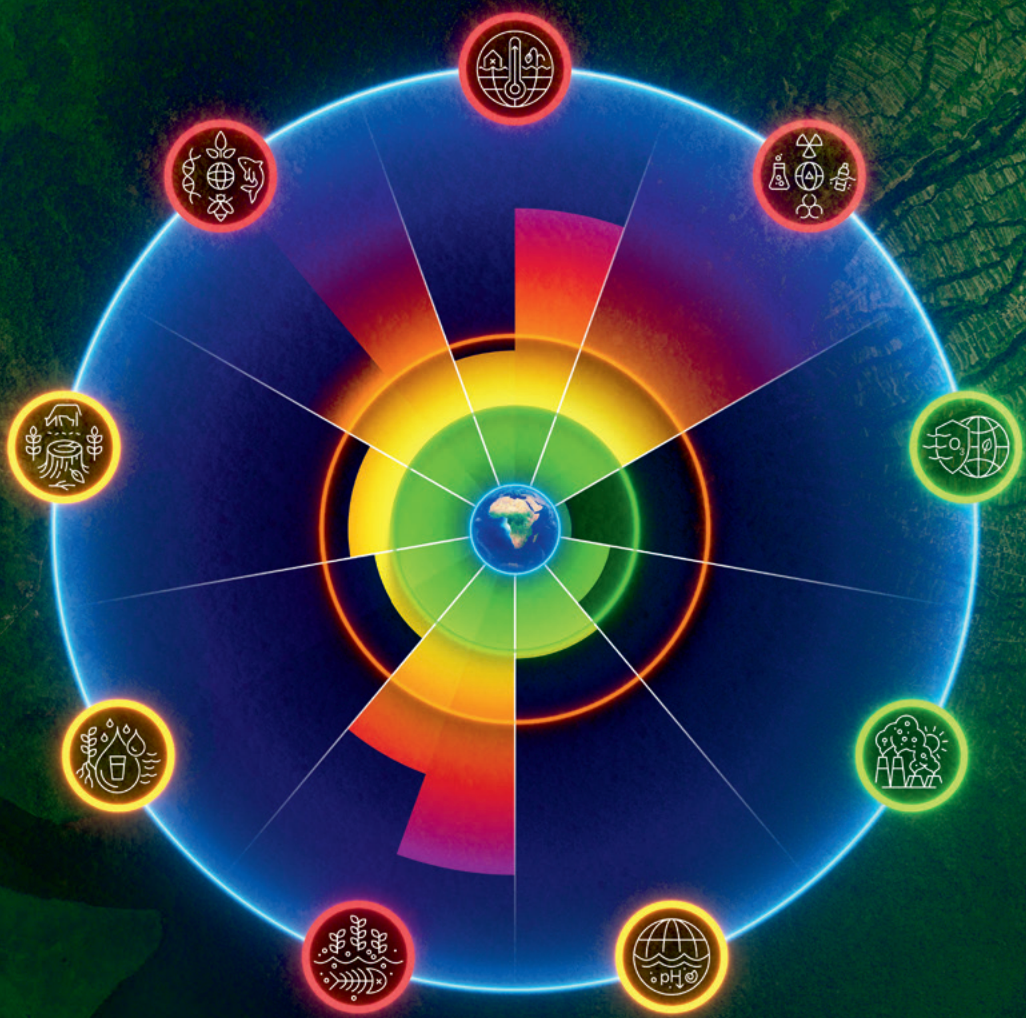
PLANETARY
HEALTH CHECK 2026

A Scientific Assessment of the State of Our Planet

SUMMARY



Planetary Boundaries
SCIENCE LAB

The Planetary Health Check reminds us that the future is not predetermined.

Photography by Mattias Klum

Foreword

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

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

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

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

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

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

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

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

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

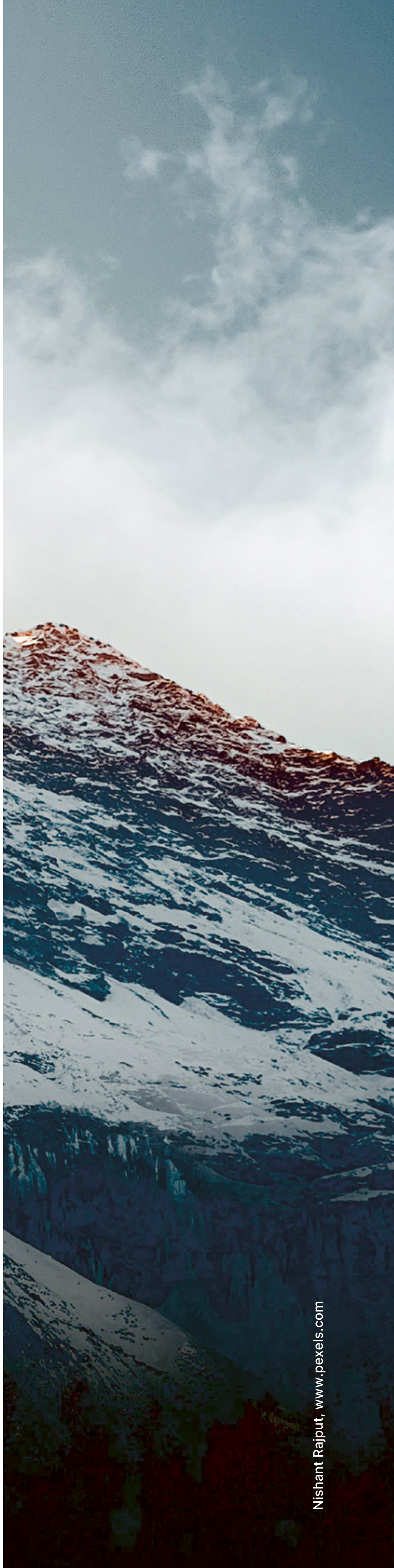
Carlos A. Nobre,
Planetary Guardian
Earth System Scientist;
Co-Chair, Science Panel for the Amazon
Full Professor for Climate and Sustainability, Institute of Advanced Studies of the University of São Paulo

About This Report

The annual Planetary Health Check presents the most up-to-date assessment of the state of the planet. This year, for the first time, we are publishing this report in two versions. You are currently reading the Summary Version, which presents the most important facts in a more condensed and accessible form. Here, you will find an introduction to our planet's health, overviews of each Planetary Boundary and its current state, as well as several "spotlights" exploring urgent Earth science topics. In this version, references to the scientific literature are largely omitted for brevity; the exceptions are the spotlight chapters, which are reproduced identically in both the Full and Summary versions.

For readers seeking a deeper dive into the science, we recommend exploring the full-length version of the Planetary Health Check, available at ↪ **planetaryhealthcheck.org**. There, we also provide additional information on tipping points, extreme weather events, Planetary Boundary interactions and many other topics, as well as extensive literature references.

● **FIGURE 1:** The dynamic Planetary Health Check symbol represents the summary of the Planetary Health Check's findings. The stylized boxplot (white lines and blue dot) describes the distribution of all Planetary Boundary Control Variables (see ● Fig. 3). It demonstrates that we have pushed Earth out of its Safe Operating Space, and are nearing the red high-risk line where irreversible damage to our planet becomes not only possible, but likely.



Nishant Rajput, www.pexels.com

5 Key Take-Aways

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

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

3. **We have to protect the seafloor.** The seafloor ecosystems play a significant role in the Earth system, yet we are destroying them at an alarming rate. Fishing techniques like bottom trawling produce long-lasting damage: Every year, 1–2% of the seafloor is trawled, with some of the most productive and diverse ocean regions being targeted most frequently. In addition, nascent seafloor mining activities are a looming threat to previously untouched regions of the deep ocean, with impacts on the Earth system that cannot yet be quantified. More effective mechanisms to protect these vital but under-explored ecosystems are urgently needed.

