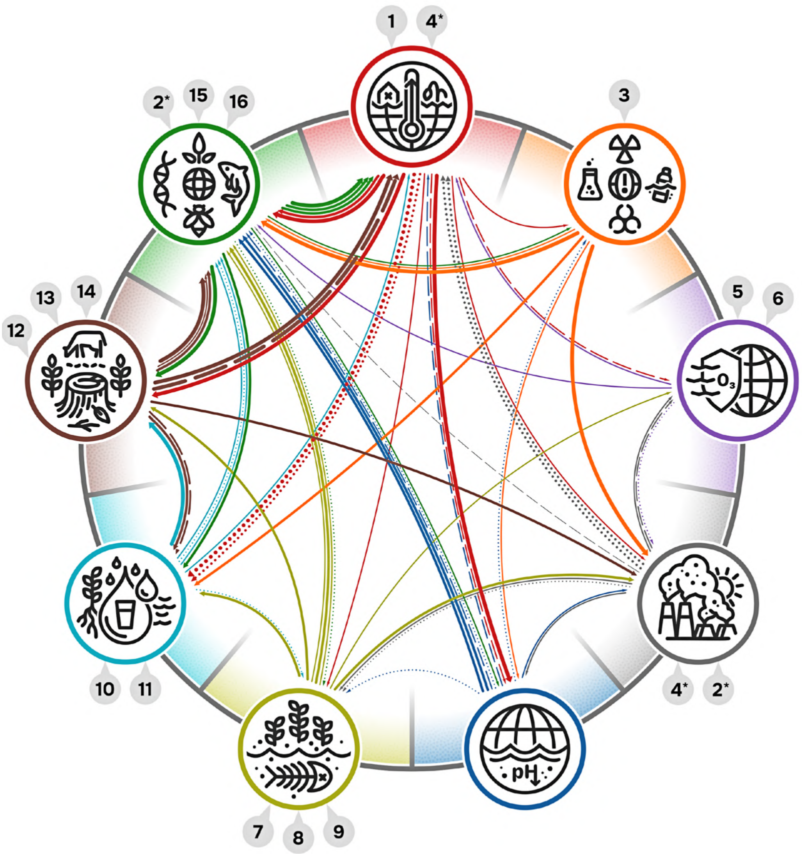


The Anthropocene began with the "Great Acceleration" in the 1950s when these parameters of environmental change shifted from gradual, linear trends to rapid, exponential ones. These trends underscore the urgency of respecting Planetary Boundaries (PBs) to prevent further ecological degradation and ensure a sustainable future for a global population projected to reach 9–9.5 billion by 2050.[16] Re-entering the Safe Operating Space is crucial for mitigating the rising pressures on Earth's resilience, which already shows signs of being overwhelmed. Image adapted by Globaïa after Steffen et al., 2015.[1] © 2015 by the Author(s). Reprinted by Permission of SAGE Publications.

3. Interconnections & Drivers

Typically, environmental challenges such as climate change, biodiversity loss, and pollution have been addressed separately. However, these issues are interconnected and collectively impact our planet's health.

The Complex Net of Planetary Boundary Processes



PB DRIVERS

* same driver shown twice for different PBs

1 **Emission of non-CO_2 greenhouse gases** (other pathways than fossil fuel burning), **albedo changes**
2 **Biomass burning**
3 **Release of untested synthetic chemicals**
4 **Fossil fuel burning**
5 **Emissions of synthetic chlorofluorocarbon molecules**
6 **N_2O release in 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**

PB INTERCONNECTIONS

COLOR — Planetary Boundaries

WIDTH — Interconnection Relevance

SOLID LINE — Connection increasing transgression

DASHED LINE — Connection decreasing transgression

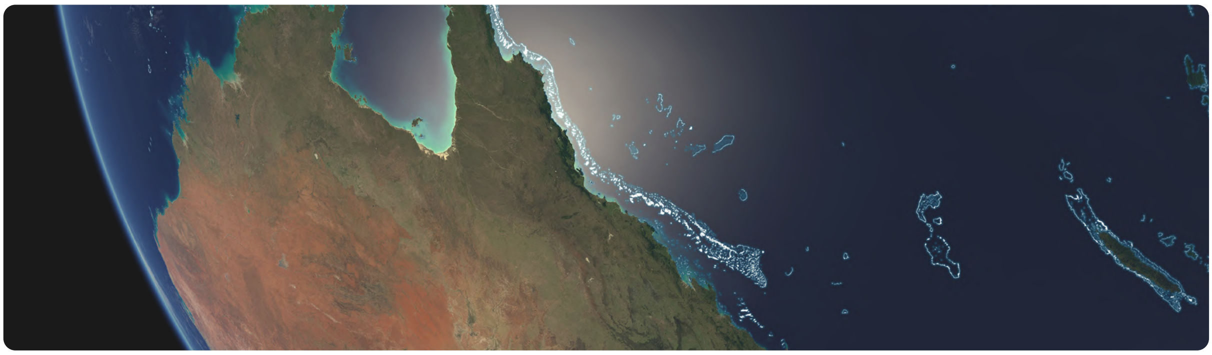
DOTTED LINE — Connection with both effects possible

FIGURE 6 The Complex Net of Planetary Boundary Processes: The diagram shows the most significant and certain 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 boundaries simultaneously. For a tabular overview of the considered PB connections, see <u>Supplementary Material, Table 1</u>. *Key takeaway: The interconnections between PBs are multidirectional and vary in strength. Addressing one issue often requires addressing them all. 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 issues.*

Human activities have pushed Earth out of its **Safe Operating Space (2)**.[2] We refer to the activities driving this shift, such as burning fossil fuels, as “drivers of transgression” because they cause control variables like atmospheric CO_2 levels, to transgress the PBs. By understanding these drivers, we can begin to explore potential solutions that address the root causes of issues or challenges.

Delving deeper into the causal chain (for instance, exploring what factors contribute to increased fossil fuel burning) reveals a wide array of interconnected causes and effects, forming a complex net of human actions and their consequences. This array is part of an even larger network linking the human sphere with biophysical Earth system processes, forming the intricate world we live in.[4,26,27]

Pinpointing the most critical parts of this causal network is challenging and depends on the latest scientific knowledge and synthesis. Fig. 6 provides a qualitative overview of the interconnections between PBs and their drivers of transgression. To illustrate some parts of this causal network, we introduce two simplified, but representative examples below.



1. **Biogeochemical Flows:** How Nitrogen and Phosphorus Fertilizer Diminish the Oceans’ Biodiversity & Fuel Climate Change

Nitrogen and phosphorus fertilizers are widely used to enhance crop yields, but their excessive use causes these nutrients to leach into freshwater and ultimately marine systems, leading to a problem known as eutrophication.[28] This nutrient leaching leads to algal and cyanobacterial blooms.

When these organisms die and their biomass decays, the oxygen in their aquatic environments gets depleted, which creates areas known as "dead zones".[29] As the name implies, these zones can lead to mass mortality events of other organisms, damaging or destroying local ecosystems, thereby reducing biodiversity. This process also produces large amounts of dead biomass, which is further respired by microbes, releasing CO_2 and fueling further climate change and aquatic oxygen depletion.[30,31] Oxygen depletion results in increased CO_2, which exacerbates local ocean acidification.[32]

The additional ocean acidification further compromises the biosphere integrity of marine life forms and ecosystems by disturbing shell and coral skeleton formations, as well as fish life cycles.[33,34]

Addressing these interconnected issues requires a holistic approach. Reducing nitrogen runoff through better fertilizer management, restoring wetlands to filter excess nutrients, and adopting sustainable water use practices can simultaneously mitigate climate change impacts, protect ocean health, and preserve freshwater resources.[35–37]

2. **Land System Change:** How Deforestation Creates a Vicious Cycle of Forest Loss Fueling Freshwater Overuse, Biodiversity Loss & Climate Change

When agricultural expansion leads to forest loss, it reduces a wide range of ecosystem services and impacts several PB processes simultaneously. Forests often transpire more water than other land cover types, for example, by accessing deep soil water through their deep roots.[38,39] Reduced forest cover means less transpiration, which in turn lowers atmospheric moisture supply and reduces local and downwind precipitation.[40,41] Additionally, the loss of forests increases near-surface wind speeds, which accelerates the drying of landscapes and reduces the time that moisture stays in the environment.[42] Trees also release organic compounds into the air that act as condensation nuclei – tiny particles that provide surfaces for water vapor to condense into clouds.[43,44] Fewer trees mean fewer condensation nuclei, leading to decreased cloud formation.[42,45]

With fewer clouds to reflect sunlight, more solar energy reaches the Earth's surface, causing increased temperatures.[46,47] Additionally, a reduced forest canopy means less shading and cooling by evapotranspiration, which further increases surface temperatures.[48,49] Forest cover loss also results in open and dry understories, which elevate the likelihood of wildfires.[50] Higher wind speeds increase erosion, the process by which soil is worn away by wind and water.[51] Reduced rainfall, higher temperatures, erosion, and increased water demands force farmers to use more freshwater for irrigation.[52,53]

Forest loss almost always results in direct biodiversity loss through habitat loss, degradation, or fragmentation.[54] Furthermore, the climate-related impacts mentioned above also lead to biodiversity loss in the remaining natural and semi-natural areas. This occurs due to drastic climatic shifts with high speed – meaning rapid changes in climate that species and ecosystems may not be able to adapt to quickly enough.[55] All these factors contribute to the loss of biomass (the total mass of living organisms in an area) and carbon sinks (natural systems that absorb more carbon dioxide than they emit) as well as their resilience, further accelerating global climate change.[56–58]

The positive feedbacks outlined above also present opportunities for future land system management. Coordinated afforestation efforts can create synergies in global change mitigation and adaptation. For example, understanding patterns of local to regional atmospheric moisture recycling and transport, enhanced by forests, can be beneficial for managing water resources, improving agricultural productivity, and enhancing ecosystem resilience.[59,60]

Conclusion

The known feedbacks in the Earth system discussed above illustrate how changes in one Earth system process can significantly impact others,[61] and by extension, the associated PBs. It is crucial to identify and understand the key synergies and trade-offs within this causal network to mitigate and adapt to the consequences of PB transgressions effectively. Planetary stewardship involves navigating this complex network using a holistic perspective.[62] This approach helps us identify opportunities to return to the Safe Operating Space and avoid actions that might worsen the multidimensional environmental crisis.

The interconnected nature of PB processes highlights the need for integrated environmental management. A holistic approach that recognizes these interconnections should guide decision-making to ensure effective action. For instance, achieving the 1.5°C climate target relies on returning to the Safe Operating Space of all PB processes. Understanding this is essential for securing a sustainable future for our planet.

PBScience will assess and quantify the causal network of the Earth system, including the PB control variables and all drivers linked to human actions. This will help identify the most promising levers of transformation at different scales and tailor solutions for various stakeholders and areas of focus.

4. Measuring 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, scientists employ numerous techniques to study the Earth system.[63] 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 measured and different requirements such as temporal and spatial resolution.[64]

Each observation 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. Since the PB processes span four broad "spheres" of the Earth system — the lithosphere (Earth's crust and upper mantle), atmosphere (the layer of gasses surrounding the planet), hydrosphere (all water bodies and rivers), and biosphere (all living organisms and the space they occupy) — the data used in their monitoring combine essentially all major Earth observation methods available.

Some essential methods for monitoring our planet, particularly within the PBs framework, are:

1. **Remote Sensing:** Collecting data, for example, on forest cover and other features using satellites and aircraft.
2. **Ground-Based Observations:** Directly measuring and recording information from the Earth's surface, including biological and ecological monitoring, as well as in situ measurements of parameters like soil moisture.
3. **Earth System Modeling:** In the context of PBs, using computer models to estimate control variables like green and blue water flow, which cannot be directly measured.
4. **Data Integration and Statistical Modeling:** Merging various data types or sets with statistical modeling is often needed to fill data gaps across time and space or to establish reference values.

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 *Planetary Health Check (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.

However, the process of collecting, verifying and processing observational data — especially on a global scale — can require a lot of time and resources, which may result in data lags of up to a few years **(Table 2, pg. 81)**. Additionally, some of the control variables of the PB processes cannot be directly observed but must be obtained through a combination of observational data and modeling, which is again resource-intensive.

To address these challenges, we are committed to improving and automating the common workflow and are actively seeking new Earth observation partners and additional support to accelerate data collection and analysis. *PBScience* is always open for new collaborations and encourages any engagement.

5. Tipping Points

In the context of Planetary Boundaries (PBs), understanding and quantifying tipping points is crucial for maintaining the stability and resilience of the Earth system. One of the primary motivations behind setting PBs is to avoid crossing these tipping points, which, if crossed, would lead to irreversible and catastrophic outcomes for billions of people and many future generations on Earth (**Safe Operating Space, 2**).

What Exactly is an Earth System Tipping Point?

Various subsystems of the Earth, from small lakes to continental ice sheets or ocean circulations, consist of self-reinforcing feedbacks.[65–67] These feedbacks can either dampen (a negative feedback) or amplify (a positive feedback) an initial change. When positive feedbacks dominate, they can lead to a permanent or semi-permanent shift, crossing a biogeophysical threshold and signaling a state change from one stable condition (a basin of attraction) to another. For example, a rainforest might irreversibly transition to a savanna due to a shift from self-moistening to self-drying feedback (Fig. 7).

Tipping points occur when feedback processes shift, causing a system to change state. However, identifying the exact level of pressure (e.g., global warming or land use change) and timing of when a tipping point is crossed is challenging. This is because feedback processes are regulated by multiple interactions – such as those between climate, water, and land – and unfold over various timescales, from less than a year to millennia. A tipping point occurs when feedbacks shift from maintaining a system to pushing it away from stability, leading to irreversible, potentially abrupt changes after resilience is gradually eroded.

Human activities like greenhouse gas emissions, deforestation, and pollution can push Earth's subsystems into self-sustaining states, such as melting ice sheets, forest degradation, eutrophication of lakes, or slowing ocean circulations **(Interconnections & Drivers, 3, Ex. 2)**. Beyond these tipping points, the system's response becomes nonlinear, meaning small changes can have disproportionately large effects, often resulting in irreversible changes.[68]

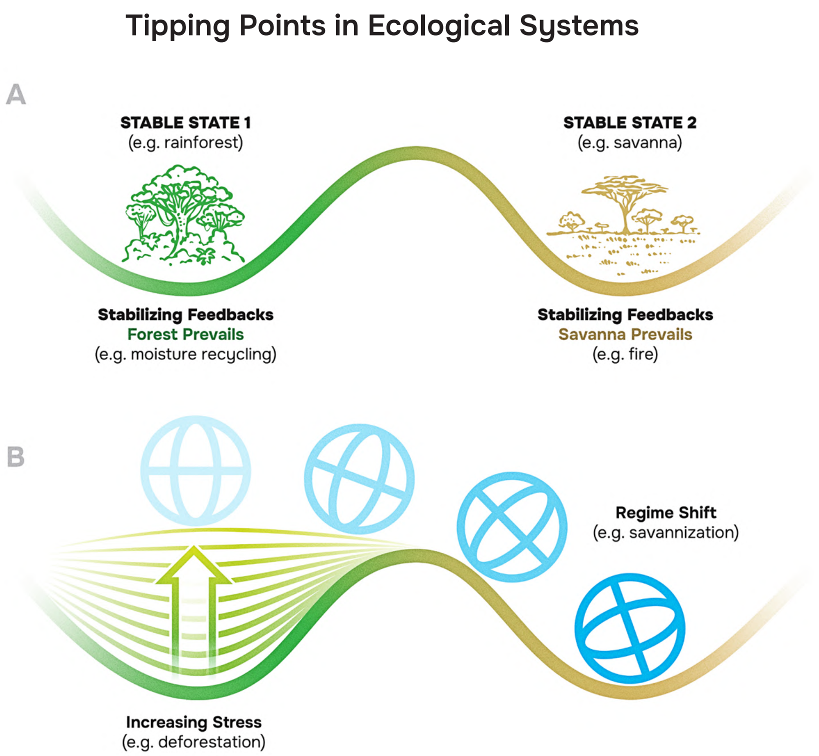
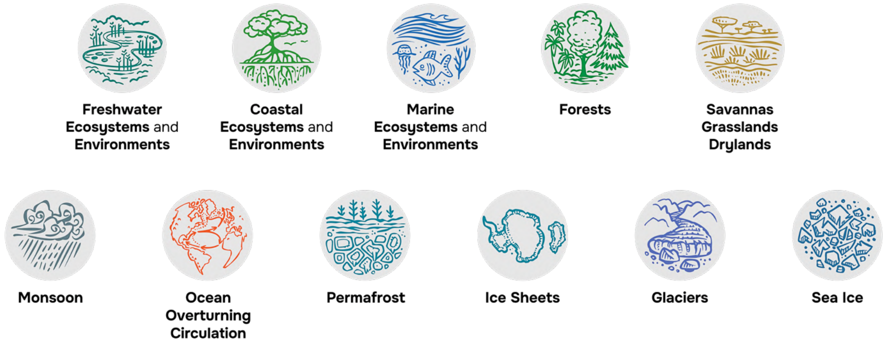


FIGURE 7 Tipping Points in Ecological Systems.

This image illustrates how ecological systems can shift between stable states, like rainforests and savannas. (A) Feedback mechanisms maintain the system in stable states, (e.g., moisture recycling in rainforests, fire in savannas). (B) However, increasing stress, such as deforestation, can push the system toward a tipping point, leading to an irreversible shift from one stable state to another, like from a rainforest to a savanna.

Broad Categories of Tipping Systems



Vital components of the Earth system are at risk of reaching tipping points.[65-67] The different categories of tipping systems like ice sheets (e.g., Greenland), forests (e.g., the Amazon) and marine ecosystems and environments (e.g., coral reefs) are represented by the icons shown above. Each icon is associated with a specific tipping system category.

Various components of the cryosphere, including the **Greenland and Antarctic ice sheets, mountain glaciers, permafrost, and sea ice regions,** are increasingly destabilizing,[68] with a growing risk of triggering self-amplifying melting. A central process driving accelerated melting in these systems is the melt-albedo feedback. The lower reflectivity of meltwater (which is darker than snow and ice) causes it to retain more shortwave solar radiation, leading to increased local heating and additional melting.[69] Global warming levels between 1.5 and 2°C could trigger irreversible loss within critical and large-scale components of the global cryosphere, such as sea ice, the Greenland ice sheet, and mountain glaciers. This would result in severe regional impacts, including significant contributions to sea level rise and destabilization of local infrastructure and water supplies. For example, this could lead to saltwater intrusion, where seawater contaminates groundwater resources near the coast.

For **the Amazon rainforest**, it's intricate moisture recycling network plays a crucial self-stabilizing role.[70] However, continued climate change and deforestation could cause a self-perpetuating collapse. If temperatures rise beyond 3.5°C, the latest studies suggest that the Amazon is likely to cross a tipping point. Additionally, risks increase if deforestation exceeds 40%. However, in reality, these factors often combine, meaning the tipping point may be reached at global warming levels of 1.5-2°C if deforestation reaches 20-25%.[67,71] Currently, we are at 1.2°C of global warming and 17% forest loss.[71] If essential forest areas stop contributing their moisture to this network, the impacts could be severe. The Amazon rainforest is a biodiversity hotspot with a global impact.[72] Its dieback would not only release significant amounts of carbon into the atmosphere but also remove a crucial regulatory system within the carbon cycle, leading to drastic global consequences. Similarly, climate change is causing **boreal forests** to retreat at their southern edges and to expand northward. This shift alters regional environmental conditions, further accelerating these changes.[73]

The **Atlantic Meridional Overturning Circulation (AMOC)** is a vital ocean current system in the Atlantic, driven by differences in salinity and temperature. Warm, salty water flows near the ocean's surface from the South Atlantic through the tropics to the subpolar North Atlantic, where it cools, densifies, and sinks to form deep currents. This sinking process is crucial in driving the AMOC. If the AMOC weakens, less salty water is transported northward, further slowing the circulation. The threshold for the AMOC's tipping point is debated, but both models and geological records[74] provide evidence of its tipping potential, along with already observed signs of weakening[75] and instability.[76]As a key player in heat exchange between the northern and southern hemispheres, the collapse of AMOC would have severe impacts on the global climate.[77]

The Difference Between Planetary Boundaries and Tipping Points

Planetary Boundaries (PBs) and tipping points are closely related but represent inherently different concepts. PBs aim to quantify the safe levels within which human activities can maintain the stability, resilience, and life-support functions of the Earth system. Tipping points, on the other hand, warn us about critical thresholds that must not be crossed to avoid catastrophic and irreversible changes.[67]

To illustrate, think of the Earth like a human body: PBs are like the safe ranges (or operating levels) of health indicators, such as blood pressure or iron levels. They provide guidelines on how far we can push the body's systems without risking a severe health crisis, helping us avoid significant and potentially irreversible damage.

Tipping points are more likely to be triggered when control variables exceed their PB values, resembling the onset of critical health events such as a heart attack or aneurysm. In this analogy, once a tipping point is reached, even a small additional change can lead to a drastic shift — just as a slight increase in blood pressure can trigger a heart attack. In the Earth system, this might mean a sudden climate shift or the collapse of ecosystems, resulting in irreversible changes.

The Link Between Tipping Points And The Planetary Boundaries Framework

PBs are set at levels designed to prevent the crossing of tipping points, adhering to the precautionary principle — a strategy emphasizing caution and preventative action to avoid entering zones of increasing or high risk, especially when scientific understanding is incomplete (Fig. 2). The risk of crossing tipping points increases significantly between 1 and 2°C of global warming above pre-industrial levels — a temperature range that aligns with the zone of increased risk for the **Climate Change** PB. This overlap underscores the need for proactive measures to prevent irreversible harm to the Earth system, even amid uncertainties.

While avoiding the crossing of tipping points is crucial, the PBs framework also aims to ensure the overall stability and resilience of the Earth system, similar to how maintaining balanced health indicators is essential for overall human well-being. The transgression of PBs increases the risk of crossing tipping points. For example, the risk of the Amazon rainforest tipping is heightened by anthropogenic climate change (resulting in more frequent and severe droughts), deforestation (which disrupts essential moisture recycling cascades), and the loss of biosphere integrity (a reduction in the variety of life forms, known as response diversity, that contribute to ecosystem resilience and functionality).[67,72]

Thus, further transgression of the respective PBs significantly increases the risk of tipping the Amazon rainforest.[71,78] Conversely, halting or even reducing PB transgression can provide nonlinear benefits, where small changes in PB adherence can lead to disproportionately large positive effects.

Conclusion

Since tipping elements are part of the Earth system's causal network, any tipping inevitably triggers feedback connections throughout the Earth system **(Interconnections & Drivers, 3)**. Consequently, changes in PB control variables can lead to tipping that will alter the same and/or other control variables within the PBs framework. To fully understand and manage this complex network, it is crucial to map and identify which PBs are connected to which tipping points. Fig. 8 presents a simplified attempt to associate the categories of tipping systems identified in the recent Global Tipping Points report and their connections with different PB processes.[67]

Planetary Boundary Processes and Their Tipping Points

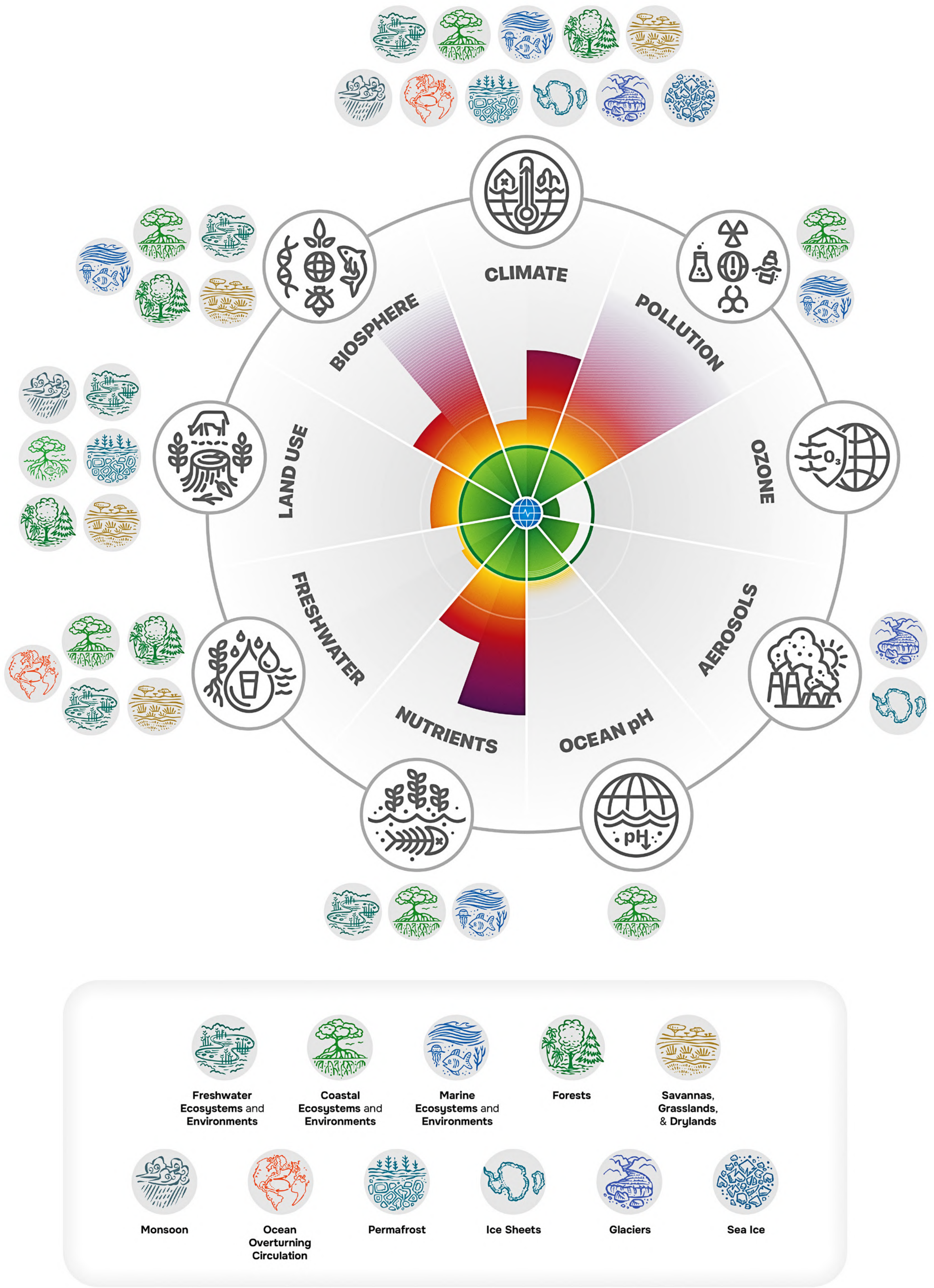


FIGURE 8 Planetary Boundary Processes and Their Tipping Points. This figure represents the first effort to link different categories of tipping systems with Planetary Boundary (PB) processes. The categories identified in the Global Tipping Points Report[67] were matched with PB processes if the PB control variables or their drivers of transgression are logically connected to the drivers of tipping systems **(Table 3, pg. 82-83)**. The potential impact of tipping systems on PBs is not documented here.

6. **Planetary Boundary** Information Sheets

6.1 **Climate Change**

Definition & **Current State**

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

2024 Status

Both the atmospheric concentration of CO_2 (419 ppm) and the total anthropogenic radiative forcing at the top of the atmosphere (+ 2.79 W m^{-2}) have long **exceeded** their safe levels.

Global Map of Changes in Energy Balance

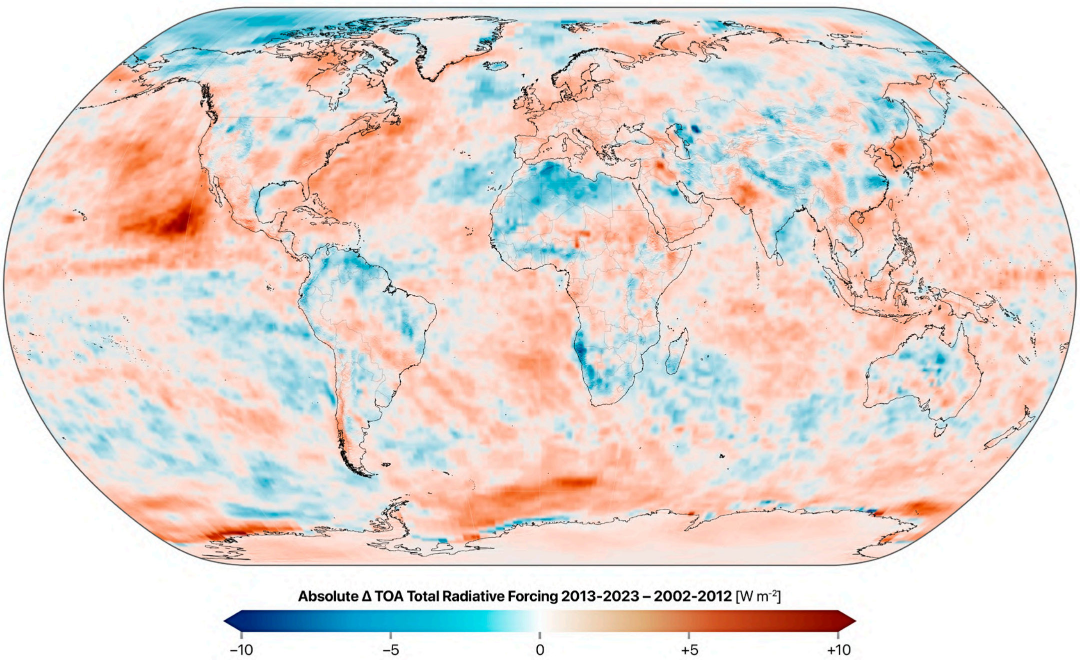


FIGURE 9 Global Map of Changes in Energy Balance. This map shows the change in the "Net top of the atmosphere radiative forcing" by comparing two solar cycles, each lasting 11 years, from 2002–2012 (11 years of measurements at the beginning of the time series) and 2013–2023 (the last 11 years of measurements) in W m^{-2} (watts per square meter). In contrast to Fig. 11 which includes only anthropogenic changes, this shows the actual measured changes in the energy flux at the top of the atmosphere (e.g., both anthropogenic and natural factors). The map highlights areas where the energy balance at the top of the atmosphere has either increased or decreased. Regions with positive values (shades of red) indicate an increase in radiative forcing, suggesting more energy is being absorbed than emitted, potentially leading to warming. Data from Loeb et al., 2018.[85] *Key takeaway: The regional patterns of changes in energy balance over the last 20 years show varied results, but overall, a general warming trend is evident.*

#1	**Atmospheric CO_2 Concentration**
Definition	Atmospheric CO_2 concentration is a key indicator of **Climate Change**. It is one of the major greenhouse gasses emitted in large quantities by human activities. Rising CO_2 concentrations are directly linked to global warming.[3]
Unit	ppm (parts per million)
Range	During glacial periods, atmospheric CO_2 levels were around 180-200 ppm. A typical Holocene value was around 280 ppm.
Planetary Boundary	Setting the PB at 350 ppm is consistent with the target of the United Nations Paris Climate Agreement to stay below 1.5˚C of warming and recent studies suggesting the possibility of extreme Earth system impacts even before reaching 1.5˚C.[4] For instance, such studies, based on paleoclimatic data and model simulations, show that CO_2 concentrations above 350 ppm could lead to significant global ice sheet loss, and a planet with 450 ppm of CO_2 would likely be largely ice-free in the millennia to come.[65,74–76]

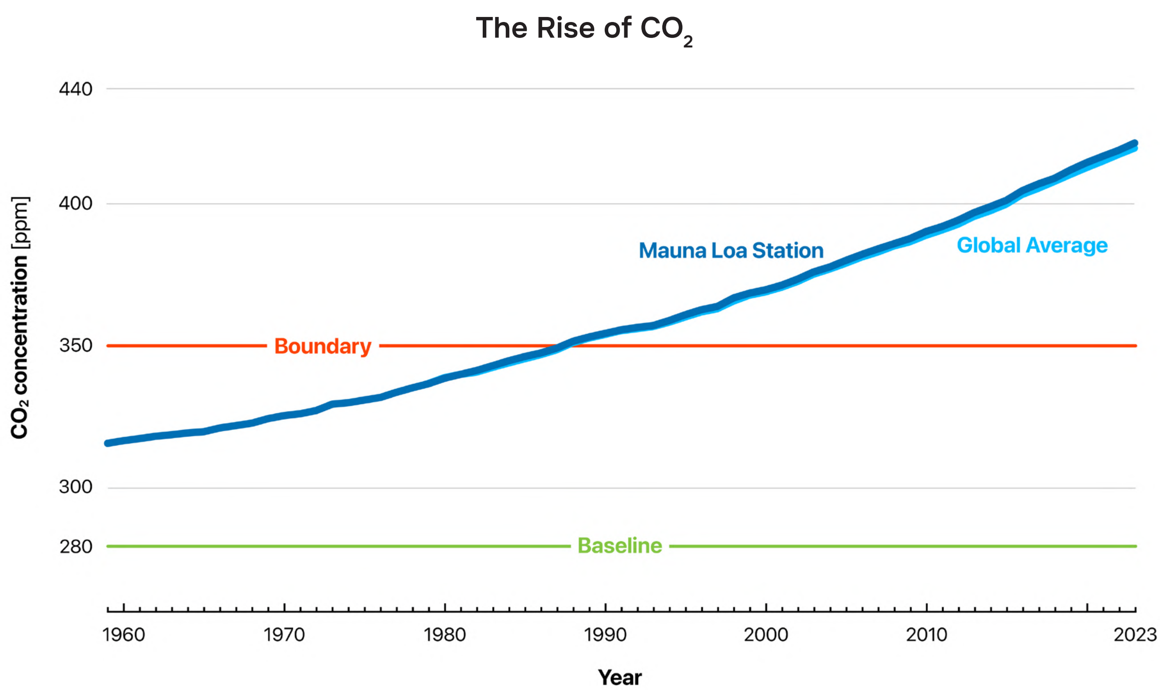


FIGURE 10 The Rise of CO_2. This figure shows the annual global mean of atmospheric CO_2 concentration from 1979-2023, and the marginally different dataset of CO_2 concentration as measured at Mauna Loa in Hawaii, which integrates data over a longer timespan (from 1959-2023). The red line shows the PB of 350 ppm, while the green line represents the pre-industrial baseline of 280 ppm. CO_2 concentrations at Mauna Loa differ slightly from the global mean CO_2 value (with the former being approximately 2 ppm above the latter for recent years). Data from Lan et al., 2024[82] and Lan & Keeling, 2024.[86] *Key takeaway: Atmospheric CO_2 concentrations have been continuously rising since industrialization and are now higher than at any time in the last 15 million years.*[87]

#2	**Total Anthropogenic Radiative Forcing at the Top of the Atmosphere**
Definition	“Anthropogenic radiative forcing” encompasses all human activities that affect the Earth's energy balance, not only CO_2 emissions. This includes other greenhouse gasses (e.g., methane, nitrous oxide), aerosols, and land-use changes. It is a direct measure of the change in energy balance at the top of the atmosphere, indicating how much energy is being added to or subtracted from the Earth's climate system. This change is a fundamental driver of **Climate Change.**[3]
Unit	W m^{-2} (watts per square meter)
Range	The Holocene baseline is close to 0 W m^{-2}, signifying a relatively stable climate system with a steady energy balance under which human civilizations developed. Significant anthropogenic radiative forcing began with the Industrial Revolution in the late 18th century, when large-scale burning of fossil fuels and deforestation led to an increase in atmospheric CO_2, methane, and other greenhouse gases that continues to the present day.
Planetary Boundary	The PB is set at +1.0 W m^{-2} relative to pre-industrial levels (Fig. 11). This is based on the climate system's sensitivity to greenhouse gas forcing, the behavior of polar ice sheets under warmer climates, and empirical observations of more recent climate conditions at a net radiative forcing of more than 1.5 W m^{-2}.[2]

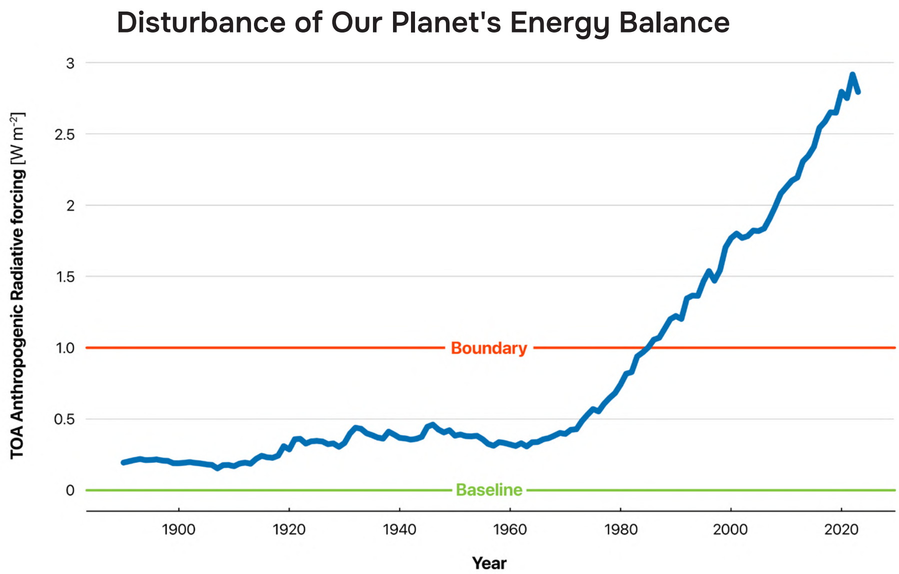


FIGURE 11 Disturbance of Our Planet’s Energy Balance. The control variable "Annual global mean of net top-of-atmosphere anthropogenic radiative forcing" is graphed from 1890 to 2023 (time series starts in 1750). This shows the change in energy flux at the top of the atmosphere due to human activities, compared to the pre-industrial baseline. The red line shows the Planetary Boundary of +1 W m^{-2} (watts per square meter), while the green line represents the Holocene baseline of around 0 W m^{-2}. Data from Forster et al., 2023.[83] *Key takeaway: Since the onset of the Anthropocene, global TOA (Top of Atmosphere) anthropogenic radiative forcing has shown a steep and continuing rise.*

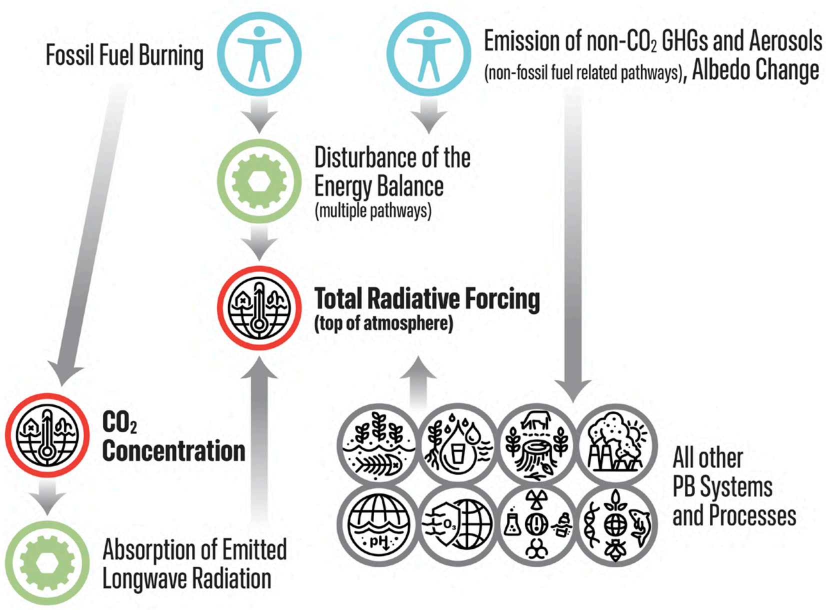
6.1 **Data Sources**

1. Atmospheric CO_2 concentration data (satellite and ground-based) are from NOAA's Global Monitoring Laboratory. Lan, X., Tans, P. and K.W. Thoning: Trends in globally-averaged CO_2 determined from NOAA Global Monitoring Laboratory measurements. Version 2024-07. https://doi.org/10.15138/9N0H-ZH07.[82]

2. Total Anthropogenic Radiative Forcing at the Top of the Atmosphere is from Forster et al., 2023.[83]

3. Top-of-atmosphere radiative balance is the CERES_EBAF_Ed4.2 product (Kato et al., 2018; Loeb et al., 2018).[84,85] These data were obtained from the NASA Langley Research Center CERES ordering tool at https://ceres.larc.nasa.gov/data/.

6.1 **Key Drivers**



Climate Change is represented by two control variables: Total Anthropogenic Radiative Forcing at the Top of the Atmosphere and Atmospheric CO_2 Concentration (CO_2). Anthropogenic radiative forcing measures all human activities impacting Earth's energy balance, including emissions of CO_2, other greenhouse gasses, and aerosols, making it a comprehensive measure. However, CO_2 is also separately measured due to its long lifetime in the atmosphere and significant emissions from human activities. The relationship between these variables can change due to varying impacts of aerosols on total radiative forcing, which have shifted over time with changes in pollution levels or environmental protection measures.

There are multiple drivers of **Climate Change**, as illustrated above. Fossil fuel burning directly increases CO_2 concentration, which subsequently affects total radiative forcing. A second pathway involves non-CO_2 greenhouse gas emissions, aerosols from sources such as agriculture, and changes in albedo resulting from land-use changes and natural ecosystem degradation. Aerosols and land-use changes exemplify how the **Climate Change** boundary is closely linked to other Planetary Boundaries. Changes in any environmental domain can impact **Climate Change**, highlighting the interconnected nature of the PB processes.

Impacts

Increasing radiative forcing means more energy is captured on our planet, raising temperatures in the atmosphere, oceans, and on land. The impacts of warming include, but are not limited to, modified extreme events like torrential rainfall, floods, heatwaves, and droughts. Additionally, it leads to both melting land and sea ice, rising sea levels, and repercussions for all forms of life on land and underwater.

6.2 **Change in Biosphere Integrity**

Definition & **Current State**

The decline in the diversity, extent, and health of living organisms and ecosystems, threatens the biosphere's ability to co-regulate the state of our planet by impacting the energy balance and chemical cycles on Earth.

2024 Status

Both the loss of genetic diversity (>100 E/MSY) and the decline in the functional integrity of the biosphere (currently ~30% HANPP) have **exceeded** their safe levels. The Planetary Boundaries (PBs) framework currently does not cover ocean biosphere integrity, and in general improved control variables for the diversity of life forms and functions (functional diversity) as well as the biocomplexity suitable for measuring biosphere integrity in different facets[88–92], all of which needs to be addressed in the future.

Global Risk Map of the Change in Biosphere Integrity Boundary Trangression - HANPP

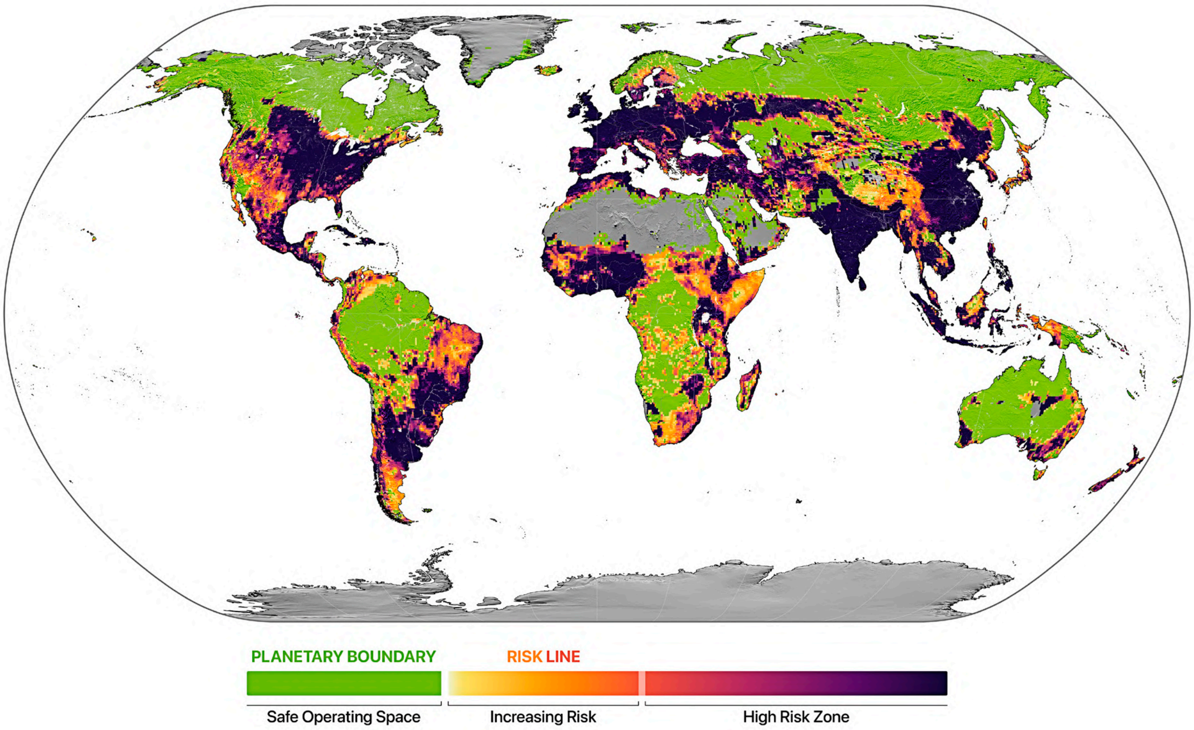


FIGURE 12 **Global Risk Map of the Change in Biosphere Integrity Boundary Transgression – HANPP.** Transgression is based on the HANPP control variable, with values ranging from within the Safe Operating Space (green) to the Zone of Increasing Risk (orange), and extending to the High Risk Zone (red/purple), as illustrated in Fig. 2. All values shown on the map refer to the year 2010. Data from Kastner et al. 2022.[94] *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. Areas in Zones of Increasing Risk are not yet stable and are likely to soon exceed the PB due to ongoing land-use expansion, underscoring humanity's current inability to manage land use within safe limits.*

#1 Genetic Diversity: E/MSY

Definition	E/MSY describes the number of extinctions per million species years, which is the rate at which species go extinct. High rates of extinction indicate a loss of genetic diversity, which is critical for maintaining ecosystem resilience and functionality.
Unit	Extinctions per Million Species-Years. For example, if 1 species out of 1 million species goes extinct every year, the extinction rate would be 1 E/MSY.
Range	The background (e.g., normal) rate of extinction loss is estimated to be 1 E/MSY.[93]
Planetary Boundary	The PB is set at 10 E/MSY.[3] This is based on the background extinction rate, adjusted for uncertainty and precaution to account for potential knowledge gaps and to minimize the risk of significant Earth system changes.

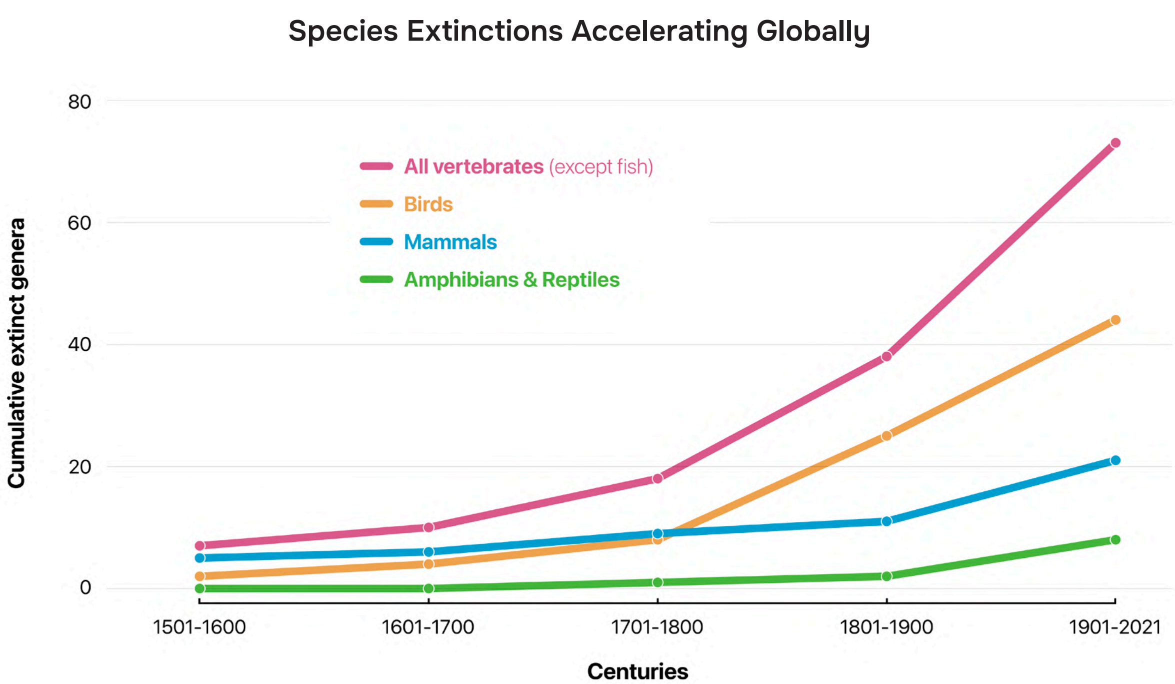


FIGURE 13 **Species Extinctions Accelerating Globally.** Cumulative number of genera extinctions per century in different classes of vertebrates. This graph shows that at least 73 genera have become extinct over the last 500 years. Similar estimates for mammals, birds, and fish indicate a total extinction rate of up to 100 E/MSY.[102] Data from Ceballos and Ehrlich, 2023.[95] *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 the different PB processes.*

#2 Functional Integrity: HANPP

Definition	HANPP stands for "Human Appropriation of Net Primary Production (NPP)." 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. It indicates the amount of energy available for consumption by herbivores and other organisms in the ecosystem. NPP is a fundamental measure of ecosystem productivity and health and influences the capacity of an ecosystem to support various forms of life. On a global scale, it 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, alter ecosystem productivity and withdraw energy by harvesting products for human use and consumption.
Unit	HANPP is measured in "carbon appropriated per unit of time." In the context of assessing functional biosphere integrity, HANPP, as the total net primary production (NPP) that is appropriated by human activities each year, is expressed as a percentage of the NPP for the Holocene reference period, which represents the state of the biosphere before significant human impact.
Range	In the absence of human activity, HANPP would be zero. For low-impact early human societies, it would be close to zero. However, HANPP has sharply increased due to the growing extent, intensity, and impact of human modification of global vegetation through land use. HANPP varies significantly across geographic regions, and there is often a spatial disconnect between the areas where NPP is appropriated and where it is consumed. In highly developed and densely populated areas, as well as regions with intense agricultural production, HANPP values can be very high.
Planetary Boundary	The PB is provisionally set at HANPP less than 10% of the pre-industrial NPP. This threshold is based on observational data and ecological modeling, which reveal negative trends in several critical metrics of biosphere functioning.[4]