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

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

Glossary

Planetary Boundary / Boundaries (PB/PBs)	The science-based guardrails that show how far humanity can push the planet's natural systems while still keeping Earth stable, resilient, and able to support human wellbeing. The PB framework identifies nine major Earth system processes that help keep the planet in a relatively stable state. For each process, scientists define a boundary: a level of human pressure that should not be exceeded. Breaching these thresholds does not mean immediate disaster, but it does mean that the risk for serious harm increases.
Safe Operating Space	The precautionary zone for human activity in which pressures on the Earth system remain within Planetary Boundaries. Staying within this space ensures Earth remains stable and supportive of life, and reduces the risk of crossing harmful large-scale tipping points.
Zone of Increasing Risk	The space just beyond a Planetary Boundary, where human pressure on an Earth system process is no longer considered within safe limits. In this zone, risks to Earth system stability, resilience, and life-support functions grow as pressure increases.
High Risk Zone	When conditions worsen beyond the Zone of Increasing Risk, they enter the High Risk Zone. Here, the risk of severe, irreversible damage to key planetary functions becomes not just possible, but likely. In this zone, immediate action becomes critical to prevent locking in permanent changes.
Control Variable (CV)	The measures (or proxies) used to check whether an Earth system process is staying within its Safe Operating Space (Planetary Boundary). Usually, scientists track one or two control variables per boundary. For instance, atmospheric CO_2 concentration is a control variable for Climate Change.
Earth System	The set of interacting processes and components that determine how our planet functions. It includes the atmosphere, oceans, land, ice, ecosystems, and human activities, all of which influence one another in complex ways. From climate and ocean circulation to biodiversity and the use of natural resources, these connections shape the conditions that support life and determine Earth's future stability.
Tipping Point, Tipping Element	A tipping point is a threshold in the Earth system where small, gradual pressures can trigger large changes, which are often impossible to reverse, and which can come on quite suddenly. Once crossed, self-reinforcing feedbacks push the system further away from its previous state. For example, melting ice exposes less reflective ocean water, which absorbs more sunlight and accelerates melting, creating a self-reinforcing cycle. Parts of the Earth system that feature such a tipping point, such as the Amazon rainforest or the Greenland ice sheet, are called "tipping elements".
Resilience	The capacity to absorb pressures, shocks, or disturbances while continuing to function. In the Earth science context, this term is used to describe the ability of ecosystems, other parts of the Earth system, or the planet as a whole to cope with change and disturbance without losing their essential functions, structure, or ability to recover.
Feedback	A Feedback occurs when the effects of a change influence how that change develops. A positive feedback amplifies and reinforces the original change, while a negative feedback counteracts and weakens it. Here, the terms "positive" and "negative" describe the direction of the effect, not whether the outcome is judged to be good or bad. In the Earth system, feedbacks play an important role in either accelerating change or promoting stability.

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1 | Earth out of Balance

Photography by Mathias Klum

1.1 The Health of the Planet

For more than 10,000 years, human societies developed within an unusually stable chapter of Earth's history. During this so-called *Holocene* epoch, the planet was relatively warm, climate patterns were comparatively predictable, freshwater and nutrient cycles supported agriculture, and ecosystems provided the foundations for food, settlement, and human well-being. The Holocene was not a period without change, but it offered a stable enough environmental corridor for agriculture, cities, trade, and modern civilizations to emerge.

Humanity is now leaving that familiar corridor. Since the Industrial Revolution, and especially since the mid-20th century, human activity has expanded at a scale and speed unlike anything in earlier human history. Population, energy use, industrial production, fertilizer use, land conversion, water use, transport, and material consumption have risen sharply. At the same time, the planet has responded: Greenhouse gas concentrations have climbed, global temperatures have increased, biodiversity has declined, oceans have become more acidic, and pollution has spread through air, water, soils, and living organisms. Scientists often describe these linked trends as the Great Acceleration.[1]

The result is a new relationship between humanity and Earth. Human societies have become a planetary force, powerful enough to alter the conditions that made their own development possible. The term *Anthropocene* captures this shift: an era in which human actions are reshaping the atmosphere, oceans, land, freshwater systems, and biosphere at a global scale.

The health of the planet depends on three closely connected qualities:

- **Stability**, the ability to hold relatively constant conditions over long periods, such as a stable climate;
- **Resilience**, the ability to absorb shocks and recover from them, like a forest being able to recover from a wildfire;
- **Life-support functions**, the processes that keep the planet habitable, including climate regulation, freshwater cycling, fertile soils, nutrient flows, ocean chemistry, and functioning ecosystems.

Human pressures on the planet are now eroding all three. The further these pressures intensify, the greater the risk that Earth becomes less predictable, less resilient, and less able to support the societies built within the Holocene.

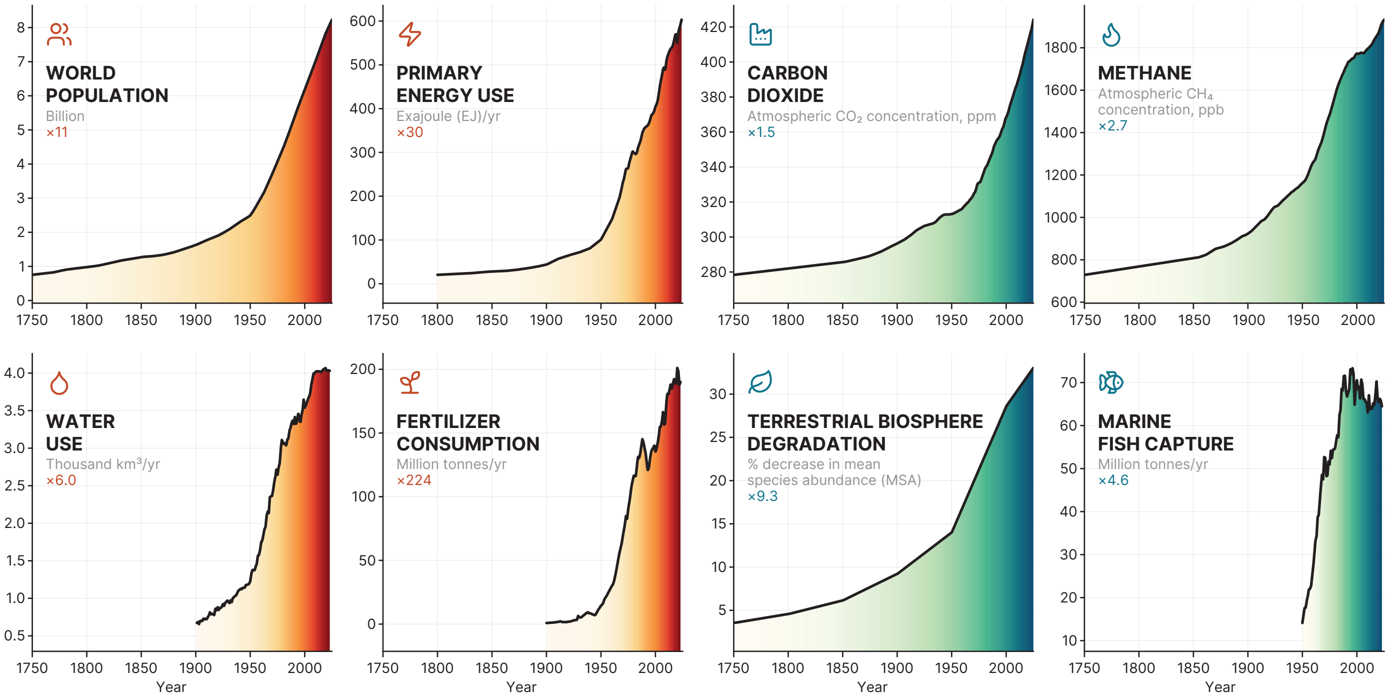


FIGURE 2: Examples of the Great Acceleration: Since around the 1950s, many measures relating to human societies have shown accelerated growth (left/orange). The world population has multiplied, with concurrent rises in the use of energy, freshwater, and fertilizers. As a consequence, human impacts on the natural world have rocketed upwards as well (right/teal): concentrations of greenhouse gases like carbon dioxide and methane in the atmosphere have increased markedly, and nature has declined significantly on land and in the ocean. For data sources and many further examples, see the full-length version of the PHC report.