The Energy We Take From Nature and Use for Our Purposes

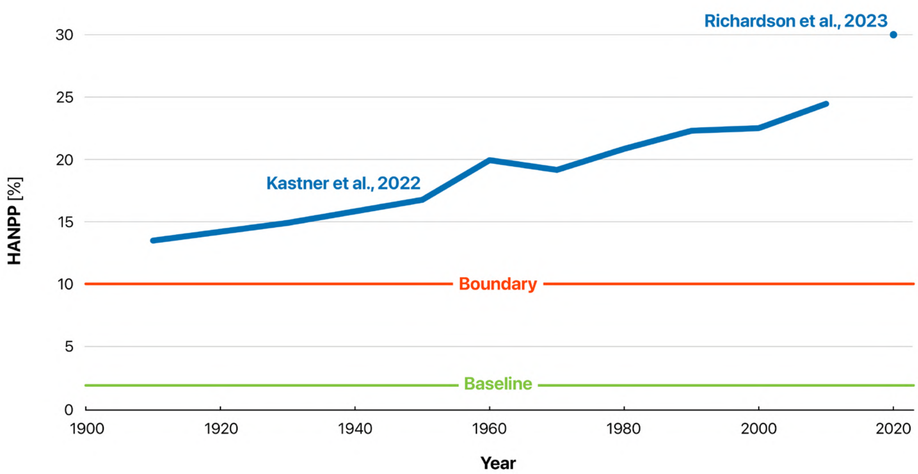


FIGURE 14 The Energy We Take From Nature and Use for Our Purposes. The plot displays the control variable "Human Appropriation of Net Primary Production (HANPP)," expressed as the percentage of the

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%, while the green line represents the baseline of around 1.9%. Based on data from Kastner et al. 2022.[94] *Key takeaway: The current HANPP has exceeded the precautionary Planetary Boundary. This trend is driven by a combination of factors, including unsustainable consumption patterns, increasing demands, and inefficient land-use practices, which further accelerate land-use change and push the system deeper into the Zone of Increasing Risk.*

Change in Land Plant Energy Used by Humanity

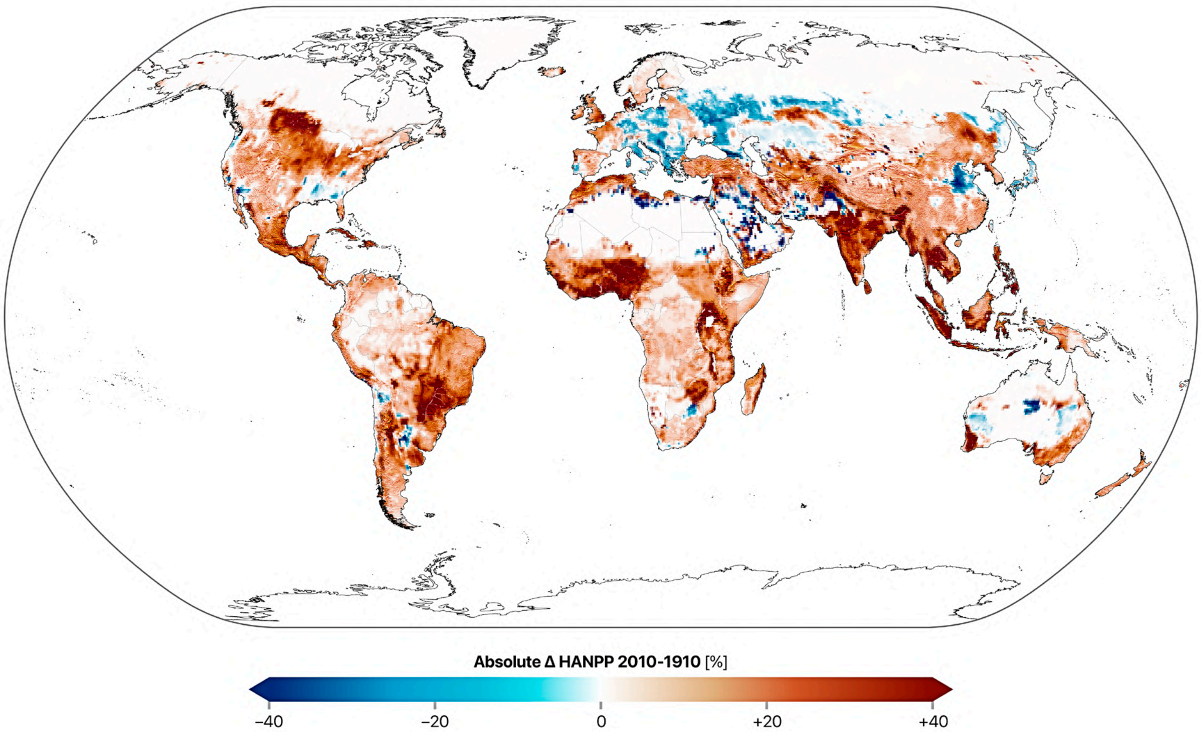
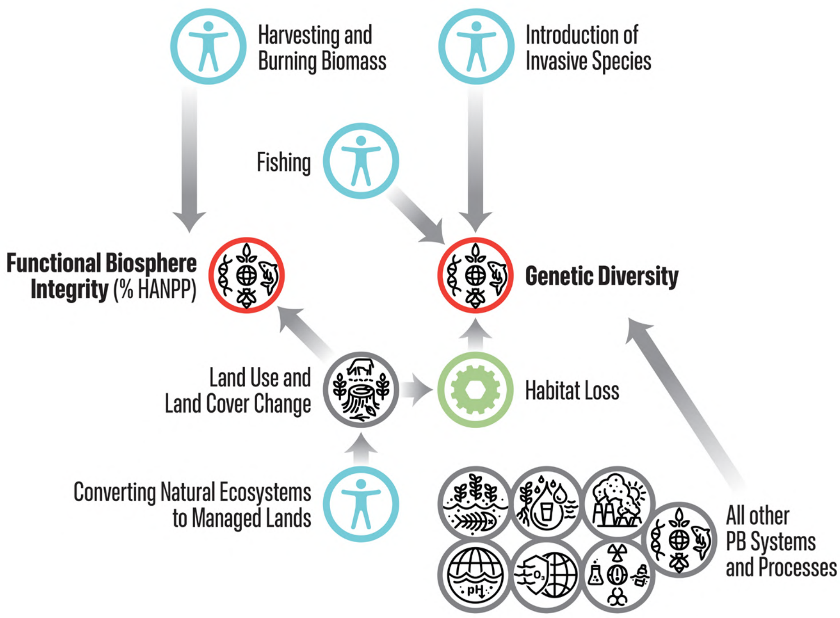


FIGURE 15 Change in Land Plant Energy Used by Humanity. Total change in the human appropriation of net primary production (HANPP) in 2010 compared to (minus) the HANPP in 1910, both expressed as a percentage of the potential (natural) NPP in 1910. A change from 10% to 30% HANPP would be indicated by a value of +20%. Shades of red indicate a HANPP increase and shades of blue indicate a decrease. Data from Kastner et al., 2022.[94] *Key takeaway: The spatiotemporal patterns of HANPP changes were historically driven by land-use expansion and intensification. HANPP increased globally, except in parts of Eurasia where HANPP values were already very high and have recently shown a slight decrease.*

6.2 Data Sources

1. HANPP data is from Kastner et al., 2022[94] and Richardson et al., 2023.[4]
2. Cumulative (1500-2022) extinctions are from Ceballos & Ehrlich , 2023.[95]

6.2 Key Drivers



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

The primary drivers of genetic diversity loss include rapid expansions in agricultural and livestock farming lands, as well as direct exploitation through activities such as fishing and logging.[96] Climate change, pollution, and the introduction of invasive species further exacerbate these pressures.[9] These stressors often interact in complex ways **(Interconnections & Drivers, 3)**, introducing significant uncertainty into predictions of future biodiversity loss.[97,98]

Human appropriation of net primary production (HANPP) for food, fodder, and fiber has historically exceeded sustainable levels for over a century.[4] This extraction of energy from the biosphere varies across different biomes; on land, it involves harvesting plant materials and conversion of natural ecosystems into less productive managed lands.[99] This diminishes the energy available to natural ecosystems, jeopardizing their functioning as vital components of the Earth system. In marine ecosystems, energy extraction primarily occurs through fishing activities, which alter ecosystem dynamics.[4,100] The **Change in Biosphere Integrity** boundary holds critical importance for sustaining all life on Earth. To deepen our understanding of ecosystem functionality and biodiversity, new datasets and indices will be incorporated into future *Planetary Health Check (PHC)* reports.

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 chemical cycles and energy balances. 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.[96] Examples are the loss of pollinators, which are needed for more than 75% of food crops, and the loss of CO_2 uptake sequestration capacity, which could significantly accelerate climate change.[96,101]

6.3 **Land System Change**

Definition & **Current State**

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 Planetary Health.

2024 Status

Globally, the remaining forest areas (global mean of 59% of the potential cover) in all three biomes (tropical, boreal, and temperate) have **fallen below the safe levels.**

Global Risk Map of the Land System Change Boundary Transgression
Forest Area

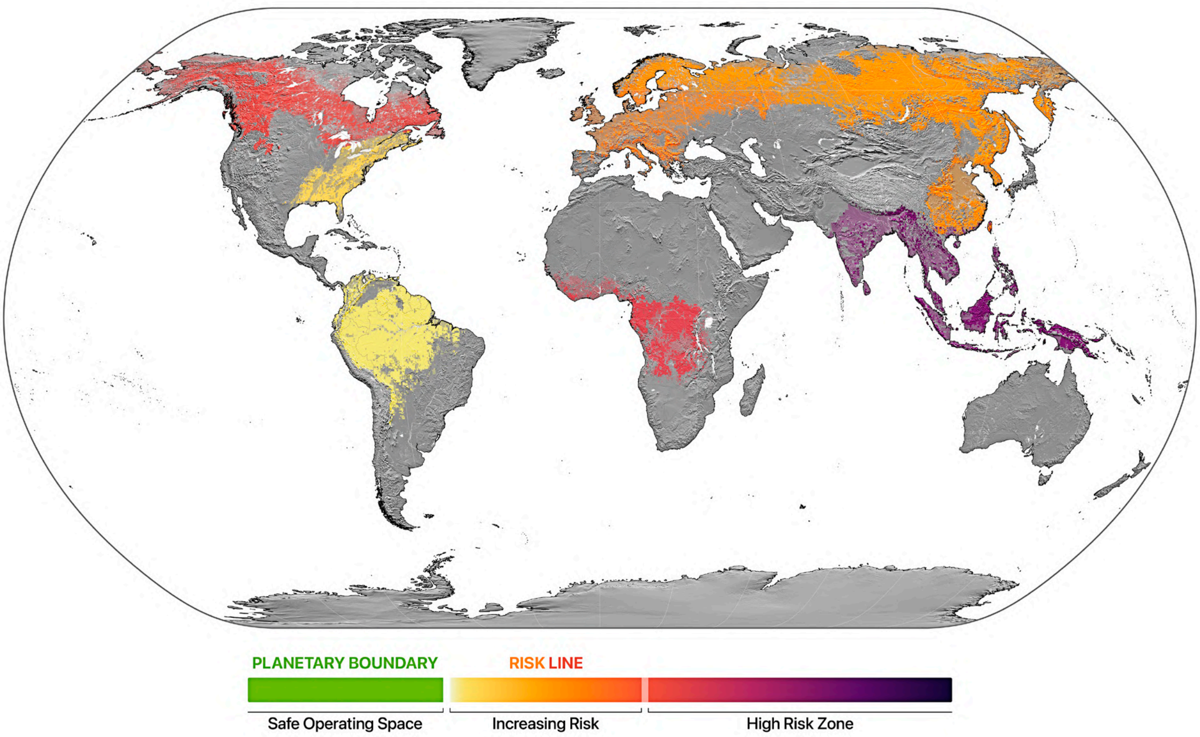


FIGURE 16 Global Risk Map of the Land System Change Boundary Transgression - Forest Area. Transgression is shown for the major contiguous forest biomes as defined in Steffen et al., 2015.[3] Transgression is based on the control variable, forest area, with values potentially ranging from within the Safe Operating Space (green) to the Zone of Increasing Risk (orange), and extending to the High Risk Zone (red/purple), as illustrated in Fig. 2. Lighter shades of a color indicate areas that were originally covered with forest but are now predominantly deforested. Based on data from Copernicus[104] and Ramankutty & Foley, 1999.[105] *Key takeaway: The large continuous forest biomes of the Earth have all transgressed the Planetary Boundary but show varying degrees of transgression.*

6.3 **Control Variable**

#1	**Forest Area**
Definition	Forest area is expressed as a percentage of the potential natural forest cover (e.g., the cover that would exist in the absence of human land-use changes), both globally and at the biome scale (boreal, temperate, and tropical forests). Although different land types have distinct functions in the Earth system, model simulations suggest that, during the Holocene, forests had the strongest functional coupling to the climate system among land biomes.[103]
Unit	Percent of potential forest cover
Range	The value of relative forest cover ranges from 100% (the maximum potential forest cover) to 0% (no forest remaining).
Planetary Boundary	The PB for forest cover is set at 75% of the original extent, with safe levels specified for different biomes: 85% for boreal and tropical forests, and 50% for temperate forests. These thresholds are based on various studies indicating that exceeding these levels risks large-scale transitions, such as the conversion of tropical forests to savanna or grassland, and leads to a loss of the ecosystem and climate-regulating functions of the forest biomes.[4]

Global Forest Decline

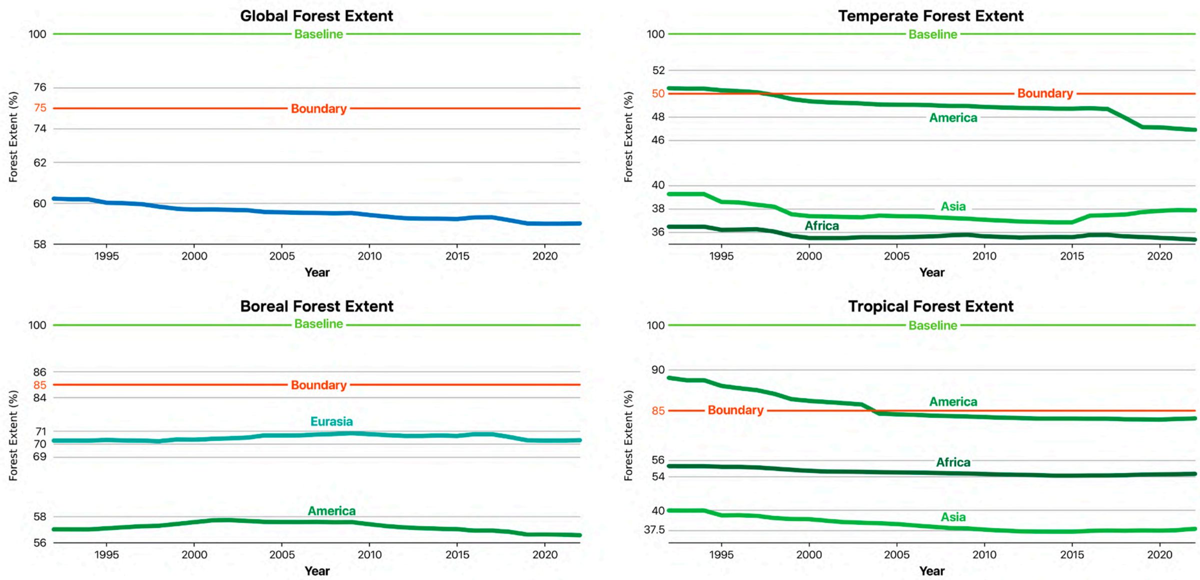


FIGURE 17 Global Forest Decline. Annual mean forest cover, expressed as a percentage of potential forest cover, globally and for three different biomes (temperate, boreal and tropical) between 1992 and 2022. Red lines show the Planetary Boundaries of 75%, 50%, 85% and 85% for global, temperate, boreal and tropical forests repsectively, while the green line always represents the baseline of 100 % potential forest cover. Data from Copernicus, 2019 and Ramankutty and Foley, 1999.[104,105] *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 regional boundaries, while some areas, such as temperate and tropical America, have just recently surpassed them.*

6.3 **Control Variable**

Global Map of Recent Forest Changes

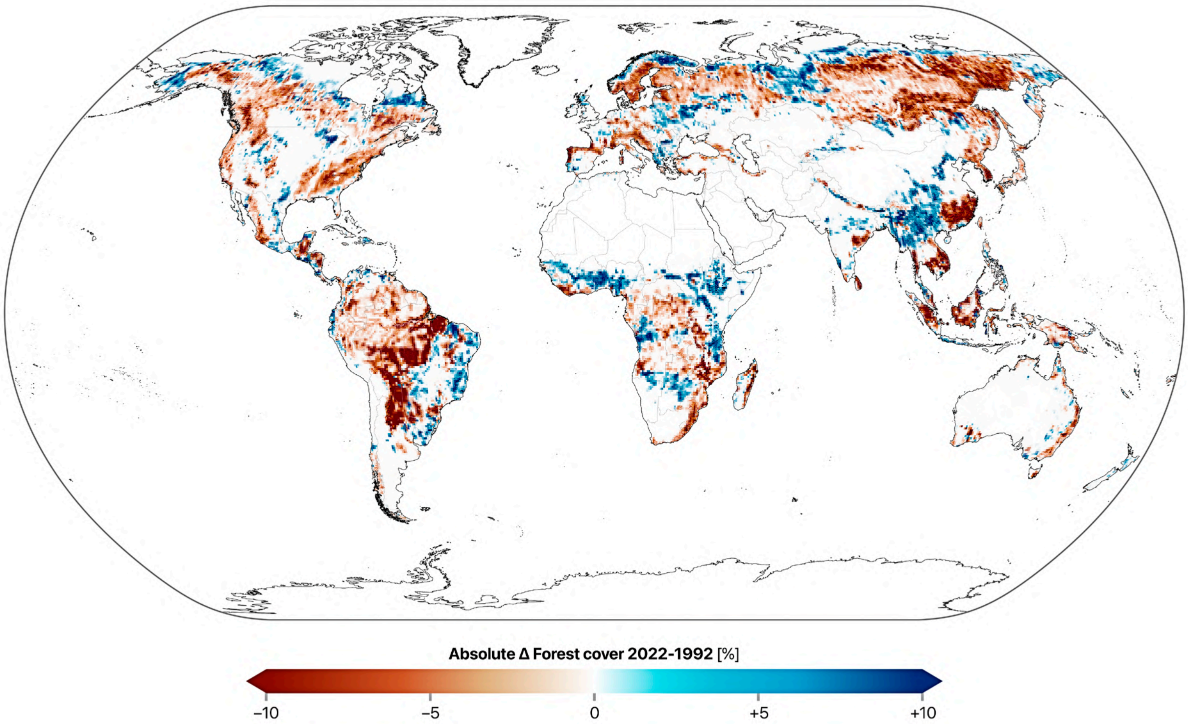
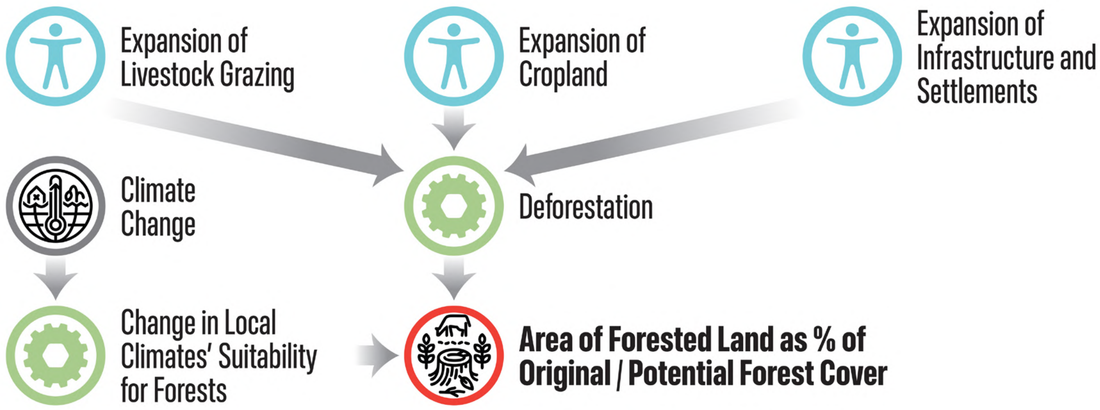


FIGURE 18 Global Map of Recent Forest Changes. Colors indicate absolute changes in the percentage of forest cover between 1992 and 2022, with shades of blue representing an increase in forest cover and shades of red a decrease in forest cover (e.g. a change from 60% to 50% forest cover would be indicated 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, 2019.[104] *Key takeaway: Spatially resolved trends between 1992 and 2022 (the time span of the data set) show a heterogeneous pattern of forest loss and gain across the globe. 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.*

6.3 **Data Sources**

1. Observed land cover data are from the Copernicus Climate Change Service, Climate Data Store, (2019): Land cover classification gridded maps from 1992 to present derived from satellite observation. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.006f2c9a (Accessed on 15-03-2024).[104]

2. Potential forest cover data from Ramankutty and Foley, 1999.[105]



In the transformation of land, especially forests, agriculture emerges as the primary driver.[106] Between 2000 and 2018, nearly 90 percent of direct deforestation was due to the expansion of cropland (52.3%) and livestock grazing (37.5%).[107]

The dominant driver of forest loss varies by region: cropland expansion primarily impacts forest loss in Africa and Asia, while the expansion of livestock grazing predominates in South America and Oceania. Timber harvesting also significantly contributes to deforestation in vital tropical rainforests.[108]

Conversely, in Europe, forest loss has been mainly caused by infrastructure and urban expansion,[107] but more recently, it is dominated by climate change and extreme drought events.[107] In general, climate change significantly affects forest loss today, as evidenced by phenomena such as the poleward shift of the treeline[110] and increased wildfire frequencies.[111]

Land cover change and forest loss are also indirectly influenced by environmental changes, including the transgression of other Planetary Boundaries (PBs). For example, alterations in the freshwater cycle, such as reduced moisture recycling, play a significant role.[109]

Impacts

The transgression of the **Land System Change** boundary has myriad consequences for the Earth system and is closely connected to other boundaries, such as **Change in Biosphere Integrity** (e.g., via habitat loss), **Freshwater Change** (e.g., via changes to evapotranspiration), **Climate Change** (e.g., via the release of stored carbon), and others.[112,113]

Regionally, many negative consequences are felt by local populations: degrading ecosystem services, changing local climates, and even outbreaks of infectious diseases.[112]

6.4 Freshwater Change

Definition & Current State

The alteration of the global hydrological cycle, manifested through myriads of shifts in flows of freshwater, including rivers and soil moisture as well as changes in precipitation levels, together impact all natural functions on land including carbon sequestration and biodiversity, and can lead to large ecological shifts undermining Earth's resilience.

2024 Status

Human-induced disturbances of both both blue water (~18% of global land area experience dry/wet deviations beyond safe levels) and green water (~16% of global land area experience soil moisture levels outside of the safe range) have **exceeded the safe level**.

Global Map of Increases in Dry and Wet Episodes for Blue Water

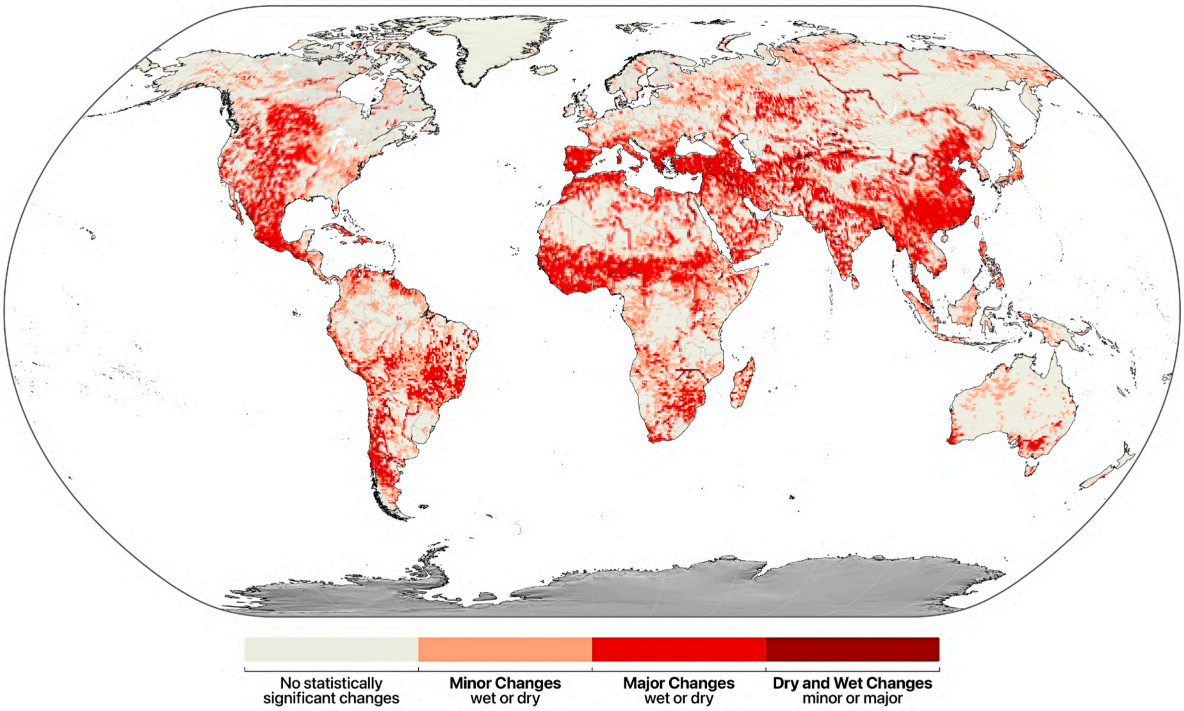


FIGURE 19 Global Map of Increases in Dry and Wet Episodes for Blue Water. This map shows the significant increases in dry and wet local deviation frequency for streamflow. Changes in the frequency of local deviations are computed by comparing deviations during 1976-2005 against 1691-1860. The changes are classified as (i) minor changes (wet or dry), (ii) major changes (wet or dry), and (iii) changes at a location where both wet and dry changes occurred, irrespective of whether they are minor or major. Data from Porkka et al 2024.[114] *Key takeaway: The increase in both wet and dry extremes in streamflow deviations across large parts of the world suggests increasing variability and instability in global freshwater systems.*

#1	**Blue Water**
Definition	Human-induced disturbance of blue water (referring to water in lakes, rivers, and reservoirs) is approximated by the annual global area with significant deviations in streamflow from pre-industrial variability. This reflects changes in surface and groundwater availability, which are crucial for the health of associated ecosystems.
Unit	Percentage (%) of annual global ice-free land area
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 pre-industrial value of about 9.4%.
Planetary Boundary	The PB is set at 10.2% of the global ice-free land area experiencing strong deviations in streamflow. This corresponds to the 95th percentile of pre-industrial variability (specifically the period from 1661 to 1860), during which anomalously dry or wet local conditions occurred with a likelihood of less than 5% across at least 10.2% of the global area.[114]

Disturbance of Earth's Freshwater Systems (I) - Blue Water

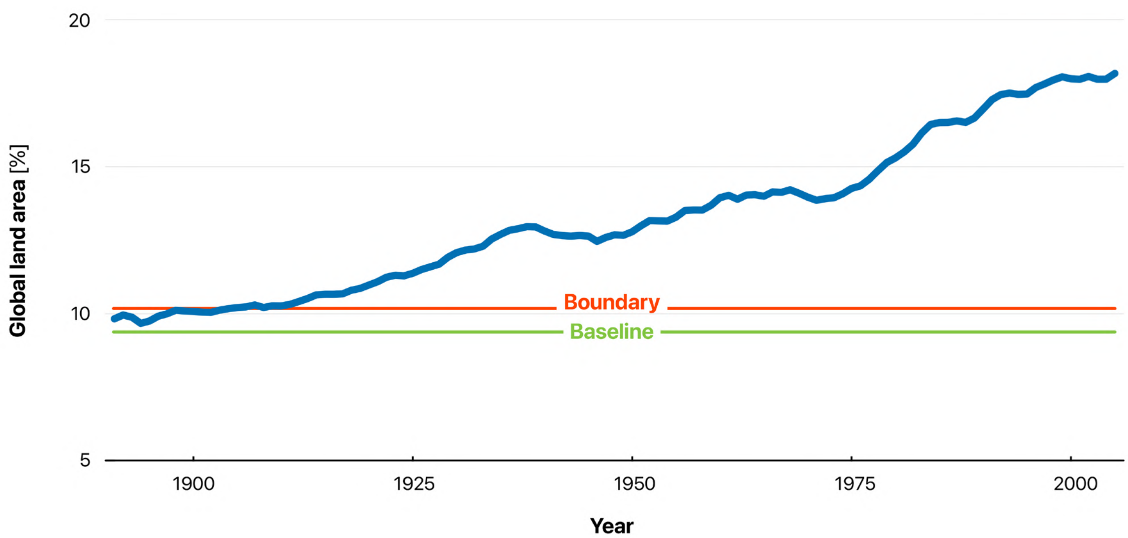


FIGURE 20 Disturbance of Earth's Freshwater Systems (I) - Blue Water. This figure shows the alteration of blue water flows (river, lake, and reservoir water flows) from 1890 to 2005, compared to a pre-industrial baseline (1691-1860), with the time series starting in 1691. Alteration is expressed as a percentage of land area showing a significant change compared to the baseline. The blue line shows the percentage of land area exhibiting local deviations in blue water. The red line shows the Planetary Boundary of 10.2%, while the green line represents the pre-industrial baseline of 9.4%. Data from Porkka et al 2024.[114] *Key takeaway: Local stream flow deviations have almost doubled since the late 19th century, already surpassing the Planetary Boundary at the beginning of the 20th century and continuing to rise since then.*

#2	**Green Water**
Definition	Human-induced disturbance of green water (referring to the stock of soil moisture which is the water available to plants, which turns into green water flow, namely evaporation and transpiration, or vapor flows). The boundary reflects changes in soil moisture in the root zone,, impacting terrestrial ecosystems, climate regulation, and biogeochemical processes.
Unit	Percentage (%) of annual global ice-free land area
Range	The percentage of land area that experiences strong deviations in green water flow can range from 0% (no area affected) to 100% (all ice-free land area affected), with a pre-industrial value of about 9.8%.
Planetary Boundary	The PB is set at 11.1% of the global ice-free land area experiencing strong deviations in soil moisture. This corresponds to the 95th percentile of pre-industrial variability (specifically the period from 1661 to 1860), during which anomalously dry or wet local conditions occurred with a likelihood of less than 5% across at least 11.1% of the global area.[114]

Disturbance of Earth's Freshwater Systems (II) - Green Water

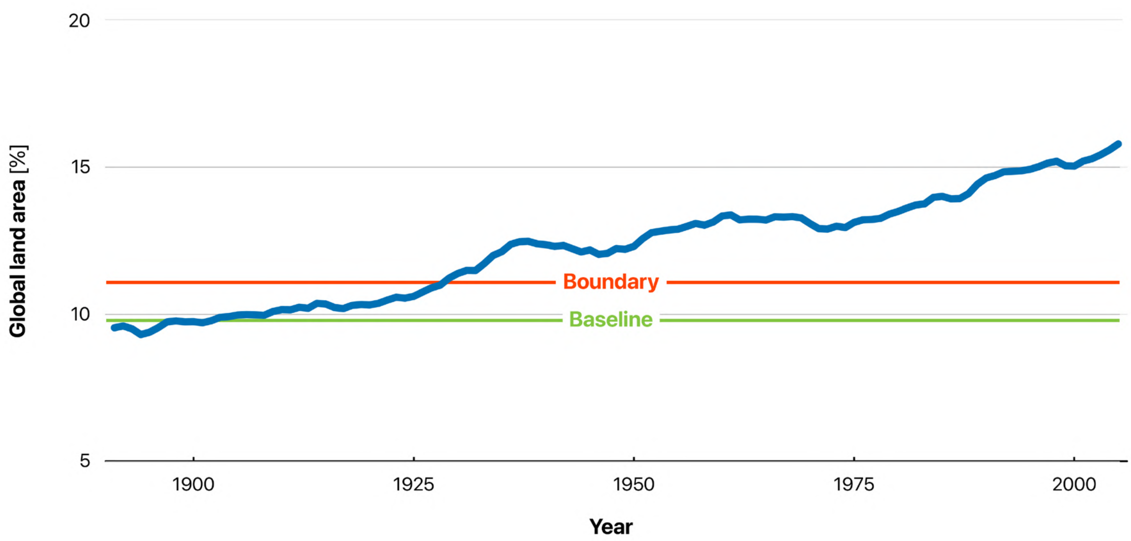


FIGURE 21 Disturbance of Earth's Freshwater Systems (II) - Green Water. This figure shows the alteration of green water flows (soil moisture in the root zone) from 1890 to 2005, compared to a pre-industrial baseline (1691-1860), with the time series starting in 1691. Alteration is expressed as a percentage of land area showing a significant change compared to the baseline. The blue line shows the percentage of land area exhibiting local deviations in green water. The red line shows the Planetary Boundary of 11.1%, while the green line represents the pre-industrial baseline of 9.8%. Data from Porkka et al 2024.[114] *Key takeaway: Local soil moisture deviations have significantly increased since the late 19th century, surpassing the PB around 1930 and continuing to rise since then.*

Global Map of Increases in Dry and Wet Episodes for Green Water

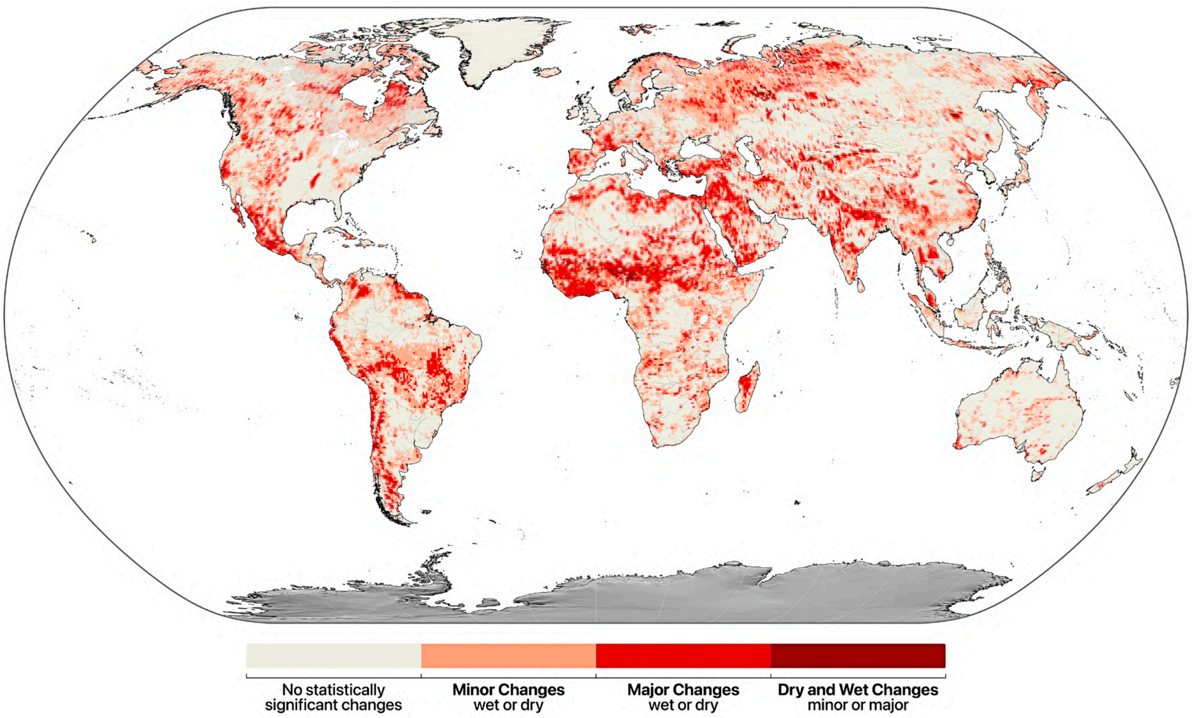
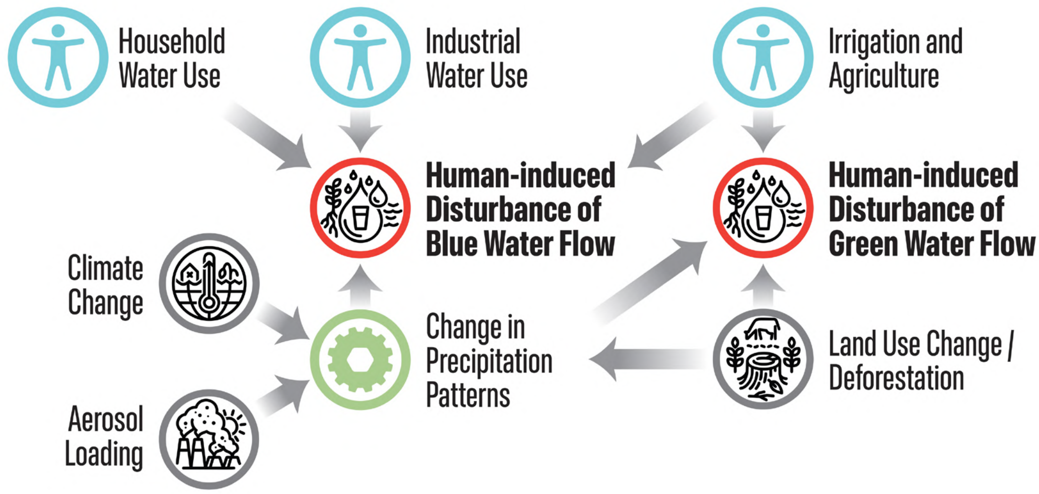


FIGURE 22 Global Map of Increases in Dry and Wet Episodes for Green Water. This map shows the significant increases in dry and wet local deviation frequency for soil moisture. Changes in the frequency of local deviations are computed by comparing deviations during 1976-2005 against 1691-1860. The changes are classified as (i) minor changes (wet or dry), (ii) major changes (wet or dry), and (iii) changes at a location where both wet and dry changes occurred, irrespective of whether they are minor or major. Data from Porkka et al 2024.[114] *Key takeaway: The increase in both wet and dry extremes in soil moisture deviations indicates growing variability and instability within global green water systems (water stored in soils and available for use by plants).*

6.4 **Data Source**

1. Blue and green water flow deviations are based on an ensemble model from Porkka et al., 2024.[114]

6.4 **Key Drivers**



Human activities have extensive impacts on the global water cycle, primarily through freshwater withdrawals from rivers, reservoirs, and groundwater, which significantly affect water levels and aquatic and surrounding ecosystems. The main driver of these withdrawals is irrigation, which accounts for approximately 70% of freshwater withdrawals and 90% of consumptive water use (water not returned to the source). Major irrigation hotspots include the Indo-Gangetic Basin, northern China, the U.S. High Plains, the Central Valley of California, Egypt, and several European countries.[115,116] Industry follows with 20% of freshwater withdrawals, while households account for 12%.[117]

Over the past century, these withdrawals, along with river diversions and dam constructions, have contributed to exceeding the blue water boundary. Additionally, land-use change and climate impacts have exacerbated transgressions of both the blue and green water boundaries.

Freshwater Change is closely linked to with activities impacting other PBs. For instance, **Climate Change** influences droughts and floods by altering atmospheric water-holding capacity, cloud formation, and circulation patterns.[118–120] Moreover, **Land System Change** related to deforestation, agriculture, and urbanization affects soil water-holding capacity, streamflow, and evaporation rates. This can intensify droughts and alter large-scale precipitation patterns like monsoons, creating feedback loops that further impact **Climate Change**.[120]

Impacts

Transgressing the **Freshwater Change** boundary 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.[109]

Dry deviations in green water 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.

Human food and fodder production is especially threatened by reduced freshwater availability. 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.[115,121]

6.5 **Modification of Biogeochemical Flows**

Definition & **Current State**

The disruption of global nutrient cycles of nitrogen and phosphorus negatively affects soil health, water quality, and biodiversity and triggers dead zones in freshwater and marine systems. Biogeochemical flows are the movement of key elements like carbon, nitrogen, and phosphorus through the environment and organisms, which are crucial for supporting life and maintaining ecosystems.

2024 Status

Both the global phosphorus flow into the ocean (22.6 Tg P $year^{-1}$) and the industrial fixation of nitrogen (extracting nitrogen from the atmosphere, 190 Tg N $year^{-1}$) are disrupting the corresponding nutrient cycles **beyond the safe level**.

Global Risk Map of the Biogeochemical Cycles Boundary Transgression
Phosphorus Cycle

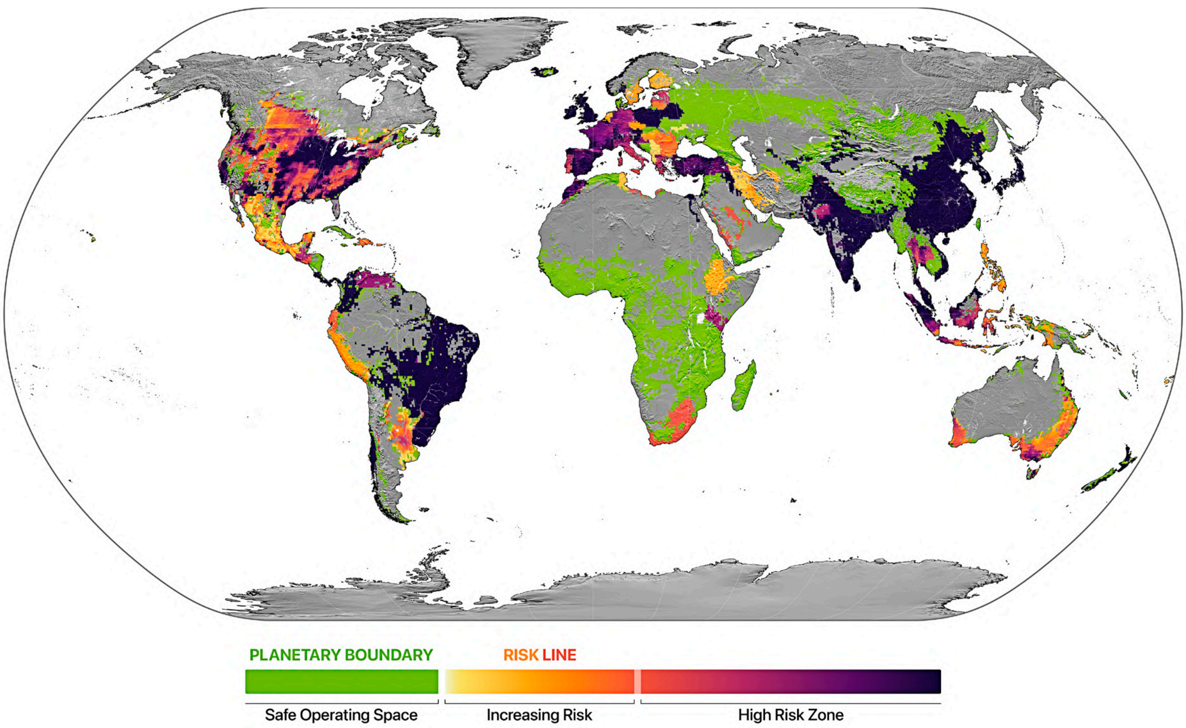


FIGURE 23 Global Risk Map of the Biogeochemical Cycles Boundary Transgression - Phosphorus Cycle. The regional boundary status is calculated based on agricultural phosphorus fertilizer use in 2013 (see Supplementary Material). Values range from within the Safe Operating Space (green) to the Zone of Increasing Risk (orange), and extend to the High Risk Zone (red/purple), as illustrated in Fig. 2. The regional boundaries were preliminarily derived from the global boundaries, assuming a uniform rate of fertilizer application on cropland. Regional pollution limits may deviate significantly from these boundaries.[3] Based on data from Lu and Tian, 2017.[130] *Key takeaway: Phosphorous cycle transgression is significant in parts of North and South America, Europe, and Asia, which leads to water pollution, eutrophication, harmful algal blooms, and "dead zones" in both coastal and freshwater ecosystems. This underscores the urgent need for better phosphorus management.*

#1	Phosphorus (P) Flows
Definition	Phosphorus is a critical nutrient applied to agricultural soils through fertilization. This causes leaching of phosphorus through soil erosion and run-off (regional boundary), and flows from freshwater systems into the ocean (global boundary). Excessive runoff and phosphorus leaching from agriculture can lead to eutrophication, causing harmful algal blooms and oxygen depletion in water bodies.
Unit	Teragrams of phosphorus per year (Tg P $year^{-1}$). 1 teragram equals 1 million metric tons
Range	Before human intervention, phosphorus flow was minimal (~0 Tg P $year^{-1}$). Human activities increased global flows to around 22.6 Tg P $year^{-1}$ (global) and 17.5 Tg P $year^{-1}$ (regional, aggregated), largely due to fertilizer use.[122,123]
Planetary Boundary	The PB for phosphorus is intended to define the safe threshold for the global flow of phosphorus from freshwater systems into the ocean, which is established at 11 teragrams of phosphorus per year. This level has been chosen as it is shown to prevent widespread eutrophication and oxygen depletion in aquatic systems, thereby enhancing the resilience of these ecosystems against human-induced impacts. The determination of this boundary takes into account historical data, the known environmental consequences of excess phosphorus, and the precautionary principle aimed at safeguarding aquatic life and ecosystem health.[4] Additionally, a regional boundary is set at 6.2 Tg P $year^{-1}$ for phosphorus flow into erodible soils, representing the maximum allowable flow to mitigate the risk of eutrophication in freshwater ecosystems.

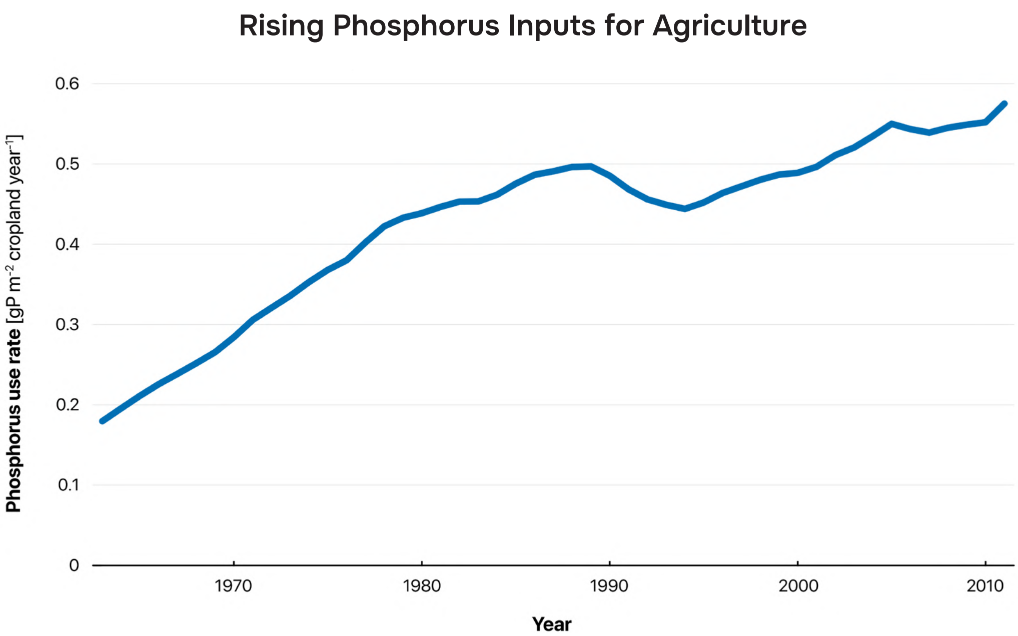


FIGURE 24 Rising Phosphorus Inputs for Agriculture. This graph shows the mean global phosphorus use rate on all croplands (in g P m^{-2} cropland $year^{-1}$, e.g., grams of phosphorus per square meter of cropland per year, see Supplementary Material) from 1961 to 2013. Data from Lu and Tian, 2017.[130] *Key takeaway: The rise in phosphorus use in agriculture is driving harmful algal and cyanobacteria blooms in freshwater systems, highlighting the urgent need for sustainable phosphorus management.*

Global Map of Change in Phosphorus Use Rate for Agriculture

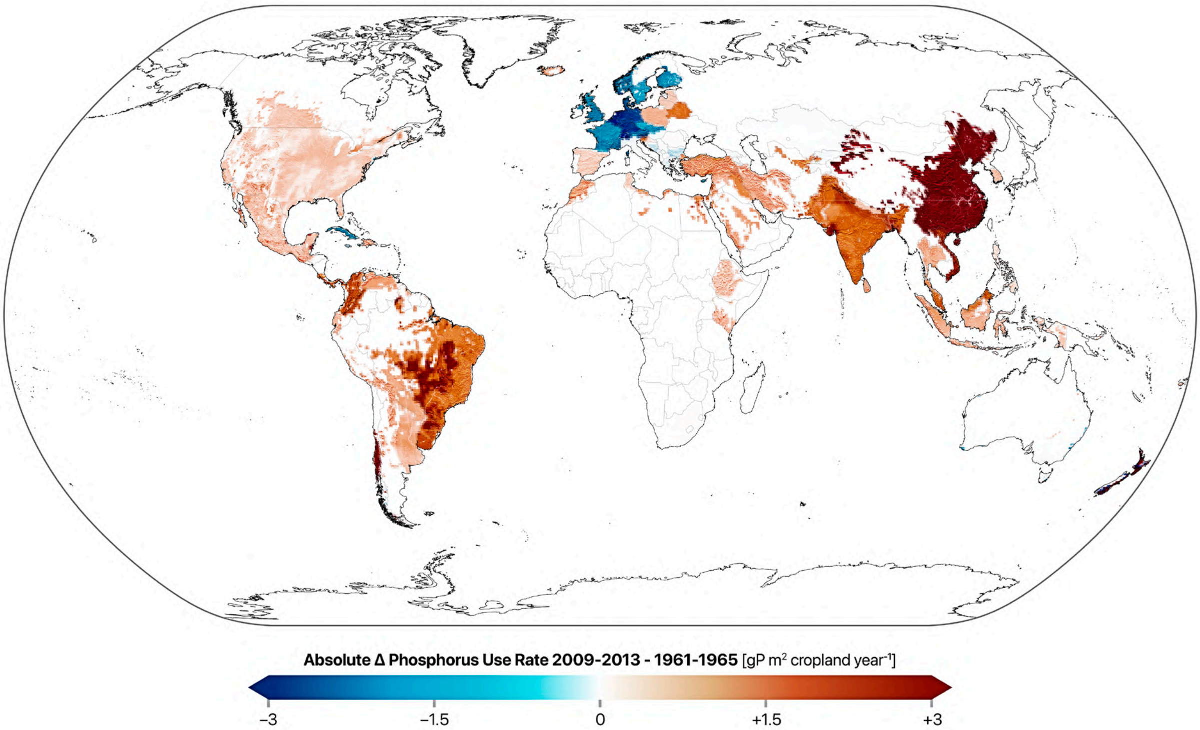


FIGURE 25 Global Map of Change in Phosphorus Use Rate for Agriculture. The total difference of phosphorus use rates (in g P m^{-2} cropland year $^{-1}$, e.g., grams of phosphorus per square meter of cropland per year) calculated as the difference between the rates during the period 2009-2013 (last 5 years of data set) and the period 1961-1965 (first 5 years of data set). Shades of red indicate an increase in phosphorus use, while shades of blue indicate a decrease. Data from Lu and Tian, 2017.[114] *Key takeaway: Strong increases in phosphorus use rates are observed, particularly in parts of South America, India, China, and Southeast Asia. In contrast, parts of Europe show a notable reduction in phosphorus use over the same period, likely due to improved agricultural practices and regulations. This map highlights the growing use of phosphorus in developing regions, raising concerns about nutrient runoff and its environmental impacts, especially in coastal and freshwater systems.*

#2	Nitrogen (N) Fixation
Definition	Nitrogen is a key nutrient for plant growth and productivity. Industrial nitrogen fixation, achieved through processes such as the Haber-Bosch process, converts nitrogen gas from the atmosphere into ammonia, which is used to produce synthetic fertilizers. Intentional biological fixation involves practices like planting leguminous crops that host nitrogen-fixing bacteria in their roots. Human activities have significantly altered the global nitrogen cycle, primarily through industrial and intentional biological nitrogen fixation.
Unit	Teragrams of nitrogen per year (Tg of N $year^{-1}$). 1 teragram equals 1 million metric tons

#2 Nitrogen (N) Fixation

Range

Historically anthropogenic nitrogen fixation rates were negligible (~0 Tg of N $year^{-1}$), but human activities have increased to approximately 190 Tg of N $year^{-1}$ globally, mainly through fertilizer use. As a result, human interference in the global nitrogen cycle is now equivalent to (and partly even exceeds) the total flux of fixed nitrogen from all natural sources, both on land and in the oceans.[127]

Planetary Boundary

The nitrogen boundary targets industrial and intentional biological nitrogen fixation, setting a threshold at 62 Tg N $year^{-1}$. Its purpose is to curb nutrient pollution and mitigate associated impacts like eutrophication and the formation of dead zones in aquatic systems. This boundary is established based on empirical data, environmental considerations, and the precautionary principle to uphold biogeochemical balance and safeguard ecosystem health.[4] For future assessments, several studies[24,124,125] suggest using agricultural nitrogen surplus as a control variable. 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.