1.2 Introduction to the Planetary Boundaries

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

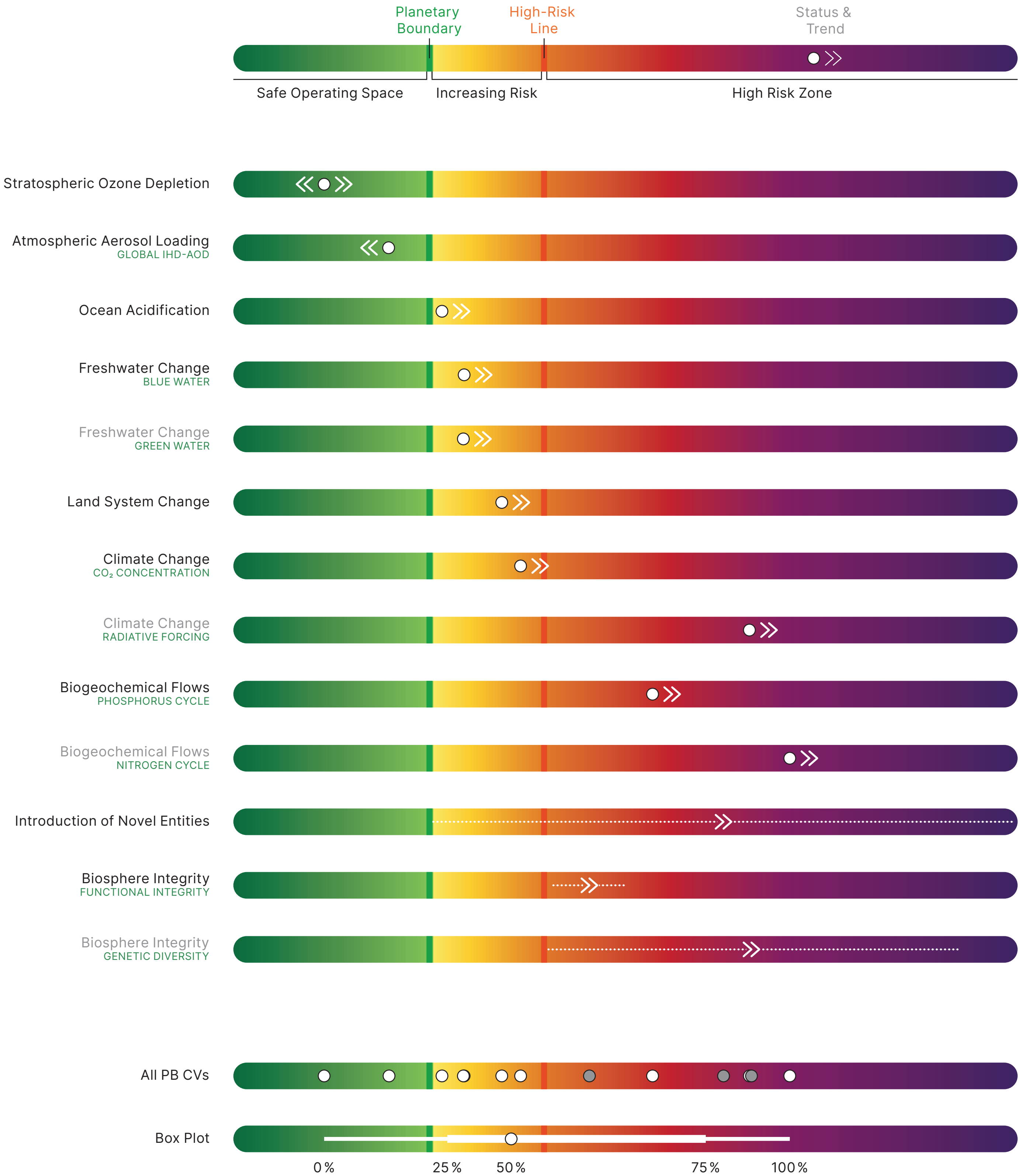
The **Planetary Boundaries framework**[2–4] brings these pressures together in one planet-level assessment. It identifies the nine critical systems and processes that are essential for planetary stability, resilience, and life-support functions. For each of them, scientists define a boundary that marks the edge of a Safe Operating Space. Staying within this space gives humanity a high chance of maintaining an Earth system similar to the one in which civilizations developed. Moving beyond a boundary means entering a zone of rising risk, where damage becomes more likely and potentially more severe and irreversible.

The nine Planetary Boundaries are:

- **Climate Change:** disruption of Earth's energy balance, mainly through greenhouse gas emissions and changes in radiative forcing.
- **Change in Biosphere Integrity:** loss of biodiversity and weakening of ecosystems' capacity to function.
- **Land System Change:** transformation of natural landscapes, especially through deforestation, land degradation, and urbanization.
- **Freshwater Change:** disruption of water flows through landscapes and ecosystems, including rivers, lakes, groundwater, and soil moisture.
- **Modification of Biogeochemical Flows:** disturbance of nutrient cycles, especially nitrogen and phosphorus.
- **Ocean Acidification:** chemical change of ocean waters as they absorb carbon dioxide, with consequences for marine life and climate regulation.
- **Increase in Atmospheric Aerosol Loading:** changes in airborne particles that influence climate, rainfall patterns, and human health.
- **Stratospheric Ozone Depletion:** thinning of the protective ozone layer, which increases harmful ultraviolet radiation at Earth's surface.
- **Introduction of Novel Entities:** release and accumulation of human-made and human-mobilized substances such as plastics, synthetic chemicals, pesticides, and other pollutants.

Planetary Boundaries are set through a broad scientific assessment. Evidence comes from observations of Holocene variability, Earth system models, resilience analysis, global assessments such as those of the Intergovernmental Panel on Climate Change (IPCC) and of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), expert evaluation of feedback mechanisms, and research on risks of crossing tipping points. The framework uses a precautionary logic: Boundaries are set at the lower end of the range in which serious risks are expected to emerge. Crossing a boundary does not necessarily mean immediate catastrophe, but it significantly increases the risk of lasting damage to Earth as a whole.

The current assessment shows that **seven of the nine Planetary Boundaries have been transgressed**. **Climate Change, Change in Biosphere Integrity, Land System Change, Freshwater Change, Modification of Biogeochemical Flows, Ocean Acidification,** and **Introduction of Novel Entities** are outside the Safe Operating Space. While Atmospheric Aerosol Loading and Stratospheric Ozone Depletion remain within their Planetary Boundaries at the global level, Aerosol Loading may have reached unsafe levels in some regions. Both boundaries still require careful monitoring.



● FIGURE 3: SEVEN OUT OF NINE PLANETARY BOUNDARIES ARE TRANSGRESSED. The Planetary Boundary assessments use representative variables, called “control variables”, to describe the state of the nine processes key to regulating the stability, resilience, and life-support functions of the Earth system. To date, the Planetary Boundaries framework uses 1–2 control variables per boundary. The colors (green for “within the Safe Operating Space”, yellow for “Zone of Increasing Risk”, and red for “High Risk Zone”) refer to the state of boundary transgression.

On the lower colorbar, a boxplot summarizes the distribution of all 13 control variable values at once. The boxplot is the dynamic core of the Planetary Health Check symbol **(see ● Fig. 1)** and denotes the distribution of all current values of PB control variables. The thin line represents the full range of all control variable values, while the thicker line represents the range that half of all control variable values fall into. The blue dot represents the median of all control variables. The PB assessments are based on the most up-to-date data available; in some cases, this means that they are based on datasets older than 2026. For detailed descriptions of the data used, see the full version of the PHC report.

1.3 Today's Impacts and Tomorrow's Risks

The consequences of breaching the Planetary Boundaries are already changing our planet. Rising temperatures, biodiversity decline, degraded land, over-fertilization, freshwater stress, ocean acidification, and the spread of persistent pollutants are visible in many parts of the Earth system. These pressures are causing damage to ecosystems, reduced harvest security, strained water supplies, declining natural buffers, growing health risks, and increasing pressure on communities and infrastructure.

Recent extreme weather events brought these interconnected risks into sharp relief. Pakistan's 2025 monsoon floods killed 1,037 people and damaged or destroyed more than 229,000 homes, affecting 7 million people, while Cyclones Senyar and Ditwah caused more than 1,109 and 1,800 deaths in Indonesia and Sri Lanka.[5] Hurricane Melissa struck Jamaica as a Category 5 storm after intensifying over exceptionally warm seas.[6] These are just a few examples from a single year. Most recently in June 2026, Western Europe experienced its most severe heatwave on record.[7] Attribution studies show that human-caused warming intensified several of these hazards, while degraded catchments, settlement in floodplains, water stress, inadequate infrastructure, and social vulnerability magnified their impacts.[8] At the same time, ocean heat content reached another record in 2025,[9] and the largest global coral-bleaching event on record exposed 84.4% of the world's reef area to bleaching-level heat stress.[10] These were not isolated disasters, but expressions of how transgressions of the climate, biosphere, freshwater, and land-system boundaries increasingly interact to produce cascading ecological, economic, and human losses.

The pace of change is adding another layer of risk. Climate change presents an especially stark example of this: Recent research finds that global warming has accelerated significantly since around 2015.[11] During 2016–2025, global temperature increased at an observed rate of about 0.30°C per decade – nearly 60% faster than the average rate of 0.19°C per decade over 1980–2020.[12] Earth's energy imbalance has more than doubled since 1976–1995, and the number of marine-heatwave days has more than tripled since 1991. Accelerated warming moves the planet more quickly away from Holocene-like conditions: It increases the urgency for reversing

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

Photography by NASA

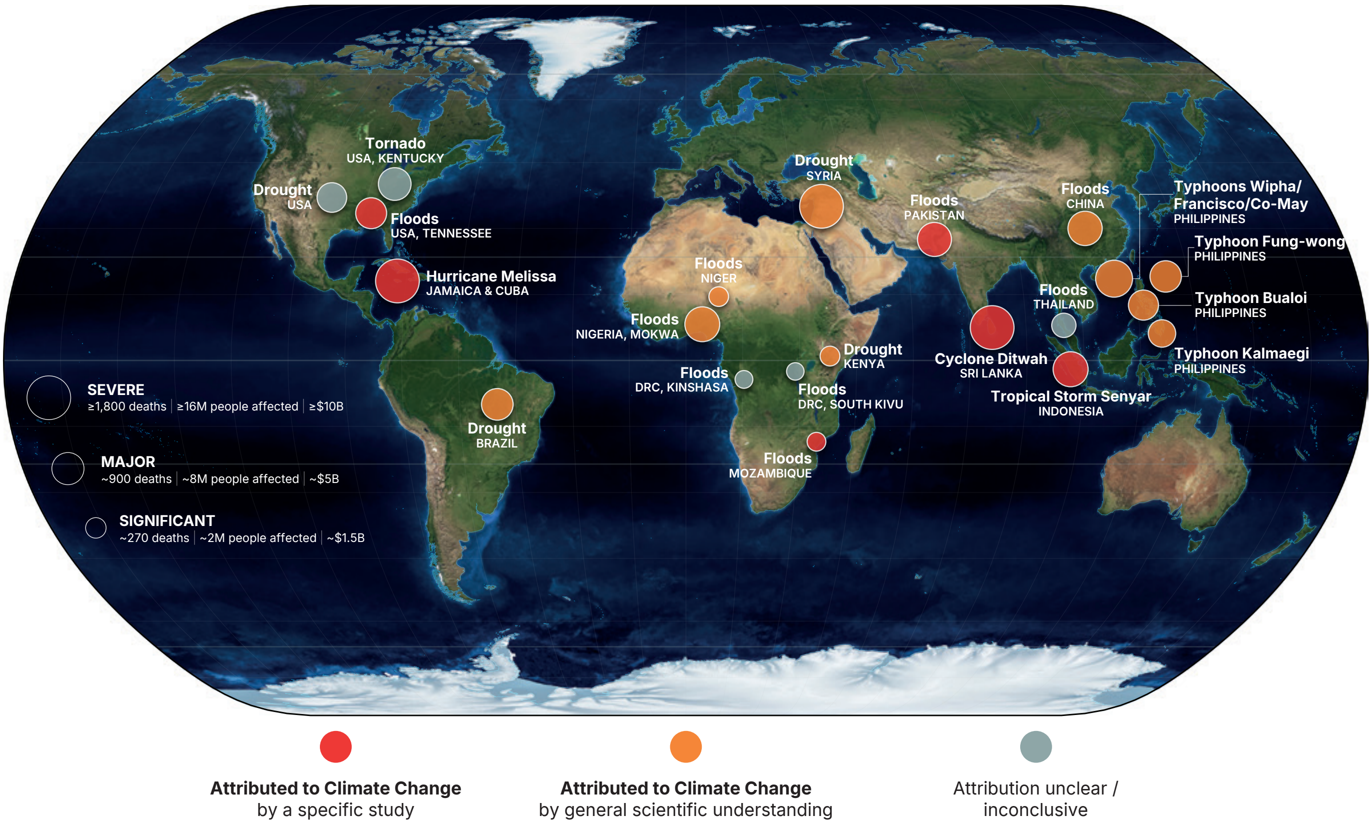


FIGURE 4: Map of the most impactful extreme weather events between April 2025 and April 2026. Most can be attributed to Climate Change, either through direct studies (red) or because the wider scientific evidence indicates that climate change likely increased the risk or intensity ("causal field"; orange).

course towards a safe landing after overshooting temperature targets, narrows the time available for humans and nature to adapt, and exacerbates the likelihood of record-breaking extremes and cascading impacts.

Future risks become especially severe if gradual pressure triggers abrupt change. Tipping points are thresholds beyond which self-reinforcing feedbacks take over, shifting parts of the planet into a new state.[10] Examples include ice sheet melting in Greenland and Antarctica, tropical forest collapse in the Amazon, thawing of permafrost regions, and the shutdown of major ocean circulations such as the Atlantic Meridional Overturning Circulation (AMOC). Recent studies indicate that some of these thresholds may be closer than previously assumed. If Amazon deforestation rises from the roughly 17–18% already lost to 22–28%, interactions between forest loss, drying, and global warming could expose around two-thirds of the remaining forest to degradation at only 1.5–1.9°C of warming.[13] Extended climate-model simulations also reveal a credible risk of deep North Atlantic overturning shutting down after 2100, even under some intermediate- and low-emission pathways.[14] Meanwhile, Antarctic basin modeling identifies a first threshold potentially as low as 1–2°C that could lead to the long-term loss of around 40% of West Antarctica's marine ice volume.[15] Meanwhile, warm-water coral reefs are already passing their thermal tipping point, with widespread dieback underway following the unprecedented global bleaching event of 2025.[10]

The warning signs are no longer abstract, and the risks ahead are no longer remote.

Together, these findings show that 1.5°C should not be understood as a safe destination, but as an upper guardrail that should not be reached. Even if this threshold is temporarily exceeded, we must return to lower warming as quickly as possible.

The warning signs are no longer abstract, and the risks ahead are no longer remote. The further we transgress the Planetary Boundaries beyond the Safe Operating Space, the harder it becomes to preserve a stable and resilient planet, and avoid dangerous and hard-to-reverse change. Returning to, and remaining within, the Safe Operating Space is essential for limiting future risks and safeguarding a stable and livable planet.

2 | Spotlights

Photography by Mattias Klum

2.1 Earth Resilience: When Land Stops Buffering Climate Change

Article by:
Boris Sakschewski and Jonathan Donges, Potsdam Institute for Climate Impact Research

Earth resilience describes the capacity of the Earth system to absorb disturbances while maintaining stable, habitable conditions for human societies and the wider living world.[4,16] A great example is that the Earth system has shown a remarkable capacity to redistribute CO_2 from the atmosphere into the land and oceans. So far, **about half of the emissions humans have added to the atmosphere since the industrial revolution have been absorbed by land and ocean carbon sinks, vastly reducing the warming that would otherwise have occurred.**[17,18] In other words, the climate change we see today would be significantly stronger without those carbon sinks. The CO_2 buffering of the Earth system is described in the global carbon budget as a balance between anthropogenic CO_2 sources, atmospheric accumulation, and uptake by land and ocean sinks **(see ● Fig. 5)**. But this buffering capacity is not guaranteed. It depends on the balance between processes that add carbon to these sinks, and processes that remove carbon from them. Today, the global land sink appears to be weakening, and it is important to better understand why.[19,20]

What makes land a carbon sink?

A useful way to understand the land sink is as a balance between gains and losses. In carbon budget terms, land carbon uptake, excluding direct land-use change, has generally exceeded land-use change emissions, so the combined land balance has remained a net carbon sink globally.[17] However, recent carbon-budget assessments indicate that land carbon uptake excluding direct land-use change has been relatively stagnant since around 2000.[17,21] This suggests that, while the land biosphere is still buffering climate change, it does so less reliably than before.