Global Risk Map of the Biogeochemical Cycles Boundary Transgression
Nitrogen Cycle

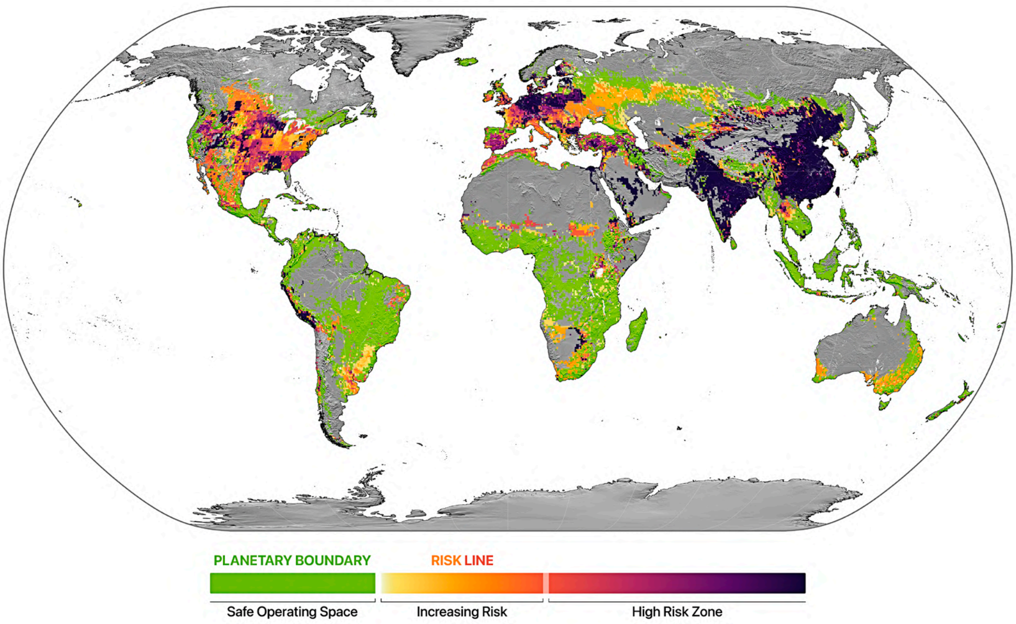


FIGURE 26 Global Risk Map of the Biogeochemical Cycles Boundary Transgression - Nitrogen Cycle. The preliminary regional boundary status is calculated based on agricultural nitrogen surplus in the year 2010 (see **Supplementary Material**) and estimates of regional surplus boundaries. The assessment aligns with the suggestion for an enhanced control variable definition[24] 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. 2. 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 Schulte-Uebbing et al. 2022.[124]

Key takeaway: Nitrogen use in agriculture has exceeded safe ecological limits in several regions of the world, particularly in parts of Asia, Europe, and North America, indicating significant environmental risks. Excess nitrogen runoff can lead to severe ecological issues, including water pollution, eutrophication, and the creation of 'dead zones,' especially in marine ecosystems. This trend underscores the importance of developing more efficient and sustainable nitrogen management practices in agriculture.

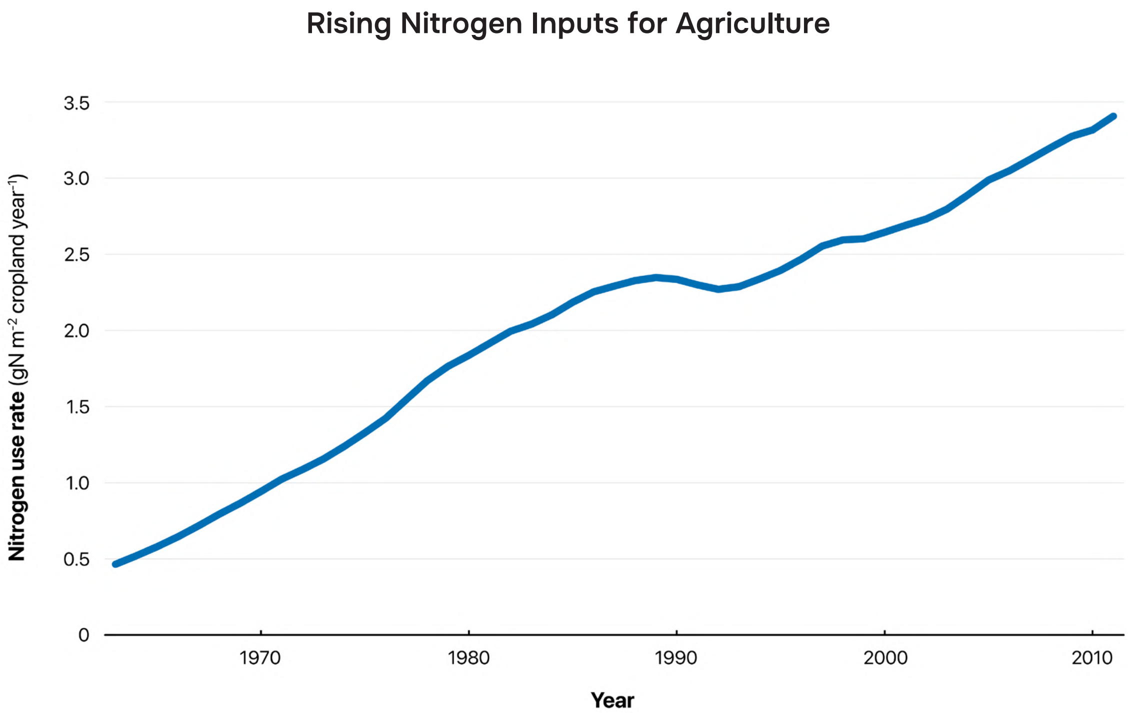


FIGURE 27 Rising Nitrogen Inputs for Agriculture. This graph shows the mean global nitrogen use rate on all croplands (in g N m^{-2} cropland year $^{-1}$, e.g., grams of nitrogen per square meter of cropland per year, see **Supplementary Material**) from 1961 to 2013. Data from Lu and Tian, 2017.[130] *Key takeaway: The steady increase in nitrogen use over the past decades reflects the growing use of nitrogen fertilizers to meet the demands of increasing agricultural production.*

6.5 **Control Variables**

Global Map of Change in Nitrogen Use Rate for Agriculture

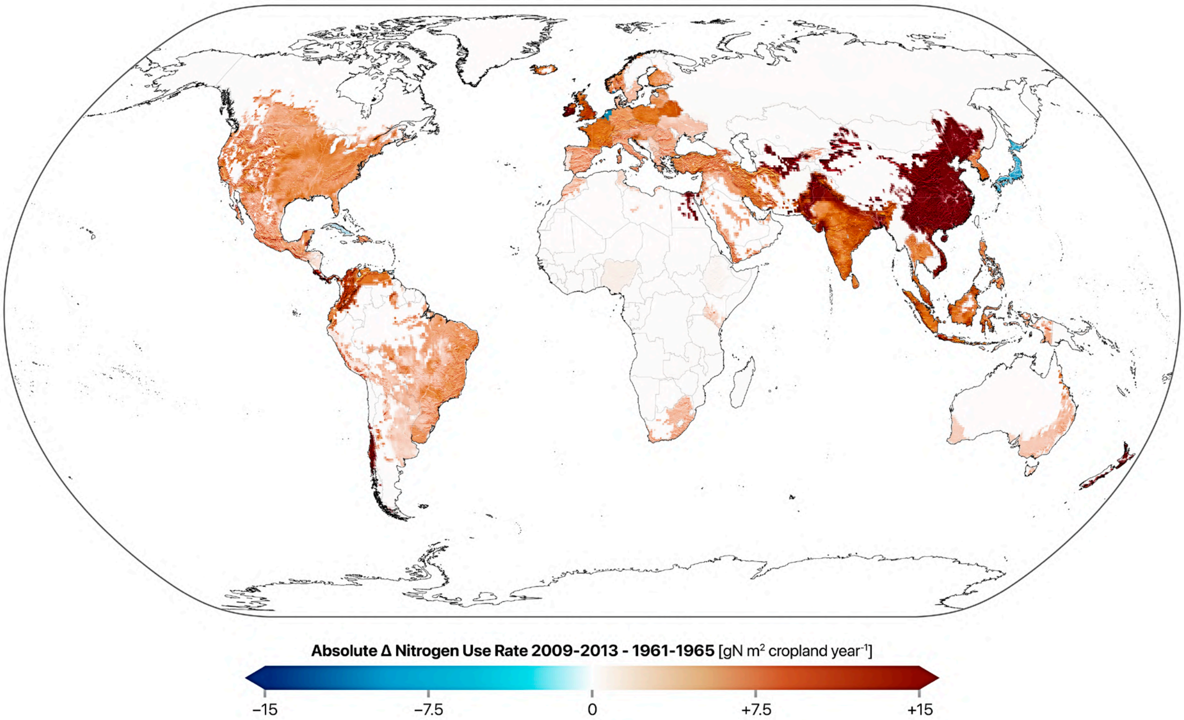
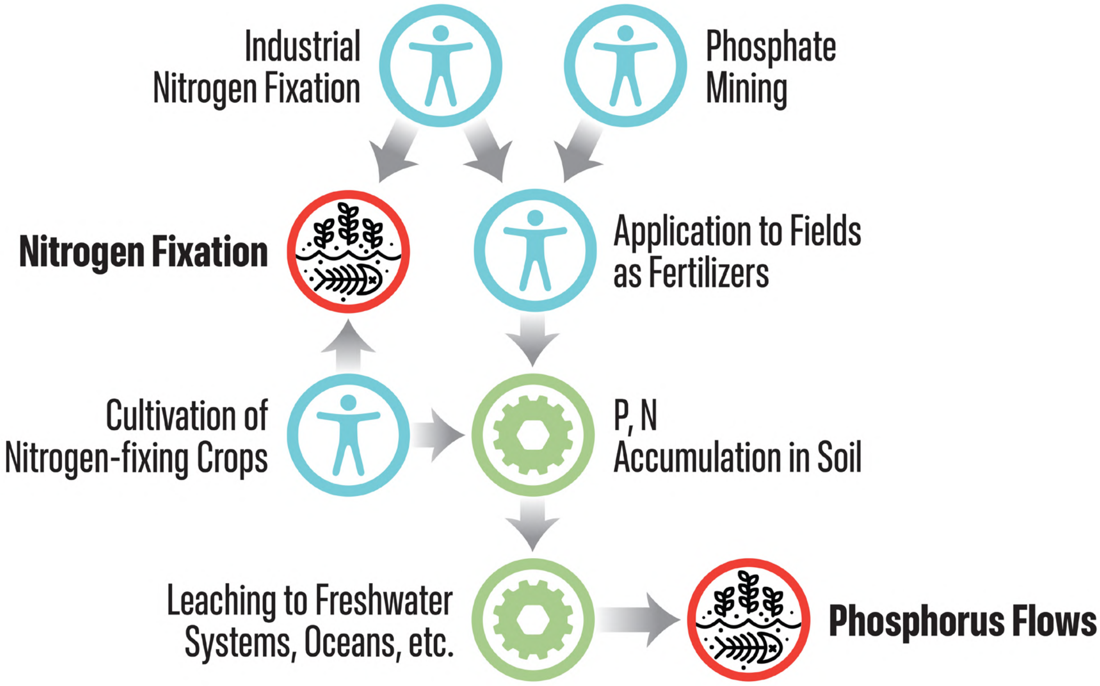


FIGURE 28 Global Map of Change in Nitrogen Use Rate for Agriculture Cycle. The total difference of nitrogen use rates (in g N m^{-2} cropland $year^{-1}$, e.g. grams of nitrogen per square meter cropland per year) calculated as the difference between the rates during the period 2009-2013 (last 5 years of data set) and the period 1961-1965 (first 5 years of data set). Data from Lu and Tian, 2017.[130] *Key takeaway: The map highlights a global increase in nitrogen use, particularly in developing regions, raising concerns about environmental impacts and the need for sustainable agricultural practices.*

6.5 **Data Sources**

1. Phosphorus and Nitrogen fertilizer input data from Lu and Tian (2016)[123] [https://doi.pangaea.de/10.1594/PANGAEA.863323]

2. Exceedance of critical N surplus data from Schulte-Uebbing et al. 2022[124] [https://doi.org/10.1038/s41586-022-05158-2]



Human activities disrupt the global nitrogen (N) and phosphorus (P) cycles, similar to how they affect the carbon cycle. Key drivers include extensive fertilizer use and the cultivation of nitrogen-fixing crops in agriculture.[4,126] The invention of the Haber-Bosch process in the early 20th century led to exponential growth in synthetic nitrogen fertilizer production, which has increased more than tenfold since 1960.[127] Today, the amount of human-generated nitrogen entering the biosphere equals all natural sources combined.[127]

Significant amounts of nitrogen escape into the biosphere through leaching, erosion, and outgassing.[106] Another major source is nitrous oxide emissions from fossil fuel combustion, which totaled about 38 Tg N per year in 2010,[127] though this is not currently factored into the boundary's control variables. Agriculture similarly disrupts the phosphorus cycle, historically through manure and now significantly through mined rock phosphate, accelerating phosphorus cycles two to three times beyond natural rates.[106,128] Agriculture accounts for over 90% of phosphorus boundary transgressions.[106]

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.[126,127,129] It's important to note that the effects of accumulated soil nutrients can persist long after initial inputs have been reduced.[126]

Impacts

Transgressing the safe boundaries for phosphorus and nitrogen has profound and widespread impacts on aquatic and terrestrial ecosystems, human health, and economic sectors such as agriculture, fisheries, and tourism. For example, excessive phosphorus promotes rapid algae growth, leading to harmful algal blooms that produce toxins detrimental to aquatic life and humans (eutrophication).

Furthermore, oxygen-depleted dead zones caused by excess nutrients result in the death of fish, invertebrates, and other aquatic organisms, reducing biodiversity and altering ecosystem structures.

6.6 **Ocean Acidification**

Definition & **Current State**

Ocean acidification is the phenomenon of increasing acidity (decreasing pH) in ocean water due to the absorption of atmospheric CO_2. This process harms calcifying organisms, impacting marine ecosystems, and reduces the ocean's efficiency in acting as a carbon sink.

2024 Status

The indicator for **Ocean Acidification**, the current aragonite saturation state, is at 2.80, which is within the Safe Operating Space (2.75) but is **close to crossing** the safe boundary. Several new studies[131,132] suggest that even these current conditions may be problematic for multiple marine organisms, indicating a need to re-evaluate the safe boundary.

Global Map of Ocean Acidification Indicator
Aragonite Saturation State Change

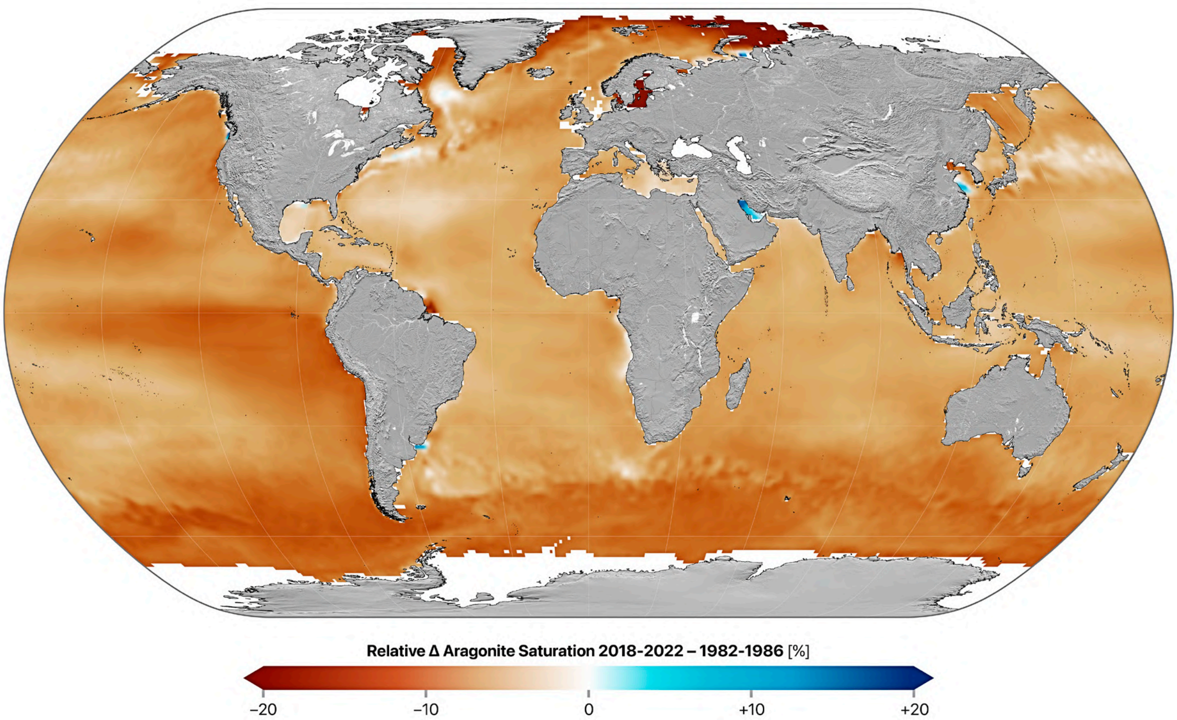


FIGURE 29 Global Map of Ocean Acidification Indicator - Aragonite Saturation State Change. This map shows trends in the surface aragonite saturation state by comparing the mean values for the years 1982-1986 (the first 5 years of available data) with those for 2018-2022 (the last 5 years of available data). The changes are expressed as a percentage (e.g., a change from 3.0 to 2.7 would be indicated as -10%). Data from Gregor & Gruber, 2020 (v2023).[133] ***Key takeaway:*** *Ocean acidification is affecting oceans worldwide, with the effects being most pronounced in the Southern Ocean and the Arctic Ocean. Some areas have already become undersaturated with respect to aragonite, posing a risk to vulnerable calcifying organisms that play an important role in the food web.*

6.6 **Control Variable**

#1	**Aragonite saturation state (Ω)**
Definition	Aragonite is a form of calcium carbonate used by many calcifying organisms (e.g., corals and shellfish) to construct their shells or skeletons. The aragonite saturation state measures the current carbonate ion concentration against the concentration needed to form stable aragonite. An aragonite saturation state of Ω < 1 indicates corrosive conditions that can lead to the dissolution of aragonite. The aragonite saturation state is sensitive to changes in CO_2 concentration because the uptake of anthropogenic CO_2 by the ocean leads to the formation of carbonic acid. This acid dissociates, producing hydrogen ions that convert carbonate ions into bicarbonate ions, thereby reducing the carbonate ion concentration. Consequently, this process lowers the aragonite saturation state, making it a reliable indicator of the impact of increased CO_2 on ocean chemistry and marine ecosystems.
Unit	Dimensionless
Range	Ω varies by region, predominantly ranging from 3.3 to 4.0 in tropical oceans and from 1 to 2 in polar oceans.
Planetary Boundary	The PB for global mean surface Ω is set at 2.75, which is 80% of the pre-industrial value of 3.44. This threshold was selected to ensure that waters at high latitudes do not experience large-scale aragonite undersaturation, while waters at low latitudes remain well oversaturated with respect to aragonite, thereby limiting harmful impacts on marine calcifiers.

Ocean Acidification Approaching its Boundary

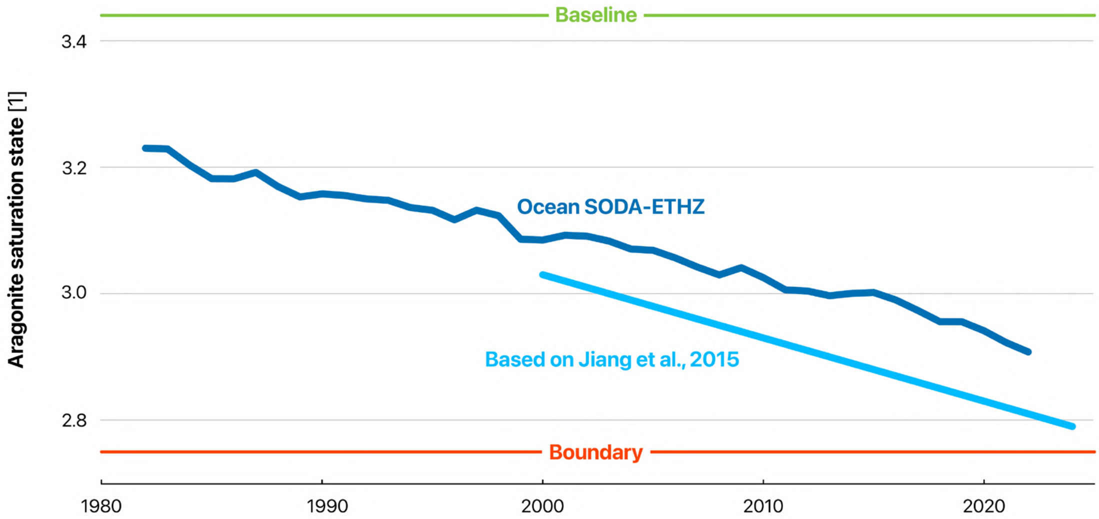
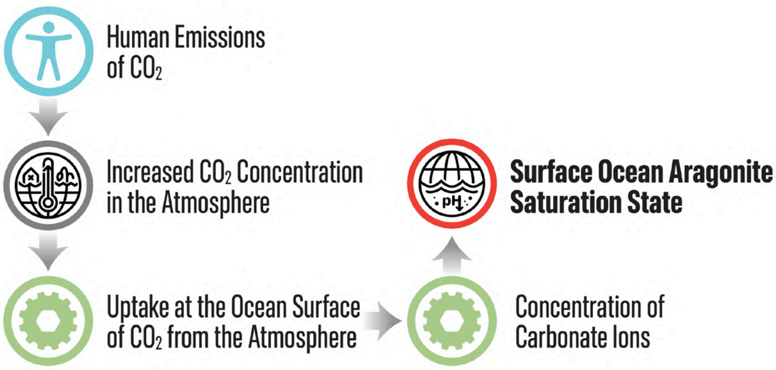


FIGURE 30 Ocean Acidification Approaching its Boundary. Shown are two datasets for the control variable "Global mean aragonite saturation state," both illustrating how the Ocean Acidification PB is nearing its limit. Although the datasets use different maximum water depths and thus indicate slightly different values, they show the same overall trend. The red line represents the Planetary Boundary of 2.75 , while the green line indicates the pre-industrial baseline of 3.44. Data from Gregor & Gruber, 2020 (v2023)[133] and Jiang et al., 2015.[136] *Key takeaway: Ocean acidification is approaching its PB, with the surface aragonite saturation state declining significantly towards the PB, posing a growing threat to marine ecosystems.*

6.6 **Data Source**

1. Surface aragonite saturation state data from Gregor, Luke; Gruber, Nicolas (2020). OceanSODA-ETHZ: A global gridded dataset of the surface ocean carbonate system for seasonal to decadal studies of ocean acidification (v2023) (NCEI Accession 0220059). Monthly aragonite saturation state (omega_ar). NOAA National Centers for Environmental Information. Dataset. https://doi.org/10.25921/m5wx-ja34. Accessed 03/07/2024.[133]

6.6 **Key Drivers**



The control variable for the **Ocean Acidification** boundary is the aragonite saturation state of the surface ocean. While "acidification" specifically refers to the reduction of water pH (increasing hydrogen ion concentration), "ocean acidification" encompasses a broader range of chemical processes.[134] These processes affect minerals like aragonite, a form of calcium carbonate used by many marine organisms. Therefore, aragonite saturation is a strong indicator of global impacts, influencing the entire food web. The shift in aragonite saturation state is driven by a decrease in carbonate ions. These ions are reduced because they react with anthropogenic CO_2 absorbed from the atmosphere at the ocean surface.

Human-caused CO_2 emissions are the primary driver of **Ocean Acidification**. There are strong regional and yearly variations due to phenomena like El Niño.[134] Overall, **Ocean Acidification** exemplifies that one process (increased CO_2 concentration) can affect more than one PB (**Ocean Acidification** and **Climate Change**).

Impacts

Crossing the boundary for **Ocean Acidification** has multiple impacts: Corals struggle to build their skeletons, weakening reef structures. Mollusks and other shellfish have difficulty forming shells, impacting their survival and growth. Certain organisms, such as high-latitude pteropods, are already experiencing shell damage.[132,135] As calcifying organisms play a central role in marine food webs, their decline can cause significant harm to the entire ocean's biosphere. Coral skeleton growth also suffers from ocean acidification, endangering global reefs, which are biodiversity hotspots and natural habitats and birthplaces for countless organisms. Changes in carbonate chemistry reduce the ocean's capacity to sequester carbon, weakening its ability to mitigate global warming.

At low latitudes, where the aragonite saturation state is still relatively high, the absolute rate of reduction is highest.[134] This can pose a risk as tropical corals become stressed when Ω falls below 3, especially in combination with other stressors such as marine heatwaves. At high latitudes, the aragonite saturation state is naturally lower, and acidification drives some areas to become undersaturated with respect to aragonite, creating corrosive conditions for aragonite shells.

6.7 Increase in Atmospheric Aerosol Loading

Definition & Current State

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

2024 Status

The interhemispheric difference in atmospheric aerosol loading (0.065) is **within the Safe Operating Space**.

Global Map of Recent Change in Aerosol Loading

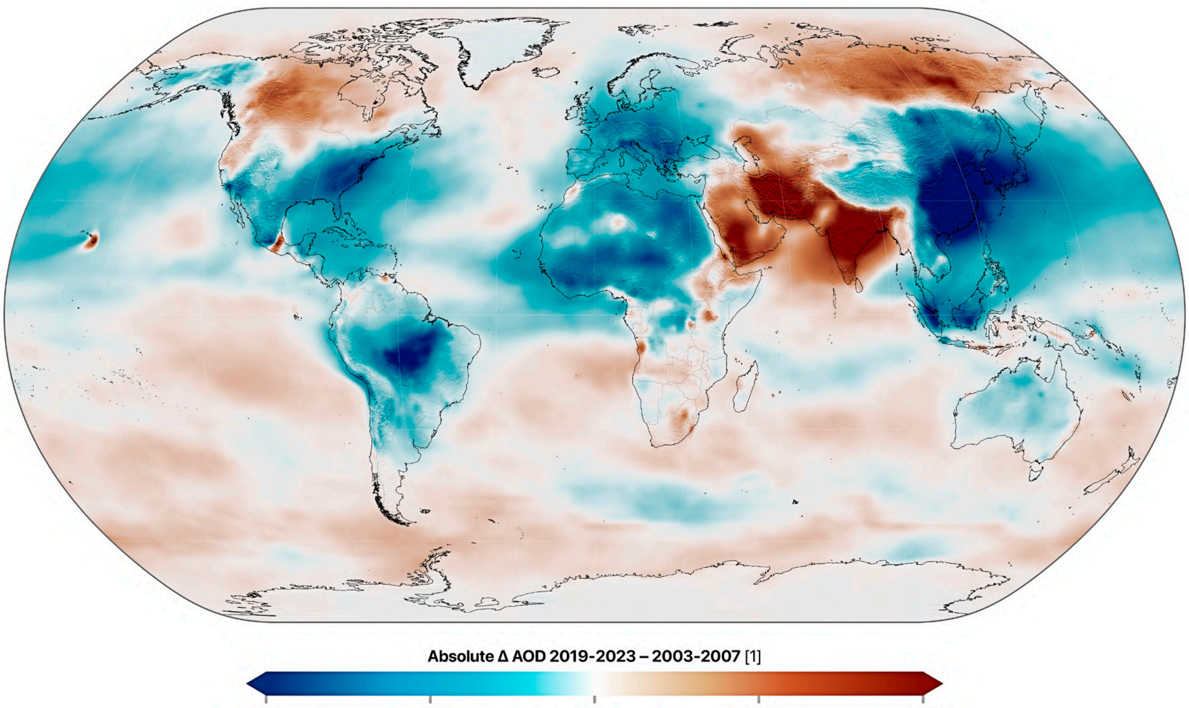


FIGURE 31 Global Map of Recent Change in Aerosol Loading. This map shows the absolute change in aerosol optical depth (AOD), calculated as the difference between AOD during 2019-2023 (the last 5 years of this dataset) and 2003-2007 (the first 5 years of this dataset). For example, a change from 0.2 to 0.15 AOD would be indicated by a value of -0.05. Areas where the AOD has increased are shown in shades of red, while areas where it has decreased are shown in shades of blue. Data from CAMS EAC4.[137] *Key take-away: Although AOD is decreasing globally, the varied patterns – with some regions seeing increases – indicate a complex mix of local factors, such as industrial emissions, deforestation, and climate change-driven events like wildfires.*

6.7 **Control Variable**

#1 Interhemispheric Difference in Aerosol Optical Depth (AOD)

Definition	AOD measures how many aerosols (small particles suspended in the air) block the transmission of light by absorbing and scattering it. The interhemispheric difference refers to the variation between the Northern and Southern Hemispheres in terms of this specific parameter or variable. Globally, this control variable measures the interhemispheric difference in aerosol concentrations. Regionally, AOD correlates with PM2.5 concentration, which is important for justice considerations regarding human health.[24] However, this regional correlation is not yet fully integrated into the Planetary Boundaries (PBs) framework.
Unit	Dimensionless
Range	AOD values range from 0 (no aerosols) to 1 or higher (very dense aerosol layer).
Planetary Boundary	This 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. Additionally, 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 for justice considerations related to human health.[24]

Bridging the Divide:
Declining Interhemispheric Difference in Aerosol Loading

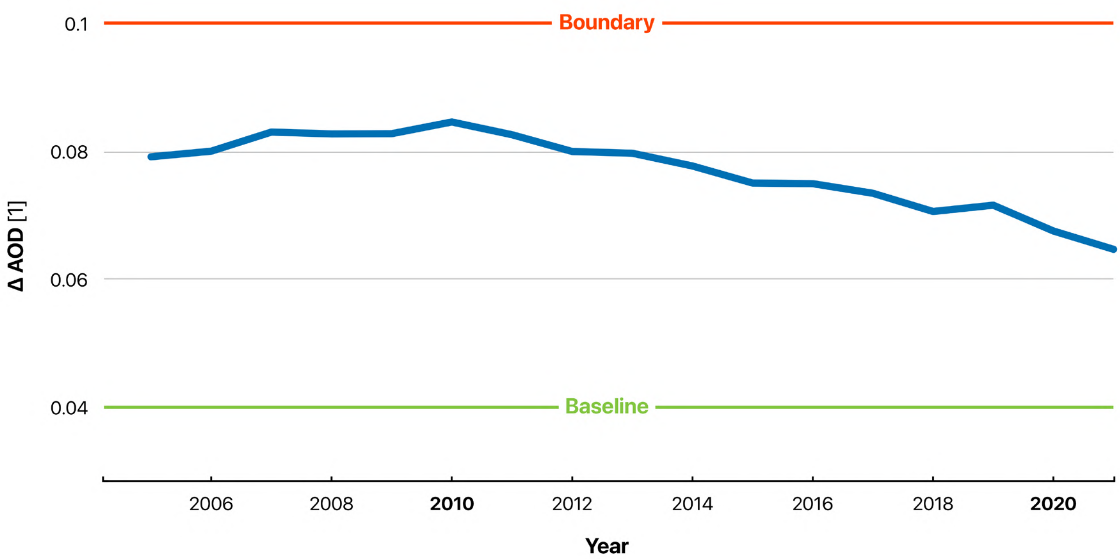
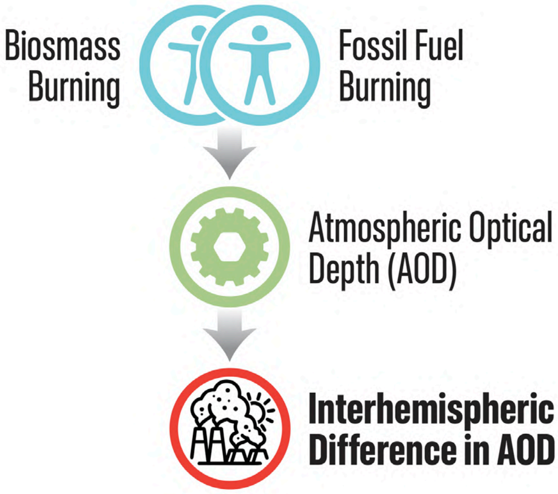


FIGURE 32 Bridging the Divide: Declining Interhemispheric Difference in Aerosol Loading. This chart shows the 5-year running mean of the difference in aerosol optical depth (AOD) between the Northern and Southern Hemispheres, calculated by averaging data from 60° north to 60° south for the period from 2003 to 2023. The red line represents the Planetary Boundary of 0.1, while the green line indicates the baseline of 0.04. Data from CAMS EAC4.[137] *Key takeaway: The difference in aerosol optical depth between the Northern and Southern Hemispheres has been decreasing from 2006 to 2023, indicating that we are moving further into the Safe Operating Space.*

6.7 Data Source

1. AOD data (total AOD at 550 nm) is the ECMWF Atmospheric Composition Reanalysis 4 product from the Copernicus Atmosphere Monitoring Service. (CAMS) [137, 138]

6.7 Key Drivers



The main anthropogenic cause of changes in AOD (i.e., the direct physical-chemical driver of transgression for the global control variable) is human activities such as fossil fuel and biomass burning.[139] A key factor influencing the global control variable, particularly the difference between the Northern and Southern Hemispheres, is that aerosol emissions historically followed divergent trends in the Northern and Southern Hemispheres. This disparity is largely explained by the greater land area and higher population density in the Northern Hemisphere, leading to higher pollution levels compared to the Southern Hemisphere.

However, the impacts, formation processes, and sources of aerosols extend beyond the current control variable selection. For instance, while the global PB remains within its Safe Operating Space, regional AOD levels can exceed safe thresholds, potentially altering precipitation patterns and affecting human health. 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

The interhemispheric difference in aerosol loading leads to an asymmetric radiative forcing, causing relative cooling in the Northern Hemisphere and a southward shift in tropical precipitation. This interhemispheric difference in AOD affects monsoon dynamics, with higher Northern Hemisphere AOD weakening monsoon precipitation.

Studies, including IPCC AR6, indicate that human-caused Northern Hemisphere aerosols have contributed to decreased global land monsoon precipitation from the 1950s to the 1980s, underscoring the sensitivity of tropical precipitation to aerosol distribution and particle size. Regionaly, higher AOD values in monsoon regions likely lead to significantly lower rainfall, ultimately affecting biosphere integrity.[4]

6.8 Stratospheric Ozone Depletion

Definition & Current State

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

2024 Status

The current total amount of stratospheric ozone (285.7) is **within safe levels**, and recovery is ongoing, with values still below mid-20th century levels.

Global Map of Recent Ozone Layer Changes

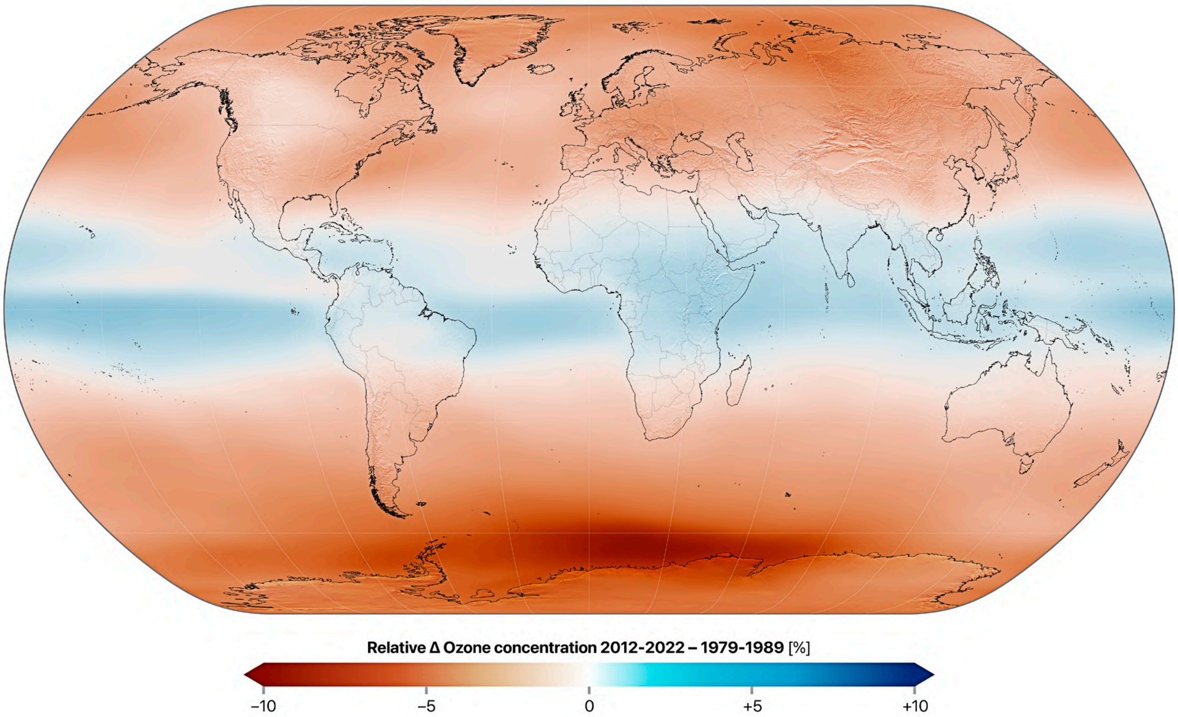


FIGURE 33 Global Map of Recent Ozone Layer Changes. This map shows the relative change in the stratospheric ozone concentration between 1979-1989 (the first 11-year cycle of this dataset) and 2012-2022 (the last 11-year cycle of this dataset). For example, a change from 260 DU to 273 DU would be indicated by a value of +5%. Areas where total ozone has increased are shown in shades of blue, while areas where it has decreased are shown in shades of red. Data from MSR 2020.[140] *Key takeaway: Regional 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.*

#1 Stratospheric Ozone Concentration (Extra-polar, 60°N-60°S average)

Definition	The stratospheric ozone layer protects life on Earth from harmful ultraviolet radiation. The extra-polar zone refers to 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, impacts on humans and ecosystems are more severe in the extra-polar region. Additionally, the ozone hole phenomenon involves complex factors beyond just anthropogenic ozone-depleting substances, making extra-polar ozone a more relevant measure for a PB.[2]
Unit	Dobson Unit (DU). One DU represents a layer of ozone that would be 0.01 millimeters thick under standard temperature and pressure.
Range	Typical values range from about 100 to 500 DU.
Planetary Boundary	For global extra-polar stratospheric ozone, there is no clear threshold for defining a boundary. As a preliminary estimate, the PB is set as a maximum reduction of 5% from the reference level (mean from 1964-1980). With the reference level estimated at 292 DU, the Planetary Boundary is set at 277.4 DU.

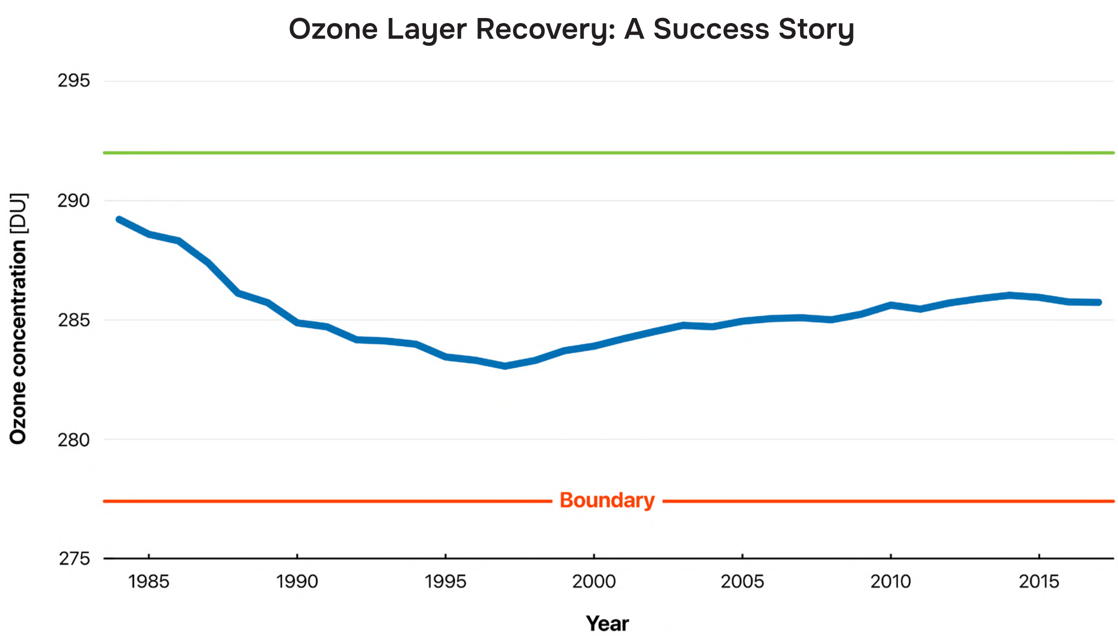
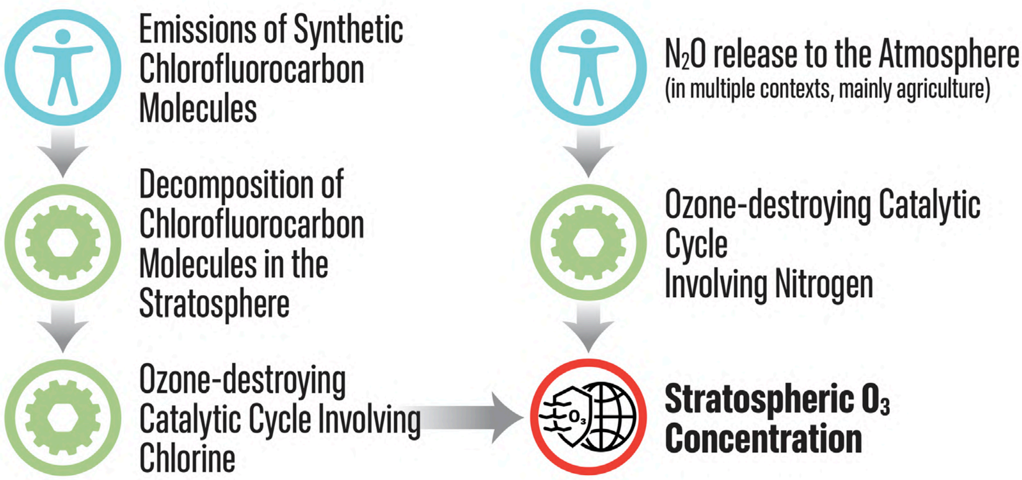


FIGURE 34 Ozone Layer Recovery: A Success Story. This chart displays the 11-year mean of the control variable "global mean stratospheric ozone concentration" measured in Dobson Units (DU) for the period from 1979 to 2022. The red line shows the Planetary Boundary of about 277 DU, while the green line represents the baseline of 292 DU (values updated with respect to Richardson et al., 2023[4] and IPCC, 2023.)[145] Data from MSR 2020.[140] *Key takeaway: While the global stratospheric ozone layer has recovered since the mid-1990s after a significant decline, this recovery may have plateaued in recent years.*

6.8 **Data Source**

1. Ozone data is from the Multi-Sensor Reanalysis product of the Copernicus Climate Change Service, Climate Data Store, (2020): Ozone monthly gridded data from 1970 to present derived from satellite observations. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.4ebfe4eb (Accessed on 17-JUNE-2024)[140]

6.8 **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 PB level.

The primary driver of ozone destruction is a catalytic cycle within the stratosphere involving chlorine. This chlorine is produced through the breakdown of stable chlorofluorocarbons (CFCs) by UV radiation. These stable molecules can persist in the atmosphere for up to a century after being emitted at Earth's surface.[141] Although the Montreal Protocol has successfully controlled CFC emissions, the most significant remaining source of ozone-depleting substances is nitrous oxide (N_2O).[142] Agricultural activities are a major source of N_2O, contributing to its presence in the atmosphere through various pathways.[143]

Impacts

Depletion of stratospheric ozone allows more harmful ultraviolet (UV) radiation to reach 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 oceans, 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.[144]

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.

6.9 **Introduction of Novel Entities**

Definition & Current State

The introduction of novel entities includes synthetic chemicals and substances (e.g., microplastics, endocrine disruptors, organic pollutants), anthropogenically mobilized radioactive materials (e.g., nuclear waste, nuclear weapons), and human interventions in evolutionary processes, such as genetically modified organisms (GMOs) and other direct modifications of evolution.

2024 Status

The amount of synthetic substances released into the environment without adequate testing (which is currently > 0) is **above the safe level**.

From Conception to Contamination: The Rise of Novel Entities

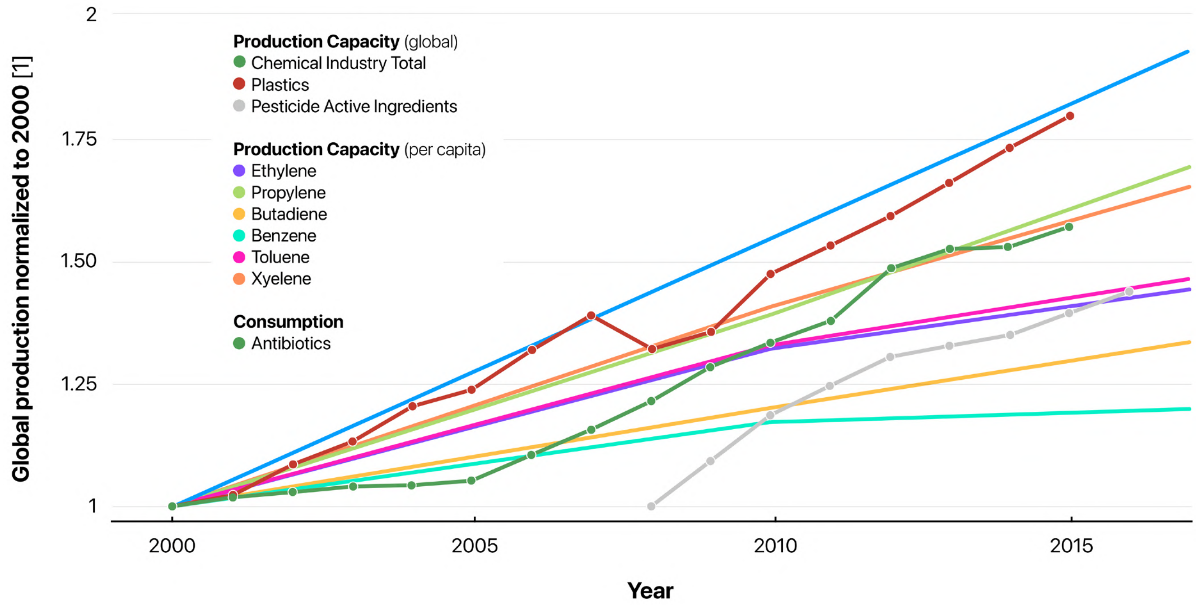


FIGURE 35 From Conception to Contamination: The Rise of Novel Entities. This chart illustrates the relative growth of various categories of novel entities and key chemicals from 2000 to 2017, a period with sufficient comparable data. The data is normalized to the year 2000. Data from Persson et al., 2022.[146] *Key takeaway: Chemical production has steadily increased from 2000 to 2017, raising concerns about environmental contamination and public health. Novel entities, such as plastics, pesticides, industrial chemicals, and antibiotics, contribute to pollution, bioaccumulation, ecosystem disruption, antibiotic resistance, and health issues like cancer and hormonal imbalances. With tens of thousands of man-made chemicals in the world, most of which have not been studied for safety, the risks are significant.*

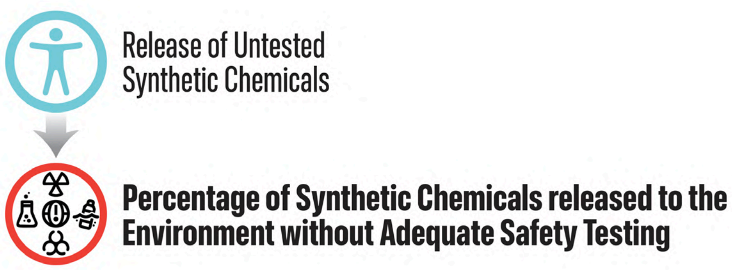
6.9 **Control Variable**

#1	**Percentage of Untested Synthetic Chemicals Released Into the Environment Without Adequate Testing**
Definition	The percentage of synthetic chemicals released into the environment without adequate safety testing is a critical measure of regulatory oversight and our understanding of chemical risks. It is essential for managing potential environmental and health impacts.
Unit	Percentage
Range	This percentage can vary from 0% (all chemicals undergo sufficient testing before release) to 100% (none are tested).
Planetary Boundary	Following the precautionary principle, the PB is set at 0% – no synthetic chemicals should be released without adequate safety testing. Historical examples such as DDT (which harmed bird populations and entered food chains) and CFCs (which depleted the ozone layer) underscore the need for strict testing. Currently, a significant portion of chemicals remains untested, indicating that the boundary is likely exceeded, though exact figures are uncertain. Additionally, testing is a rudimentary measure, as it does not ensure that measures to control release are present or adequate. Furthermore, many jurisdictions lack the capacity to even identify which chemicals are being released, let alone regulate and ensure compliance with regulations.