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

On the gain side, several processes strengthen the land carbon sink by increasing carbon uptake and storage. This includes the fertilizing effect of higher CO_2 levels on plants, forest regrowth in some regions, longer growing seasons in some climates, changes in land management, and carbon accumulation in vegetation and soils.[21–23] But none of these gains are unlimited. They depend on water availability, nutrient supply, suitable temperatures, healthy soils, ecological recovery and connectivity, and time (see also Info Sheets on Climate Change, Biosphere Integrity, Land System Change, and Freshwater Change).[24–28] Forests and soils cannot accumulate carbon indefinitely: growth slows as forests mature, while carbon continues to be lost through natural turnover.[22,29,30]

On the loss side, many factors weaken the land carbon sink by directly or indirectly increasing the amount of carbon released into the atmosphere. Climate change is one of the leading reasons: Warming can reduce plant productivity, increase ecosystem respiration, intensify drought stress, and amplify disturbances such as fire, disease outbreaks and mortality.[19,20,26–28,31–35] In other words, the same land biosphere that has buffered Climate Change is increasingly being stressed by it.

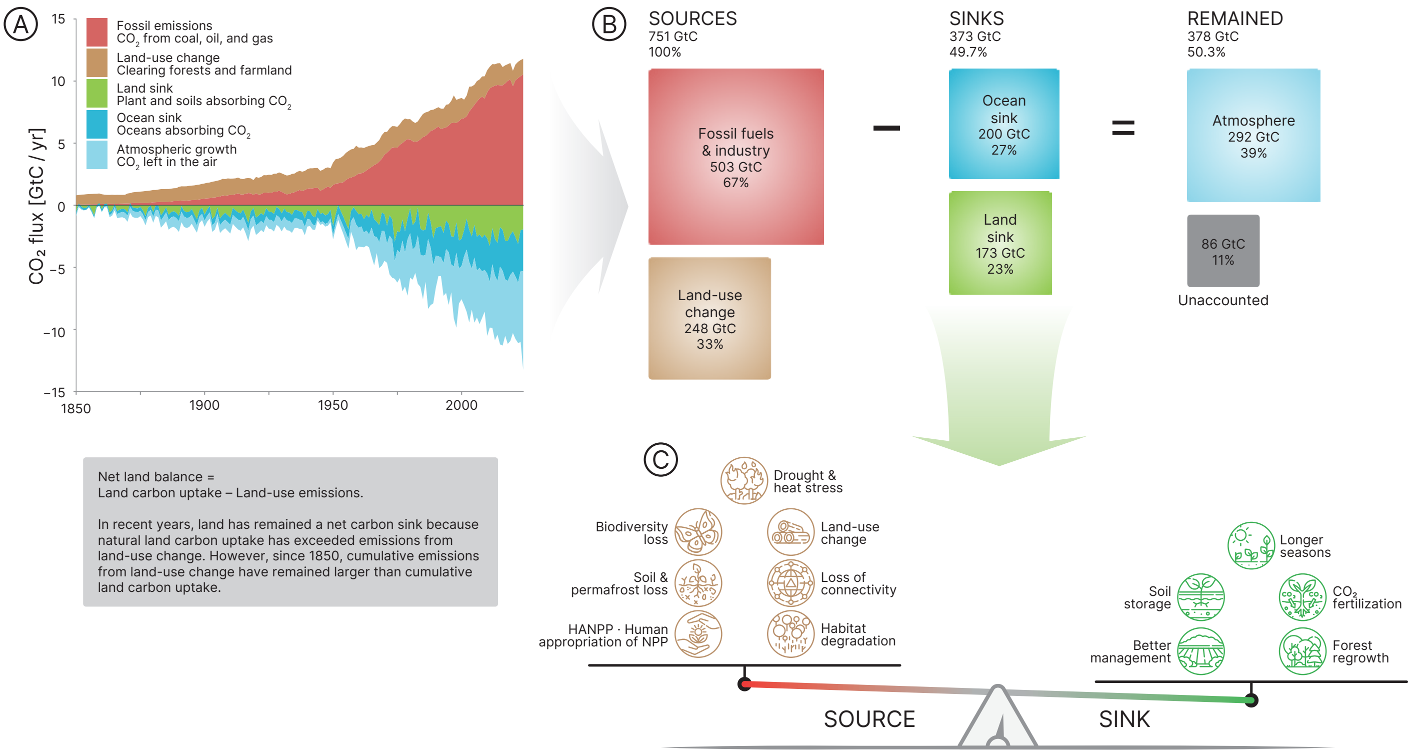
Declining ecological integrity and functioning also play a considerable part in reducing the land carbon sink. The current land sink is carried disproportionately by the few remaining relatively intact and recovering ecosystems **(see ● Fig. 6)**.[17,22] Meanwhile, human societies appropriate a large share of global plant productivity for their own purposes, leaving less energy available for natural ecosystems. Today, humans use roughly one quarter of potential plant productivity on land.[36,37] Alongside and beyond this redistribution of energy, ecosystems are losing area, quality, and biodiversity, as well as connectivity. Habitats are being converted, fragmented, degraded, polluted, simplified, and disrupted by infrastructure, resource extraction, and other forms of interference.[3,4,38–41]

Hence, the continued existence of the global net land carbon sink should not be mistaken for a healthy and resilient biosphere. So far, carbon gains are still outweighing carbon losses in the global balance, but only by a limited margin. These gains can mask ecosystem degradation and make the land system appear more stable than it really is. The central concern is not only that the land carbon sink could weaken; it is that the living systems that make the sink possible are being undermined at the same time, gradually losing their ability to store additional carbon or hold the carbon they already store.

The complexity of the system shows that the land sink is not simply the sum of independent gains and losses. Many of the processes involved are interconnected through feedbacks, linking Climate Change, Change in Biosphere Integrity, Land System Change, Freshwater Change, and the Modification of Biogeochemical Flows.[3,4,39,42] Some feedbacks help stabilize the system, while others amplify ongoing change. Earth resilience therefore depends not only on the current balance, but also on which feedbacks become stronger over time. As losses increase and carbon is released, these feedbacks become particularly important, because they can further reinforce the very processes that weaken the sink.

Historically, several land processes have acted as **stabilizing, or negative, feedbacks**. CO_2 fertilization is the clearest example: Higher atmospheric CO_2 can enhance photosynthesis and water-use efficiency, increasing carbon uptake and partially offsetting emissions.[21,23] This has helped slow the rate of atmospheric CO_2 accumulation and warming. Yet stabilizing feedbacks have limits. In the case of CO_2 fertilization, nutrient constraints, water stress, heat stress, ecosystem degradation, and saturation effects can reduce its effectiveness.[24–28,30,33,34,43] Importantly, a weakening negative feedback already means more warming than expected, even if it never fully disappears: The land system does not need to become a net carbon source for resilience to decline.

There is also a hidden vulnerability in this buffering effect. Additional carbon stored through past CO_2 fertilization has increased biomass and soil carbon stocks in many regions. This can be viewed as a kind



● **FIGURE 5: THE GLOBAL CARBON BUDGET AND THE FRAGILE LAND SINK.** Panel A shows annual anthropogenic CO_2 emissions and their partitioning between atmospheric growth, ocean uptake and land uptake, based on the Global Carbon Budget 2025.[17] Positive values indicate emissions from fossil fuels and land-use change, while negative values show the fraction of emissions taken up by land and ocean sinks. Panel B translates this accounting into a simplified balance: Anthropogenic sources are partly offset by ocean uptake and land uptake excluding direct land-use change, with the remainder accumulating in the atmosphere; the budget imbalance is shown as a residual accounting term, not as a physical sink. Panel C zooms into the green land-sink term. This inset is conceptual and not to scale. It shows that land uptake excluding direct land-use change is not one process, but the residual of competing gains, limits, and losses. Gains such as CO_2 fertilization, longer growing seasons, forest regrowth, improved management, and soil carbon storage strengthen uptake. At the same time, drought and heat stress, soil and permafrost carbon loss, biodiversity loss, habitat degradation, loss of connectivity, and human appropriation of plant productivity weaken sink capacity and recovery. The key message is that the land sink is still tilted toward uptake, but only slightly: The global carbon buffer depends on ecological processes that are increasingly under stress.

of ecological credit: carbon that has been kept out of the atmosphere for now. But larger carbon stocks also create more carbon that can potentially be released later through drought, fire, pests, mortality, or land-use disturbance. In that sense, successful buffering today can increase what is at risk tomorrow.[29,30,33–35]

Other feedbacks work in the opposite direction. Climate extremes provide a clear example of **change-amplifying, or positive, feedback**. Heatwaves and droughts reduce productivity directly, but they also increase mortality risk, fire weather, pest outbreaks, and recovery times.[26–28,31–33,35] These impacts can release carbon to the atmosphere, contributing to further warming and increasing the likelihood of future extremes. Mortality and repeated disturbance reduce biomass and can shift ecosystems toward lower-carbon states with weaker recovery potential.[33,34] Such feedbacks are not necessarily runaway processes. They may eventually be constrained by ecological limits or by the amount of carbon available to lose. Nevertheless, extreme events will become even more intense and frequent under future climate change,[18,44] and they can cumulatively worsen the situation and push Earth towards less habitable states.