6.9 **Data Source**

1. Data for "Growth in Novel Entities" is from Persson et al, 2022.[14]

6.9 **Key Drivers**



The control variable for this PB, which measures the percentage of untested synthetic chemicals released, is directly driven by human activities, specifically the release of these chemicals.

6.9 **Key Drivers**

The underlying causes of this driver of transgression include the:

- **Rapid increase in chemical production** (both in volume and diversity) since the mid-20th century.

- **Persistent and bioaccumulative nature of some chemicals**, which pose widespread and long-term risks, along with the high production volumes and releases of non-persistent chemicals, which effectively become "pseudo-persistent."

- **Insufficient institutional capacity for chemical testing**, including research into new toxicological pathways and effects, as well as a lack of monitoring to keep up with the rates of production of both existing and new chemicals.

- **Limited capacity to translate testing information** into effective regulatory controls and to enforce monitoring and legal actions to ensure compliance with regulations.

For example, in the U.S., "over 80,000 chemicals have been registered for use since the Toxic Substances Control Act (TSCA) was enacted in 1976, yet the majority have not undergone regulatory testing."[147] According to Persson et al., 2022,[146] "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 rise of novel entities can disrupt critical Earth system processes. For instance, chlorofluorocarbons (CFCs) have notably damaged the ozone layer, fluorinated gasses contribute to climate change by trapping heat, and polycyclic aromatic hydrocarbons (PAHs) are involved in aerosol formation, which impacts air quality.

Novel entities also harm ecosystems by affecting the health and functioning of various species. Pesticides, for example, have caused significant declines in insect and pollinator populations. Persistent organic pollutants like PAHs, which come from sources such as vehicle emissions and industrial activities, along with microplastics, inflict physical harm and toxic effects on marine and terrestrial life.

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 water bodies and the alteration of natural habitats. Radioactive elements can cause immediate and long-term health effects, including mutations and cancerous growths.

2024

Planetary Boundaries

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7. Early Symptoms of Transgressing Planetary Boundaries

Planetary Boundaries (PBs) are essential safeguards for the stability, resilience, and life-support functions of the Earth system.[2–4] Transgressing these boundaries endangers at least one of these functions. Additionally, transgressing or even approaching a PB can lead to significant and often unpredictable environmental impacts. These impacts can vary widely by region and time – for example, causing floods in one area and droughts in another – due to the complex interactions within the Earth system. Scientific understanding continues to evolve, uncovering new impacts and expanding our knowledge of existing ones.

In this section, we outline well-known symptoms of boundary transgressions, including extreme weather events, wildfires, water scarcity, pollution, the loss of global carbon sinks, and other early warning signals in different Earth system processes. These symptoms illustrate the diverse potential consequences of boundary transgressions. Some are directly tied to the control variable of a specific PB process (e.g., deforestation linked to **Land System Change**), while others have more indirect connections (e.g., the increase in atmospheric CO_2 from crossing the **Climate Change** boundary, leading to global warming and its associated extreme weather patterns). We focus on a wide range of symptoms, particularly those not already represented by PB control variables.

Extreme Weather Events and Wildfires

The most direct link between the transgression of PBs and extreme weather events occurs through **Climate Change**. Exceeding this boundary results in global warming, which intensifies the hydrological cycle and leads to changes in circulation patterns. This, in turn, causes more frequent and severe droughts and heatwaves, along with increased instances of extreme precipitation and flooding.[148]

Research indicates that anthropogenic climate change has already heightened the likelihood of extreme weather events (Fig. 37), and it is estimated that attributable anthropogenic impacts may be occurring across 80% of the world's land area.[149] For example, increased temperatures and altered precipitation patterns are major factors behind prolonged droughts and intensified storm systems.[150]

Global Map of Countries that Declared Drought Emergencies in 2022-2023

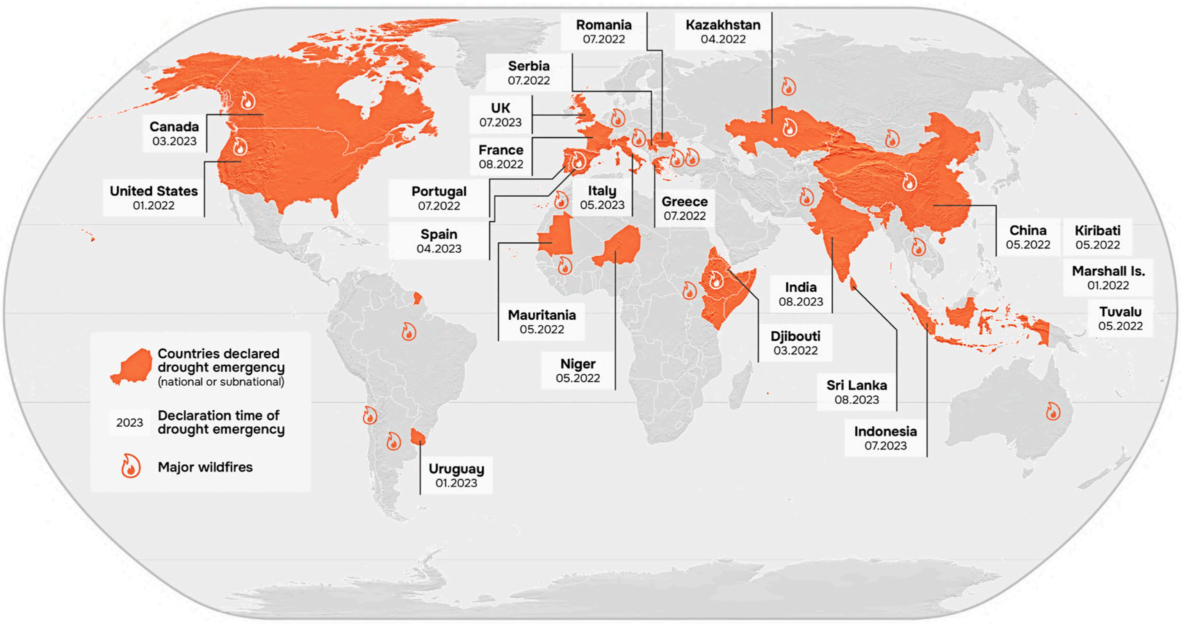


FIGURE 36 Global Map of Countries that Declared Drought Emergencies in 2022-2023. During 2022-2023, widespread drought conditions affected various regions, including North America, Europe, Asia, and Africa, and were often accompanied by major wildfires. This underscores the severe impact of prolonged dry conditions on different parts of the world. Adapted from UNCCD.[156]

Climate change effects on oceans are similarly profound. In 2024, the Earth experienced its second global coral bleaching event in the past decade, which was exacerbated by marine heatwaves intensified by climate change. These events severely affect foundational marine species such as corals, seagrasses, and kelps, leading to extensive ecological damage and biodiversity loss.[151]

There is also mounting evidence of increased frequency and intensity of economically and ecologically devastating wildfires globally due to anthropogenic climate change.[111,152] In 2022-23, over 20 countries worldwide declared drought emergencies (Fig. 36), a trend linked to the transgression of several PB processes. Rising temperatures as well as decreased or more seasonal precipitation patterns can dry out living and dead biomass, leading to more fire-susceptible vegetation.[153] Deforestation and land conversion further contribute by increasing dry fuel availability and reducing natural fire barriers.[154]

The positive correlation between droughts and wildfires has led to a rise in compound drought-wildfire events, affecting more than a third of global vegetated areas. These events result in greater reductions in gross primary production compared to isolated droughts.[155]

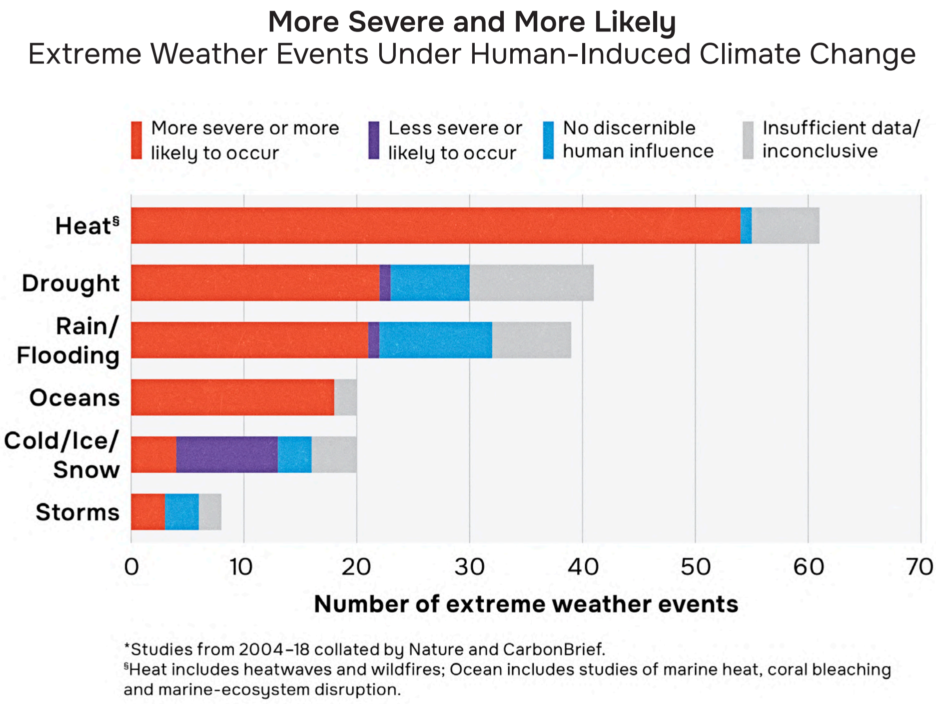


FIGURE 37 More Severe and More Likely - Extreme Weather Events Under Human-Induced Climate Change. An analysis of over 170 studies compiled by Nature and CarbonBrief shows that human-induced climate change has increased both the likelihood and severity of extreme weather events. Adapted from Schiermeier, 2018.[148] Reproduced with permission from Springer Nature. For an extensive and up-to-date overview of these numbers, refer to the latest attribution map of Carbon Brief (v2023).[133]

Changes in Vegetation Productivity

Several processes related to PBs affect plant productivity and, consequently, food production. While current trends indicate an increase in vegetation productivity due to CO_2 fertilization and enhanced water use efficiency from increased stomatal closure, these gains are increasingly offset by disruptive processes.[66, 107, 150] Climate extremes, such as droughts and heat waves, create water scarcity, damage plant tissues, and increase respiration, leading to decreased productivity and biomass in natural and land-use areas.[118, 155] Other factors, often secondary, such as insect infestations, wildfires, and excessive fertilizer application, cause nutrient imbalances, soil degradation, and water pollution, all of which ultimately harm plant health.[111, 157] These opposing forces suggest that while some regions are experiencing productivity increases, others are already seeing declines due to these disruptive processes.[107, 150]

Water Scarcity

Water scarcity has increasingly become a significant barrier to socio-economic progress and a serious threat to livelihoods in many regions around the globe.[158] This scarcity is driven by multiple factors related to the crossing of PBs. Transgressions of the **Freshwater Change** boundary, particularly through irrigation and related land-use changes, affect both green water (soil moisture available for plants) and blue water (surface and groundwater).[159] Poor water quality due to pollution further reduces the water available for use. Climate change further exacerbates this scarcity by altering precipitation patterns and increasing the frequency of droughts.[160]

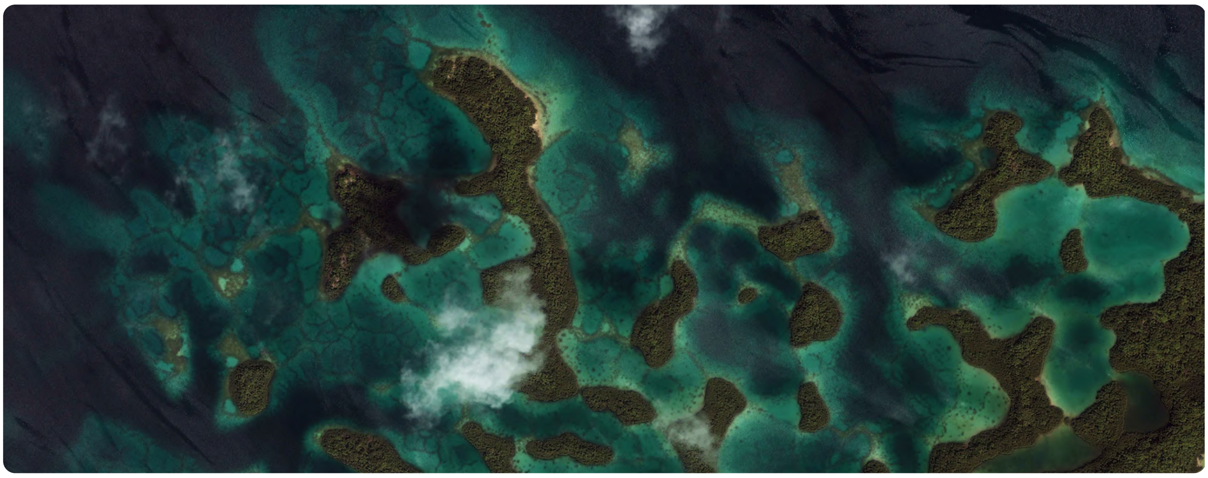
Increase in Waste

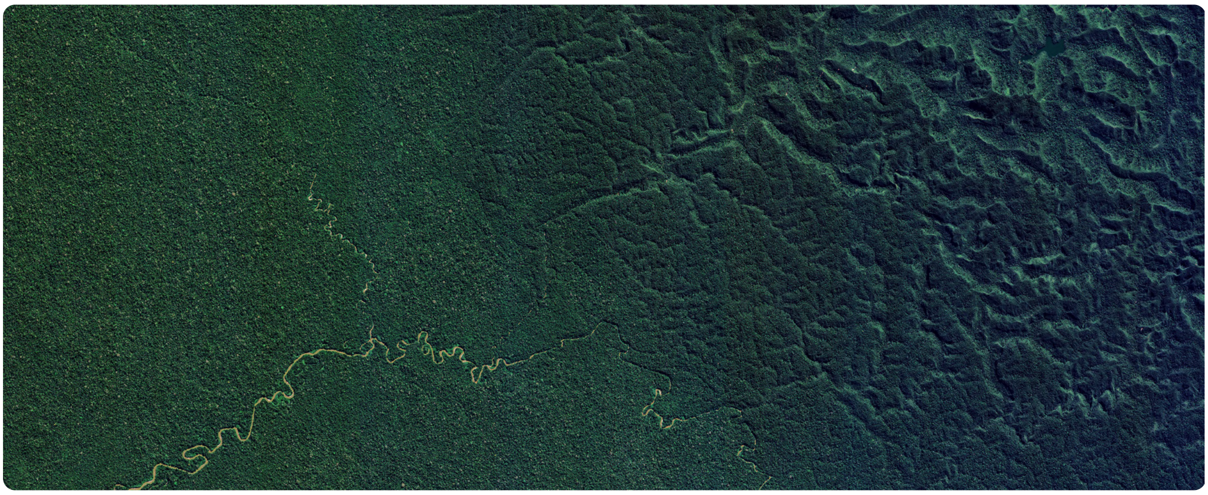
All nine PB processes involve either extracting resources from the Earth system or adding waste to it. Consequently, transgressions of these boundaries, particularly the **Introduction of Novel Entities** boundary, are associated with increased global waste. For example, studies indicate that plastic debris is widespread in the majority of the world's freshwater ecosystems[161] and coral reef ecosystems.[162] Additionally, the amount of plastic entering the oceans annually is expected to almost triple by 2040.[163] Simultaneously, plastic weathering has been discussed as a potential global threat.[164] Today, plastic pollution is pervasive worldwide, appearing in oceans, lakes, rivers, soils, sediments, and the atmosphere, as well as within animal biomass, including human tissue, making it the focus of current PB research.[163, 164]

However, it's important to recognize that waste issues extend beyond novel entities; climate-related impacts (like greenhouse gases), aerosols, ozone depletion, nitrogen (N) and phosphorus (P) cycles, and ocean acidification are all fundamentally linked to waste management challenges. Addressing these interconnected waste issues is critical for maintaining planetary health and ensuring sustainable environmental practices.

Declining Global Carbon Sink

Human activities and climate change are rapidly degrading the carbon sequestration capacity of terrestrial ecosystems, with potentially catastrophic consequences for global climate stability. Major carbon sinks, such as the Amazon rainforest and boreal forests, are increasingly becoming carbon sources due to deforestation, degradation, and climate extremes like droughts and wildfires.[165,166] In 2023, the global land carbon sink was at its lowest since 2003, contributing to a record high CO_2 growth rate of 3.37 ppm.[67] This shift threatens global climate stability, as these ecosystems historically absorbed a substantial portion of anthropogenic CO_2 emissions. The increasing instability in the land-atmosphere carbon exchange[168] and the dramatic increase in global tree mortalities[169] underscore the urgent need for enhanced biosphere stewardship to protect and restore these vital carbon sinks.[170]





Resilience Loss & Early Warning Signals in Earth System Processes

Several components of the Earth system show evidence for a loss in resilience. A typical indicator of this is a slower recovery from perturbations, as seen in various Earth system processes such as the Amazon rainforest[171] and other ecosystems.[172] Factors such as deforestation, increasing dry-season length, and drought frequency are decreasing vegetation resilience globally. Resilience loss is not only observed in the biosphere; the large system of ocean circulations in the Atlantic, known as the Atlantic Meridional Overturning Circulation (AMOC), also shows early-warning signals of a potential collapse,[173] with some studies estimating that the AMOC tipping point could be crossed within the 21st century.[174]

Profound Consequences for Humanity

While the PBs framework focuses on Earth system stability rather than direct human impacts, the transgressions of these boundaries are already having profound consequences for humanity. Over the past two decades, climate change has been linked to 7,348 major disasters, resulting in 1.23 million deaths and $2.97 trillion in economic losses.[175] Decreased crop yields due to droughts and heatwaves are straining food security,[176] while 2.2 billion people lack safely managed drinking water, and 3.5 billion lack adequate sanitation,[177] contributing to 1.4 million deaths annually.[178]

Furthermore, 2 billion tons of waste are generated each year,[179] with 45% mismanaged,[180] leading to hazardous pollution and nearly 7 million deaths linked to air pollution.[181] In 2023, 600 million people were already living outside the optimal human climate niche,[182] underscoring the urgent need to address the various environmental and human challenges resulting from PB transgression for the sake of both planetary health and human survival.

Conclusion

PBs are critical for maintaining Earth's stability and resilience. Transgressing these boundaries can lead to severe, unpredictable environmental impacts, such as extreme weather, wildfires, water scarcity, and reduced vegetation productivity. These impacts are not only immediate but also contribute to long-term changes, such as the degradation of carbon sinks and the loss of ecosystem resilience. The interconnectedness of PB processes means that addressing one boundary violation often requires tackling others simultaneously. Overall, these changes pose significant risks to Earth's life-support systems, emphasizing the urgent need for global efforts to restore and protect these boundaries.

8. The Food System: Present Impacts & Future Transformation Requirements

Sometimes overlooked compared to the impacts of energy production and consumption – particularly the use of fossil fuels – the food systems we depend on are among the largest drivers of environmental degradation. The global food system is the single largest driver behind the transgression of multiple Planetary Boundaries (PBs). From water withdrawals and fertilizer use to greenhouse gas emissions, the agriculture sector significantly impacts our planet, posing challenges to global sustainability.

- Producing food is the world's most water-intensive human activity, whether through rain-fed agriculture or the storage of water in dams for irrigation. Over 90% of human use of freshwater is for food, from production to processing.[116]
- Overuse of nitrogen fertilizers has created a significant global nitrogen surplus on agricultural land, exceeding 119 Tg N per year.[124]
- Although the global area used for food production has nearly stabilized at around 40% of ice-free land,[107] land-use conversion from natural habitats to agricultural land continues in some regions. Agriculture remains the largest driver of tropical deforestation.
- Greenhouse gas (GHG) emissions from food production (including agriculture, forestry, and other land use) contribute to approximately 30% of total GHG emissions.[183]

Overall, almost half of all global food production currently depends on PB transgressions.[184] These transgressions vary spatially: the **Freshwater Change** boundary is often exceeded in subtropical regions due to irrigation, the nitrogen portion of the **Modification of Biogeochemical Flows** boundary is often crossed in parts of China, Europe, and the US due to intensive fertilizer use, and the **Land System Change** and **Change in Biosphere Integrity** boundaries are transgressed in the many locations where natural vegetation is converted for agriculture.

To maintain Earth's Planetary Boundaries and operate within a Safe Operating Space, several actions are imperative:

1. **Constraining agricultural activities in protected areas**, especially to preserve forests and biodiversity.
2. **Reducing water use and consumption for irrigation** to protect aquatic ecosystems and groundwater stores.
3. **Decreasing fertilizer application rates** to minimize freshwater contamination and eutrophication risks.

Conclusion

A fundamental overhaul of the food system is necessary to respect PBs while ensuring food security for a growing global population projected to reach 9-10 billion by 2050[183] (Fig. 38). This transformation involves reconsidering dietary patterns globally and investigating where and how we produce and procure food.[184,185] Sustainable crop production – which improves water, land, and nutrient management, and reallocates cropland, irrigation, and fertilizer use to enhance yields in underperforming regions – holds significant potential. Aligning diets with recommendations from the EAT-Lancet Commission, which advocate for reduced animal protein consumption, is crucial for both environmental sustainability and human health.