Feedbacks are also the precondition for known or suspected tipping elements: critical, large-scale components of the Earth system characterized by threshold behavior. The global land carbon sink as a whole may not show tipping behavior, but it is certainly linked to tipping elements, including tropical forests, boreal forests, and permafrost regions.[45–47] Weakening land sinks can therefore increase the risk of crossing tipping points elsewhere, while tipping-like change can in turn further reduce land carbon storage.[47,48]

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

Why our models are probably too optimistic

Current Earth system models have improved substantially and represent exceptional scientific achievements in our understanding of the Earth system. However, they still simplify many of the processes that determine land carbon resilience.[49,50] One important example is the representation of natural vegetation, because vegetation currently plays a major role in the global net land carbon sink.

Many models rely on a small number of average representative plant types rather than the diverse, locally adapted plant communities found in the real world.[51] In practice, this often means simplified tree morphology, forest structure, and "big leaves" operating on grid cells that can span tens to hundreds of kilometers.[49–51] A whole biome may be represented by an average plant with broadly constant traits over space and time. These simplifications can still reproduce reasonable large-scale biome patterns, but they smooth away exactly the real-world ecological constraints that matter for resilience: local adaptation, limits to how species can spread and regenerate, age structure, pests, cumulative damage, and mortality.[31,35,49–53]

This makes many modeled ecosystems behave like fertilized, teleporting, generalist biomass blobs. Modeled vegetation can creep into suitable climate space, respond smoothly to elevated CO_2, and recover after disturbance more easily than real ecosystems. Real species depend on seed sources, establishment conditions, landscape connectivity, soils, other species, and the ability of ecological communities to recover.[28,31,33,35,51–53] Real forests also do not fail as one collective biomass. Trees die as individuals, through interacting water, carbon and defense failures, including failure of water transport within trees, carbon starvation, impaired defense against insects and pathogens, heat stress, fire, and repeated drought. These mortality spirals are much harder to represent than gradual changes in average productivity.[31,33,35]

Such simplifications become especially problematic under extreme events. Observations show that droughts and heatwaves can have strong and persistent effects on productivity, mortality, and recovery.[26–28] Yet model evaluations repeatedly point to difficulties in reproducing the magnitude, duration and legacy effects of such events.[49,50] Climate models can capture broad changes in many extremes, especially heat, but droughts, storms, and circulation-driven compound events are harder to capture. If the physical event is underestimated, or if the modeled ecosystem response is too resilient, carbon losses and recovery times will be underestimated. The greatest risk arises when both biases occur together: underestimated extremes acting on overly resilient ecosystem models.[18,44]

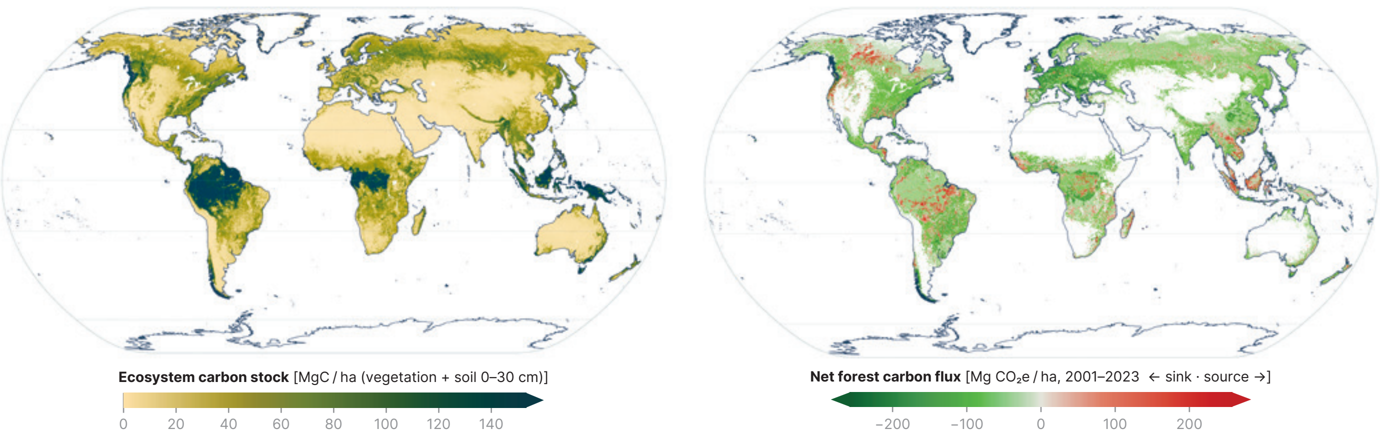


FIGURE 6: SPATIAL PATTERNS OF FOREST CARBON STOCKS AND NET FOREST CARBON FLUXES. The left-hand map shows ecosystem carbon stocks in vegetation and upper soil layers, highlighting regions where large carbon stores are concentrated and where degradation or disturbance could turn existing carbon assets into future liabilities. The right-hand map shows net forest carbon fluxes from the Global Forest Watch / Harris et al. forest carbon flux product.59 It represents the balance between forest carbon removals from growth and regrowth and forest carbon emissions from deforestation and stand-replacing disturbances. This is not a complete map of the global terrestrial land carbon sink: Full land carbon fluxes could look different when non-forest ecosystems, soils, peatlands, permafrost, lateral fluxes, and ecosystem respiration are included. Nevertheless, it gives a sharp and intuitive picture of where living forests are currently acting as carbon sinks or sources, illustrating that the forest component of the land sink is spatially uneven and linked to land use, ecosystem integrity, disturbance, and climate stress.

Some missing processes might also make models underestimate resilience. Vegetation diversity, local adaptation, acclimation, selective survival, and succession can buffer ecosystems in some contexts.[54] But these processes are not free-floating safety mechanisms. They are slow, uneven, and constrained by dispersal, seed supply, soils, mutualists, competition, disturbance history, and fragmentation.[28,33,35,41,51–53] Local adaptation is especially ambiguous: It can increase fitness under familiar conditions, but also make real populations vulnerable when climates, soils, seasonal rhythms, and biotic interactions shift beyond past experience. If models currently reproduce broad biomass and productivity patterns without representing these details, this does not mean the details are unimportant. It may simply mean that today's large patterns can be approximated without the ecological processes that will determine future sensitivity.

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

Implications for Earth resilience

The limitations and potential over-optimism of current land-carbon modeling matter, because many mitigation scenarios and remaining carbon budget estimates rely on land carbon sinks remaining functional throughout the transition to net-zero emissions.[18,49] If this assumption proves too optimistic, the effective remaining carbon budget would be smaller than expected, warming during the transition could be higher, tipping risks would increase, and reliance on future carbon dioxide removal would grow despite uncertainties about feasibility, permanence, land competition, and biosphere integrity.[18,34,47,48,55,56]

Within the Planetary Boundaries framework, this highlights the tight coupling between Climate Change, Change in Biosphere Integrity, Land System Change, Freshwater Change, and Modification of Biogeochemical Flows.[3,4] Human appropriation of net primary production, land degradation, soil disturbance, biodiversity loss, and disrupted vegetation–water interactions directly undermine land carbon storage.[36–40,42,57] Healthy ecosystems store carbon while regulating soil moisture, the release of water from plants and soils, cooling, and moisture recycling. Protecting and restoring them is therefore not only a matter of conservation, but part of maintaining Earth-system stability.[56]

In summary, Earth resilience cannot be assessed by climate forcing alone. It also emerges from the integrity of living systems that regulate carbon, water, and energy flows. Maintaining a stable climate trajectory requires safeguarding these systems and acknowledging the limits of current models in representing their response to rapid and compounding change.[47,58]

2.2 Seafloor Integrity: Why the Bottom of the Ocean Matters

Guest article by:
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"I believe there is not a portion of the ground but what the trawl destroys. I have dragged 50 miles off Aberdeen. I have got fast there and brought up coral about 2.5ft in circumference, lumps of soft coral, and I am prepared to say that whatever is in the way of the trawler will not escape." The statement of a Scottish fisherman, which was part of an article entitled "Bottom trawling: how to empty the seas in just 150 years" (The Guardian, 10 February 2014),[60] dramatically illustrates how anthropogenic pressures can modify the seafloor to a degree that it threatens its integrity.[1] Because when we disturb the seafloor, we do not just scrape mud. We damage habitats, alter nutrient cycling, and in some places may even weaken one of the ocean's long-term carbon stores.