Reducing food loss and waste by half could further increase global food availability.[184] Most importantly, a combination of these measures is required to effectively reduce environmental impact.[125]

A thorough examination of how agriculture and other factors influence changes in PB statuses over time and across regions is still needed, especially regarding interactions between crossed boundaries. Currently, only broad global estimates are available.[106,186] Additionally, while Willett et al., 2019[183] have made preliminary identifications of PBs related to the food system, they addressed only five of them. More detailed assessments are underway to evaluate the impact of agriculture on all nine PBs and to outline pathways for sustainable and equitable transformations of the food system.[187]

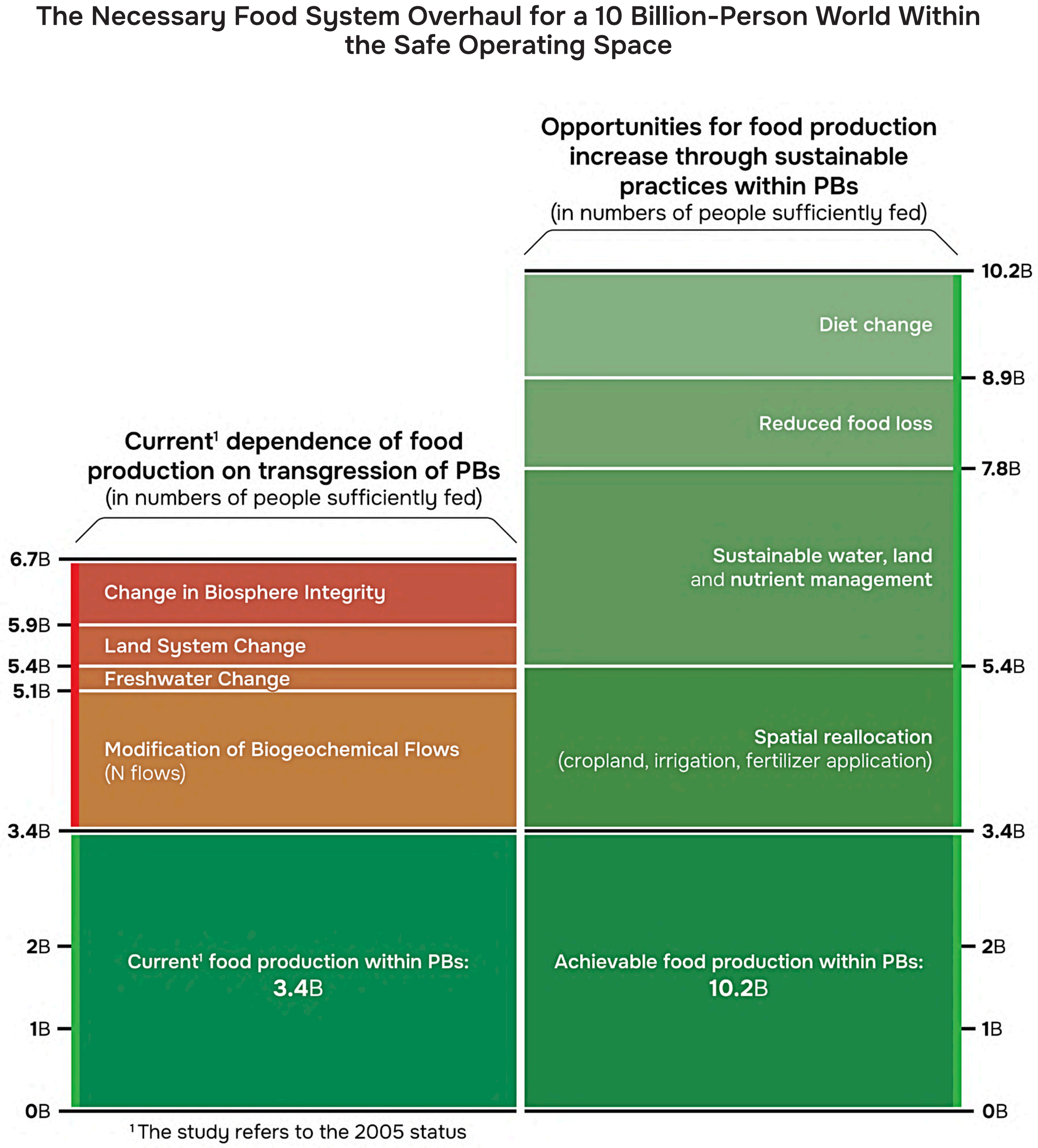


FIGURE 38 The Necessary Food System Overhaul for a 10 Billion-Person World Within the Safe Operating Space. This chart compares the number of people worldwide who can receive an average of 2,355 calories per day (including sufficient protein) under current farming practices (left side) versus with improved farming techniques, expanded farmland opportunities, and more sustainable consumption within safe levels (right side). Adapted from Gerten et al., 2020.[184]

9. **Solution Space: Towards Effective Earth System Stewardship**

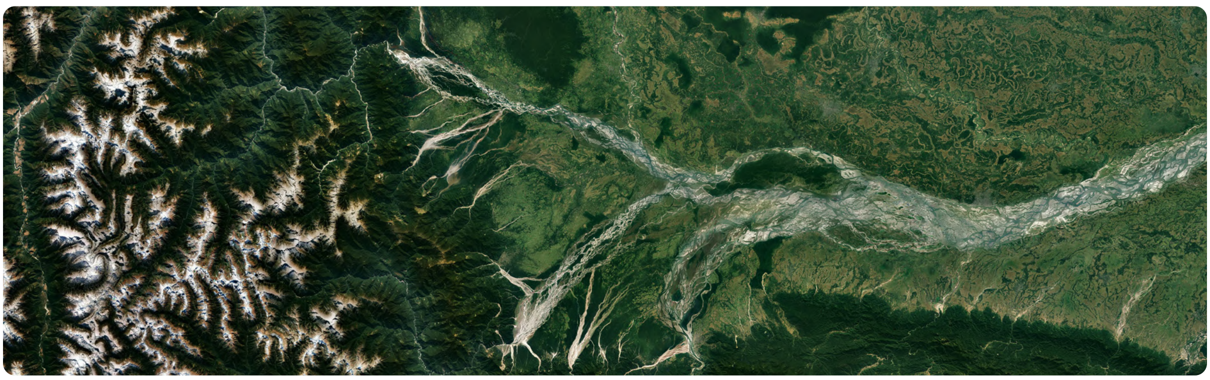
The latest science shows that transformations across all sectors of the global economy and all geographic regions are urgently needed in order to have a chance of a safe landing for humanity within Planetary Boundaries (PBs) — a prerequisite for a prosperous and equitable future for people. However, the world is not starting from scratch: efforts are already underway by a diverse range of actors, including scientific communities, non-governmental organizations, national and international institutions, and the business and finance sectors. As this report shows, these efforts are still far from sufficient. Nevertheless, many initiatives, organizations, and frameworks are demonstrating promising and scalable approaches to stewarding the Earth system within PBs. While the first *Planetary Health Check (PHC)* primarily focuses on diagnostics, this section will highlight an illustrative selection of these initiatives in the solution space.

For instance, the *Global Commons Stewardship Framework (GCSF)*[188,189], developed by the *Center for Global Commons, SYSTEMIQ,* the *Sustainable Development Solutions Network (SDSN)*, and the *Potsdam Institute for Climate Impact Research (PIK)*, offers a holistic approach to managing and protecting shared natural resources like the atmosphere, oceans, and polar regions. It emphasizes integrated management, international collaboration, and governance involving diverse stakeholders to achieve four core systems transformations: decarbonization of energy use, circular production and consumption, sustainable cities and communities, and a transformation of food, land, and ocean use.

The framework aligns with the UN Sustainable Development Goals (SDGs), focusing on equitable resource access and distribution, especially for marginalized groups. It advocates for using scientific research and technological innovations to support evidence-based decisions and encourages adaptive management practices to respond to changing conditions. Overall, it aims to ensure the sustainable and fair use of global commons for current and future generations. This framework is translated into action agendas for governments, businesses, finance sectors, civil society organizations, multi-stakeholder coalitions, and international organizations and financing institutions. The GCSF directly addresses the challenges posed by PBs through its emphasis on coordinated global action to safeguard critical Earth system functions.

The GCSF builds on and confirms previous assessments indicating that nothing less than global transformations are required. For example, the SDSN identified six major transformations needed to deliver the SDGs while staying within PBs.[190] The *Earth4All initiative* of the *Club of Rome* identifies five turnarounds necessary for an equitable future within PBs,[191] and the *Food Systems Economics Commission (FSEC)* shows that a global food systems transformation is required to meet both people and planet requirements.[192]

Several initiatives translating the PBs framework for business strategy and operations reflect a growing recognition of the importance of sustainable practices across sectors. Examples include the *Science-Based Targets initiative (SBTi)*,[193] the *Science-Based Targets Network (SBTN)*,[194] the *World Business Council for Sustainable Development (WBCSD)*,[195]



and the *Business for Nature* coalition.[196] To operationalize PBs for businesses, *SYSTEMIQ* and the *Planetary Guardians* are developing a "Planetary Risk and Opportunities" tool that will assess exposure to physical and transition risks related to PBs. This tool will help companies expand their climate strategies into comprehensive planetary risk and opportunity strategies, bridging the gap between existing business standards like SBTi and SBTN. Additionally, cost abatement curves for all PBs will be provided for various sectors to illustrate the costs and benefits of different interventions, aligning business and economic development with global sustainability.

The growing recognition of the role of the financial sector in the transition towards a more sustainable economy is represented by the *Task Force on Climate-related Financial Disclosures (TCFD)*,[197] now integrated into the *IFRS (International Financial Reporting Standard) S2 Climate-related Disclosures* issued by the *International Sustainability Standards Board (ISSB)*,[198] and the *Taskforce on Nature-related Financial Disclosures (TNFD)*.[199] These initiatives work on shifting capital markets towards practices that recognize and respect PBs, and guide investments to maintain our planet's natural systems.

Another avenue of action emphasizes the interconnectedness of a safe and stable planet with human health: The *Planetary Health Alliance*, a consortium of over 420 universities, non-governmental organizations, research institutes, and government entities from more than 70 countries, has recently released the first global *Roadmap and Action Plan for Planetary Health*.[200] It promotes a holistic approach involving interdisciplinary collaboration across health, environmental science, and social sciences to address complex global challenges. The roadmap focuses on areas such as climate change, biodiversity, and sustainable land and water use, aligning with the PBs framework's emphasis on maintaining ecological integrity and preventing environmental degradation. Both the roadmap and the PBs framework advocate for integrated policies that consider environmental sustainability and human health, emphasizing the importance of global and local governance. They prioritize education, awareness, and capacity building to enhance public understanding and the implementation of sustainable practices. Additionally, the roadmap supports developing metrics for monitoring environmental and health indicators and promotes innovative solutions to reduce environmental impacts and improve health outcomes, ensuring a sustainable future within our planet's ecological limits.

Taking PB science seriously implies major changes across all facets of societies worldwide, from individual behaviors and justice to business innovation and governance. While it is often suggested that for global societies to become “stewards of the entire planet” is too ambitious, if not utopian, we beg to differ. The global community has been making significant efforts to support global governance of various PBs. One example is the successful implementation of the *Montreal Protocol*, signed in 1987, which enabled humanity to avert the existential threat of depleting the stratospher-

The following existing conventions and frameworks play a significant role in safeguarding our planet by addressing key aspects of the PBs:

- The ***United Nations Framework Convention on Climate Change (UNFCCC, 1992)*** provides a framework for international climate action, with key agreements such as the Kyoto Protocol and Paris Agreement setting targets for emission reductions and global temperature limits.
- The ***United Nations Convention to Combat Desertification (UNCCD, 1994)*** focuses on combating desertification and land degradation in dry regions through sustainable land management.
- The ***Convention on Biological Diversity (CBD, 1992)*** aims to conserve biodiversity, promote sustainable use, and ensure fair benefit-sharing from genetic resources, with protocols on biosafety and access to genetic resources.
- The ***Ramsar Convention (1971)*** emphasizes the conservation and sustainable use of wetlands, which are crucial for biodiversity and ecosystem health.

ic ozone layer (one of the nine PB processes). Additionally, United Nations Conventions are in place that address several PBs related to climate change, nature degradation, and biodiversity loss, among others. These are generally legally binding global agreements, signed by a majority or all countries in the world (such as the *2015 Paris Agreement* on climate change). The challenge is not primarily the lack of global governance frameworks but rather the failure of nations to deliver on their promises.

The conventions listed in the call-out box were vital in drafting, negotiating, and adopting legally binding multilateral agreements like the *2015 Paris Agreement*, to which signatory countries are obligated to comply and can be held accountable for non-compliance. To date, states have adopted more than 1,450 multilateral environmental agreements (MEAs).[201] Even though not all MEAs are legally binding, they can still have significant impact by creating a shared understanding and commitment among states. A recent example is the *Kunming-Montreal Global Biodiversity Framework* (GBF), adopted in December 2022, which sets ambitious targets to halt and reverse biodiversity loss by 2030.

This includes the "30 by 30" goal, aiming to protect 30% of our planet's land and marine areas by 2030. These ambitious targets will guide countries in developing national biodiversity strategies and action plans. Notably, the science behind PBs played a significant role in formulating the GBF targets by providing a scientific basis and conceptual foundation for the "Nature Positive" concept[202] that is reflected in the GBF's ambitions.

Optimally leveraging existing institutions and mechanisms to improve the state of PB processes has been the focus of an effort by the *Yale Center for the Study of Globalization*. In a set of matrices, domains such as freshwater, biosphere integrity, and climate change were mapped to monitoring, governance, and incentive dimensions. The matrices provide a structured approach for addressing the main challenges in improving planetary health, including weak governance, inadequate global coordination, low political will, market distortions, and information asymmetry. This work clearly demonstrates that the institutions, governance mechanisms, and multilateral agreements already in place have the potential to advance humanity significantly towards operating within the Safe Operating Space of the PBs.

In order to design effective “planetary commons” governance, further research needs to focus on improved integration of diverse knowledge domains, including law, politics, science, and indigenous wisdom. For example, Rockström et al. (2024)[203] emphasized the need for improved governance frameworks for the planetary commons that account for PBs. By combining established international environmental law concepts (e.g., the precautionary principle and the no-harm principle) with novel principles emerging from the "Earth system law" paradigm (e.g., differentiated degrowth, interconnectivity, and ecological sustainability), a transition towards better governance of Earth's critical biophysical systems is possible. Another important research direction is the down-scaling of global PB processes and their boundaries to national,[204] regional,[124] and city levels,[205] making them accessible to policy development at all levels.

These examples demonstrate the rapidly growing recognition across sectors of the need to operate within PBs. Significant initiatives and movements from civil society (e.g., *Fridays for Future*), philanthropy (e.g., WEF's *Giving to Amplify Earth Action (GAEA)*), and NGOs (e.g., WWF's *One Planet Business Framework*) continue to emerge, addressing climate change and nature protection.

- ***Planetary Boundaries Science* (*PBScience*)** will provide up-to-date assessments of our planet's health and risks to humanity, as well as outlining pathways for translating science into action needed to navigate towards a safe, just, and sustainable future for all.
- The ***Planetary Health Check (PHC)*** will evolve into a first-of-its-kind tool that combines pioneering Earth and world data, science, technology, and multidisciplinary insights to inform equitable solutions for bringing our planet back to a safe operating zone. By bridging the gap between scientific understanding and action, PHCs will aim to transform environmental decision-making, offering governments, civil society, and businesses the data, insights, and pathways needed to safeguard humanity's future.

10. **Learn More**

If you are interested in learning more about our work, we recommend several online resources:

PBScience: Recently established to address key gaps in understanding and monitoring the Earth system, *PBScience* will provide annual *Planetary Health Checks (PHCs)* and advance the science behind the PBs framework to ensure state-of-the-art assessments. Its work includes enhancing Earth system modeling, integrating and analyzing Earth observation data, and refining the PBs framework itself. In collaboration with the *Planetary Guardians*, *PBScience* strives to elevate global awareness and drive action toward maintaining planetary stability.

Planetary Boundaries
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Online Version: Access the digital version of this report, including high-resolution figures, hyperlinked references, data sources, and supplementary material,* on our website hosted by Earth-HQ. The website also features interactive graphics and further reading on the current PHC and beyond. Scan the QR code or visit the link below to explore more.

www.planetaryhealthcheck.org

PBScience Outlook

As we look to the future, our commitment to advancing the *Planetary Health Check* remains steadfast. Our ultimate goal is to provide an annual report that offers in-depth information to decision-makers, the media, and the interested public about the health of our planet as well as pathways to return to safe levels of Planetary Boundaries (PBs).

To achieve this, we need to deepen our scientific understanding of PB processes, their drivers and interconnections, and integrate the latest Earth observation (EO) data and technological innovations into the framework. This includes incorporating additional control variables and data sources. We cannot do this alone; therefore, *PBScience* continuously seeks new partners in science, Earth observation, and modeling.

The work of PBScience has only just begun.

We believe that understanding the health of our planet is crucial for everyone, which is why this report is written in occasionally simplified language. For those interested in delving deeper into the scientific foundations and detailed analyses behind this report, we offer online* ***Supplementary Material* *with additional details on data sources and scientific methods.*

11. Outlook

Broader Vision: A Mission Control for the Planet

We stand at a pivotal moment in human history. Significant advancements in technology and Earth science, particularly in Earth observation, big data, and AI, have converged towards a groundbreaking possibility: measuring our entire planet's health and providing guidance on how to improve it.

Turning this knowledge into action requires a diverse range of actors beyond science, including technical support, policymakers, activists, communicators, and more. *PBScience* is therefore planning to establish a wider Planetary Boundaries Initiative (PBI) in collaboration with a growing network of partners.

The PBI ultimately aims to provide decision support that enables stakeholders at various levels to act according to the PBs framework and guide global development in the Anthropocene back into the Safe Operating Space. To achieve this ambitious goal, the PHC will serve as our central anchor to the stepwise development and introduction of our methods and products.

Next Steps:

1. We will continue to produce annual PHC reports that offer up-to-date knowledge on PB processes.
2. By introducing new control variables which focus on human-system interfaces and PB interactions, we aim to make the PBs framework more accessible for translation and enable the PHC to find the most effective levers of transformation.
3. The continued development of our Earth system simulation models that assess and project PB processes, combined with AI-powered analysis of causal data structures and literature, will enable the PBI to integrate the information needed to understand interactions within our Earth system and turn the PHC into the envisioned decision support tool.
4. In parallel, we are developing a near-real-time dashboard and interactive website for the PHC, which will provide time series and spatial maps of control variables at various resolutions and scales, as well as offer customized data analysis and explanations.
5. Successful decision support and implementation requires acceptance, public awareness, and a certain level of scientific understanding. The PBI's communications team will work closely with the *Planetary Guardians* and other external partners to make scientific insights and decision support widely comprehensible, ensuring this crucial knowledge reaches public, corporate and governmental audiences.

Humanity has left its Safe Operating Space and it is humanity's obligation to return to it again. The growing number of *PBScience* members and partners reflects this understanding of global urgency. Never has there been more support to build and maintain such an initiative.

Table 1: Latest Planetary Boundary (PB) Assessment in Numbers

This table lists the Earth system processes, descriptions of the control variables, the current values of those control variables (as of 2024 or the latest documented year), and their reference values (Holocene-like baseline or similar; see their respective **Information Sheets (6)** for the specific period used). The table also includes the value of the PB, indicated by a green circle in Fig. 2, which delineates the Safe Operating Space, as well as the high-risk threshold, marked by an orange circle in Fig. 2, 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 their respective Information Sheets. For comparison, we present the results of the latest PB assessment within the 2024 *Planetary Health Check (PHC)* alongside the most recent PB assessment from Richardson et al. (2023),[4] referred to here as "R23".

EARTH SYSTEM PROCESS	CONTROL VARIABLE	CURRENT VALUE OF CONTROL VARIABLE		REFERENCE VALUE*		PB VALUE		HIGH RISK VALUE	
Version		PHC	R23	PHC	R23	PHC	R23	PHC	R23
Climate Change	Atmospheric CO_2 concentration (ppm CO_2)	419 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)	+2.79 W/m^2	+2.79 W/m^2	0 W/m^2	0 W/m^2	+1 W/m^2	+1 W/m^2	+1.5 W/m^2	+1.5 W/m^2
Change in Biosphere Integrity (genetic/ functional)	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: Energy available to ecosystems (NPP) (% HANPP) as a percentage of pre-industrial NPP	30% HANPP	30% HANPP	1.9% 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%

Table 1 : Latest Planetary Boundary (PB) Assessment in Numbers (Cont.)

EARTH SYSTEM PROCESS	CONTROL VARIABLE	CURRENT VALUE OF CONTROL VARIABLE		REFERENCE VALUE*		PB VALUE		HIGH RISK VALUE	
Freshwater Change (blue/ green)	Blue water: human-induced disturbance of blue water flow.	18.20%	18.20%	9.4%	9.4%	10.20%	10.20%	50%	50%
	Green water: human-induced disturbance of water available to plants (% land area with deviations from preindustrial variability)	15.80%	15.80%	9.8%	9.8%	11.10%	11.10%	50%	50%
Modification of Biogeochemical Flows (P/N)	Phosphate (global): P flow from freshwater systems into the ocean; Phosphate (regional): P flow from fertilizers to erodible soils (Tg of P / year)	Global: 22.6 Tg/year Regional: 17.5 Tg/year	Global: 22.6 Tg/year Regional: 17.5 Tg/year	Global: 0 Tg/year Regional: 0 Tg/year	Global: 0 Tg/year Regional: 0 Tg/year	Global: 11 Tg/year Regional: 6.2 Tg/year	Global: 11 Tg/year Regional: 6.2 Tg/year	Global: 100 Tg/year Regional: 11.2 Tg/year	Global: 100 Tg/year Regional: 11.2 Tg/year
	Nitrogen global: industrial and intentional fixation of N (Tg of N / year)	190 Tg/year	190 Tg/year	0 Tg/year	0 Tg/year	62 Tg/year	62 Tg/year	82 Tg/year	82 Tg/year
Ocean Acidification	Global mean saturation state of aragonite in surface seawater (Ω)	2.80	2.81	3.44	3.44	2.75	2.75	2.41	2.41
Increase in Atmospheric Aerosol Loading	Interhemispheric difference in AOD	0.065	0.076	0.04	0.03	0.1	0.1	0.25	0.25
Stratospheric Ozone Depletion	Stratospheric O_3 concentration, (global average) (DU)	285.7	284.6	292	290	277	276	263	261
Introduction of Novel Entities	Percentage of synthetic chemicals released to the environment without 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 **Planetary Boundary Information Sheets (6) for the specific period.*

Table 2: Planetary Boundary Control Variable Information

This table lists the global control variables of the PB processes, their observation and modeling periods, as well as temporal resolutions. Control variables for which there are no direct and continuous observations as of today are marked in bold. Please find the detailed sources of data in the Supplementary Material for this report.

EARTH SYSTEM PROCESS	CONTROL VARIABLE	OBSERVATION METHOD	PERIOD COVERED	RESOLUTION
Climate Change	Atmospheric CO_2 concentration	Remote Sensing	Jan 1979 - April 2024	Monthly
	Total anthropogenic radiative forcing at top-of-atmosphere	Remote Sensing	Mar 2000 - April 2024	Monthly
Change in Biosphere Integrity	Genetic Diversity: (E/MSY)	Biological and Ecological Monitoring	~1500 - 2022	Centennial
	Functional integrity: HANPP	Data Integration and Modeling	1910 - 2010	Annual
Land System Change	Forest Area	Remote Sensing	1992 - 2022	Annual
Freshwater Change	Human induced disturbance of blue water flow.	Data Integration and Modeling	1691 - 2005	Annual
	Human induced disturbance of water available to plants	Data Integration and Modeling	1691 - 2005	Annual
Modification of Biogeochemical Flows	Phosphate flow from freshwater systems into the ocean	Data Integration and Modeling	1961 - 2013	Annual
	Industrial and intentional fixation of Nitrogen	Data Integration and Modeling	1961 - 2013	Annual
Ocean Acidification	Global mean saturation state of aragonite in surface seawater (Ω)	Data Integration and Modeling	1982 - 2022	Monthly
Increase in Aerosol Loading	Interhemispheric difference in AOD	Remote Sensing	2003 - 2023	Monthly
Stratospheric Ozone Depletion	Stratospheric O_3 concentration	Remote Sensing	1970 - 2022	Monthly
Introduction of Novel Entities	Percentage of synthetic chemicals released to the environment without adequate safety testing	Biological and Ecological Monitoring	2000 - 2017	Annual

In these cases, observed data and CV do not completely agree. For more detailed information, please refer to the individual **Planetary Boundary Information Sheets (6).*

Table 3: Planetary Boundary(PB) Processes and Their Tipping Points

Table 3 categories tipping systems within PB processes, based on the Global Tipping Points Report.[67] It lists tipping systems influenced by PB control variables or related drivers of transgression. Symbols representing these categories are placed alongside each PB, as determined by the report. The categorization reflects the direct connections between tipping systems and identified PB drivers (see also **Supplementary Material, Table 2**). While other potential connections exist, they currently lack evidence of direct association.

CLIMATE CHANGE	CHANGE IN BIOSPHERE INTEGRITY	FRESHWATER CHANGE
Kelp forests (die-off)	Lakes (DOM loading – 'browning')	Amazon rainforest (dieback)
Marine oxygenation (hypoxia)	Seagrass meadows (die-off)	Congo rainforest (die-back)
Southern Ocean Circulation (Antarctic Overturning Collapse/Rapid continental shelf warming)	Fisheries (collapse)	Atlantic Meriodional Overturning Circulation (shutdown/collapse)
North Atlantic Subpolar Gyre (SPG) (collapse)	Marine communities (regime shift)	Boreal forest (dieback)
Atlantic Meriodional Overturning Circulation (shutdown/collapse)	Kelp forests (die-off)	Savannas & Grasslands (degradation)
West African Monsoon (WAM) (collapse/ strengthening)	Mangroves (die-off)	North Atlantic Subpolar Gyre (SPG) collapse
Seagrass meadows (die-off)	Warm-water coral reefs (die-off)	Mangroves (die-off)
Fisheries (collapse)	Amazon rainforest (dieback)	Lakes (eutrophication-driven anoxia)
Marine communities (regime shift)	Congo rainforest (dieback)	Boreal forest (northern expansion)
Boreal forest (northern expansion)	Boreal forest (southern dieback)	Drylands (land degradation)
Warm-water coral reefs (die-off)	Savanna & Grasslands (degradation)	-
Mangroves (die-off)	Drylands (land degradation)	-
Congo forest (dieback)		-
Greenland Ice Sheet (collapse)	-	-
West Antarctic Ice Sheet (collapse)	-	-
Non-marine East Antarctic Ice Sheet (collapse)	-	-
Marine basins East Antarctica (collapse)	-	-
Glaciers (retreat)	-	-
Amazon rainforest (dieback)	-	-
Boreal forest (dieback)	-	-
Savannas & Grasslands (degradation)	-	-
Drylands (land degradation)	-	-

Table 3: Planetary Boundary Processes and their Tipping Points (Cont.)

Table 3 categories tipping systems within PB processes, based on the Global Tipping Points Report.[67] It lists tipping systems influenced by PB control variables or related drivers of transgression. Symbols representing these categories are placed alongside each PB, as determined by the report. The categorization reflects the direct connections between tipping systems and identified PB drivers (see also **Supplementary Material, Table 2**). While other potential connections exist, they currently lack evidence of direct association.

CLIMATE CHANGE (CONT.)	CHANGE IN BIOSPHERE INTEGRITY (CONT.)	FRESHWATER CHANGE (CONT.)
Lakes (eutrophication-driven anoxia)	-	-
Lakes (DOM loading – 'browning')	-	-
Land permafrost (thaw)	-	-

LAND-SYSTEM CHANGE	CHANGE IN BIOGEOCHEMICAL FLOWS	INTRODUCTION OF NOVEL ENTITIES
Amazon rainforest (dieback)	Lakes (eutrophication-driven anoxia)	Warm-water coral reefs (die-off)
Boreal forest (dieback)	Warm-water coral reefs (die-off)	Seagrass meadows (die-off)
Savannas & Grasslands (degradation)	Seagrass meadows (die-off)	Fisheries (collapse)
Drylands (land degradation)	Marine oxygenation (hypoxia)	-
West African Monsoon (WAM) (collapse/ strengthening)	Mangroves (die-off)	-
Mangroves (die-off)	Marine communities (regime shift)	-
Lakes (DOM loading 'browning')	Kelp forests (die off)	-
Land permafrost (thaw)	-	-

ATMOSPHERIC AERSOL LOADING	OCEAN ACIDIFICATION	STRATOSPHERIC OZONE DEPLETION
Greenland Ice sheet (collapse)	Warm-water coral reef (die-off)	-
Glaciers (retreat)	Marine oxygenation (hypoxia)	-
-	-	-

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