The hidden foundation of the ocean

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

In many cases, once disturbed, seafloor systems may not recover on human timescales.

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

Protecting this crucial and underexplored part of the Earth system is urgent. In many cases, once disturbed, seafloor systems may not recover on human timescales. At the same time, scientific understanding and governance frameworks are struggling to keep pace with the growing demand for marine resources.[61]

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

The stabilizing effect of the seafloor for the Earth System

The seafloor as habitat: Benthic ecosystems

The seafloor is not empty. In many places it is living architecture composed of biogenic reefs, sponge grounds, kelp, shell habitats, burrowing communities, and microbial systems. These benthic ecosystems – communities of organisms living on or within the seabed – build food webs, recycle nutrients, and regulate how carbon is stored at the seafloor. Many benthic habitats are threatened by increasing human use of the seafloor. Today, bottom trawling physically disturbs around 1–2% of the global seafloor each year – an area about half the size of Europe. Although much of this disturbance repeatedly affects the same fishing grounds, it is concentrated on continental shelves, which cover only a small fraction of the global ocean but support much of its biological productivity, fisheries, nutrient cycling, and long-term carbon burial.[62] In the future, mining for deep-sea mineral resources could add substantial new areas of disturbance with more than 200 km^2 per polymetallic nodule mining operation.[63] The direct effects on the seafloor may be best understood by comparison to terrestrial deforestation: In places that are trawled frequently, structurally complex benthic landscapes that were once rich in biodiversity are turned into “marine deserts” of sand or mud.[64]

What is lost is not only biodiversity, but a whole ecological machinery: Burrowing animals, microbes, and sediment chemistry together regulate how nitrogen, phosphorus, and carbon move between sediments and the overlying water. When these exchanges are disrupted, the consequences can cascade to marine ecosystems and food webs.[65] Many shelf and coastal seas have already experienced the loss of their “marine forest”, reducing habitat complexity, nursery areas for commercially important fish, biodiversity, sediment stabilization, and nutrient cycling, and leaving these ecosystems less resilient to future disturbances. By contrast, the deep sea has until recently remained largely beyond direct human disturbance. Experimental studies show that even limited disturbances here can suppress ecosystem functioning for decades[66] or even lead to their permanent loss.[67]

The seafloor as carbon store

Marine sediments form one of the largest active carbon reservoirs in the Earth system, with continental shelf sediments storing around 360 billion tonnes of organic carbon in their upper meter, accounting for 75–90% of global marine carbon burial.[68] Before the Anthropocene, these sediments were out of reach for humans and only subject to natural disturbance. In the modern ocean, however, some of these sediments are repeatedly suspended through anthropogenic stressors such as bottom trawling,[64] marine mining,[67] anchoring,[69] and shipping.[70] When sediments come into contact with oxygen-rich waters, the stored carbon can be broken down and released as CO_2. Global modeling suggests that bottom trawling may release 160 – 400 million tonnes of carbon per year, with part of this potentially reaching the atmosphere.[71,72] While these estimates are still uncertain, they highlight an important point: Anthropogenic processes that disturb seafloor sediments may weaken a natural carbon store that would otherwise keep carbon locked away for geologic times.

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

Ways to protect the global seafloor

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

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

Protecting seafloor integrity requires a precautionary approach.

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

Finally, governance and monitoring need to keep pace with expanding human activities in the ocean. International agreements and conservation targets are beginning to address these challenges, but significant gaps remain – particularly in areas beyond national jurisdiction and in the deep sea.

Strengthening protection, improving monitoring, and closing knowledge gaps are essential steps toward safeguarding seafloor integrity.

Governance of seafloor integrity

Legal governance of marine spaces depends upon the relevant maritime zone. The different zones are established by the UN Convention on the Law of the Sea (UNCLOS) and are recognized by customary international law. They indicate who enjoys the competencies to enact and enforce laws for the use and protection of the marine environment, including the seafloor.

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

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

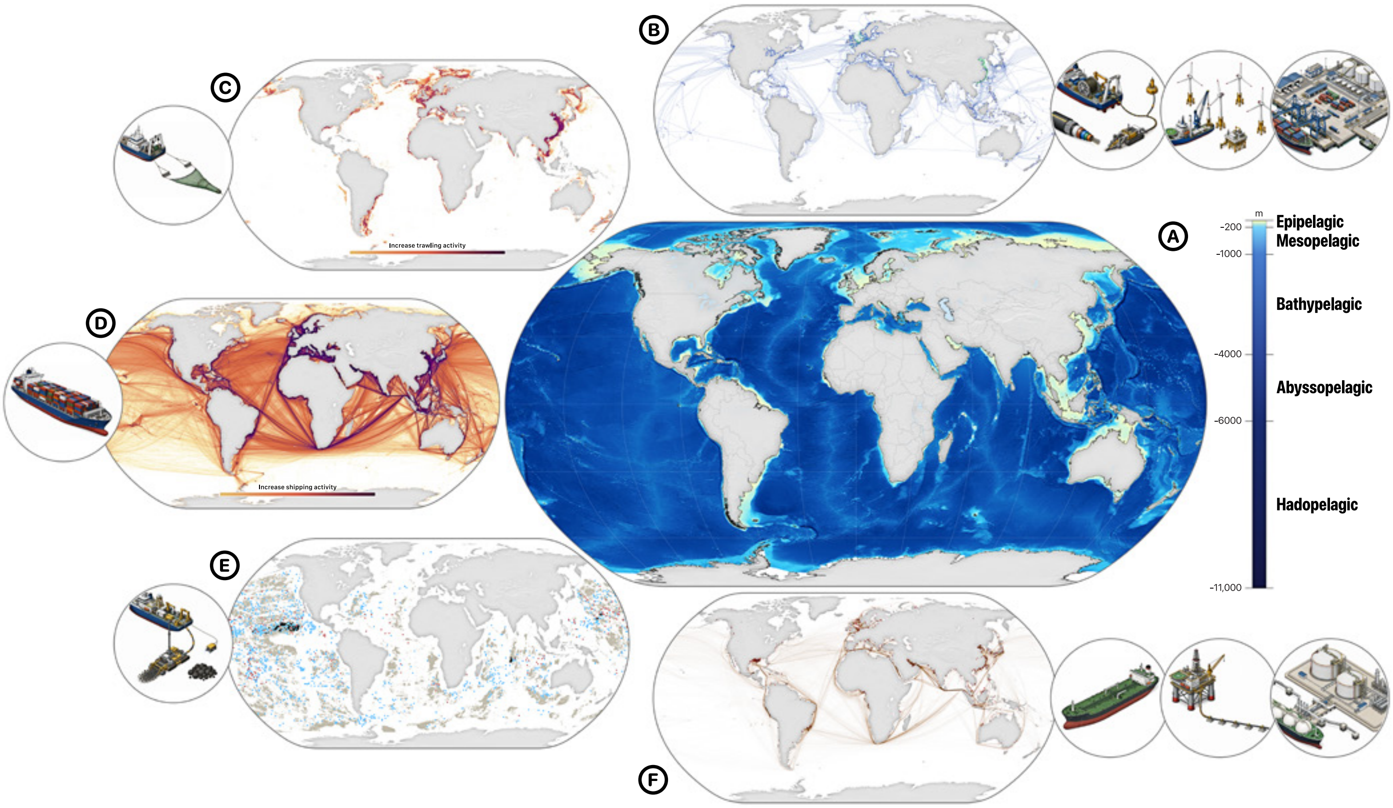


FIGURE 7: HUMAN PRESSURES ON THE GLOBAL SEAFLOOR AND THE WATER COLUMN Six global maps illustrating the spatial extent of human activities and industrial interests in the marine environment, from the coastal shelf to the abyssal plains. (A) Global bathymetry and pelagic depth zones, highlighting the principal vertical domains of the water column, together with major basins, mid-ocean ridges, and trenches.[75] (B) Non-hydrocarbon marine infrastructure including submarine telecommunications cables (blue lines),[76] major commercial ports (blue dots),[77] offshore wind farms and their associated vessel activity (green density),[78] together with major sea-crossing bridges and submerged tunnels.[79] Offshore wind farms remain largely confined to the epipelagic shelf (typically <60 m for fixed foundations, extending to several hundred meters for floating systems). Combined with shipping lanes and coastal engineering, this network of non-extractive built infrastructure spans the full water column from the shoreline to the deep ocean floor (0 to >6,000 m). (C) Bottom-contacting fishing effort: trawlers and dredges. Apparent fishing effort (hours) by industrial bottom trawlers and dredgers, 2020–2025, based on vessel tracks derived from Automatic Identification Systems (AIS).[80] Bottom trawling currently impacts the seabed from the coastline to roughly 4,000 m depth, and the operating depth has been steadily increasing as continental shelves are depleted and gear is adapted for deeper grounds. The footprint highlights chronic seabed disturbance along continental shelves, slopes, and seamounts. (D) Global shipping density. Cumulative density of commercial vessel traffic, revealing the principal trans-oceanic shipping corridors and choke points.[80–82] Although vessels themselves operate at the surface (epipelagic), shipping lanes are sustained by a coastal-to-deep-sea infrastructure footprint (ports, dredged channels, anchorages, cables, and pipelines) extending from 0 to more than 6,000 m. (E) Polymetallic nodule fields and exploration contracts. Composite map of abyssal areas geologically favorable to manganese-nodule formation (beige areas)[83]; documented nodule occurrences enriched in iron (blue dots) and manganese (red dots)[84]; and polymetallic-nodule exploration contract areas issued by the International Seabed Authority in the high seas (black polygons).[85] Whereas seabed mining as a whole could potentially affect any depth from the shore to 6,000 m, commercial interest in polymetallic nodules is concentrated in the abyssopelagic zone, between approximately 4,000 and 6,000 m. (F) Offshore hydrocarbon system: extraction, transport, and export. End-to-end footprint of the marine hydrocarbon value chain, from wellhead to liquefaction terminal: offshore oil-and-gas platforms and their associated vessel activity (brown density, 2017–2021)[78]; submarine oil and gas pipelines (red lines)[86]; LNG export and import terminals (red dots) and the global density of LNG tanker traffic linking them.[87] The hydrocarbon system reaches from coastal LNG terminals through the epipelagic, mesopelagic, and bathypelagic zones into the abyssopelagic, with platforms now operating at depths exceeding 3,000 m.

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

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

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

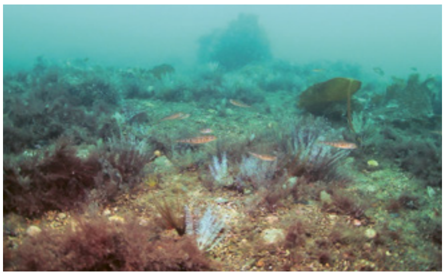
The main governance challenges are structural. Fragmentation between additional legal regimes – covering fisheries, shipping, seabed mining, and biodiversity in separate silos – makes integrated governance of cumulative impacts on the seafloor especially difficult. Monitoring and enforcement capacity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

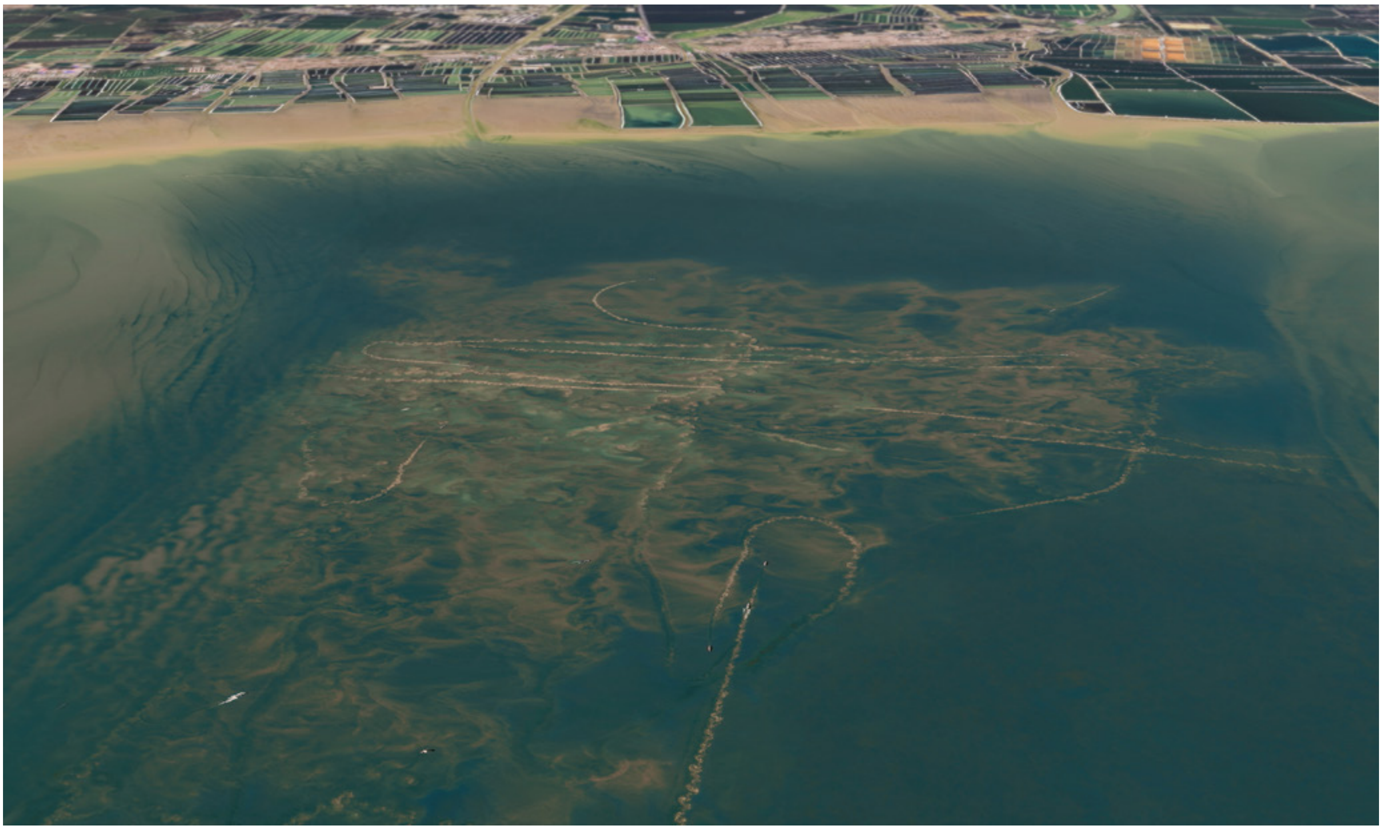
The formal legal role of non-State actors remains limited, since international law binds States rather than individuals or companies directly. Nevertheless, civil society advocacy, scientific advice, and corporate due diligence can exert real influence. Ultimately, however, effective protection of the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

CASE STUDY

Loss of seafloor integrity in the Baltic Sea

The Baltic Sea has a long history of anthropogenic disturbance, which began earlier than in most other oceans and marginal seas.[73] Today, the health state of the Baltic Sea is disastrous. Considering morphology, biogeochemistry, and the benthic ecosystem, there is not a single square meter of Baltic seafloor that is not anthropogenically altered. Decades of bottom trawling, eutrophication and oxygen depletion have transformed large parts of the Baltic seafloor, reducing habitat quality, biodiversity and benthic ecosystem functioning. These changes reinforce one another, making recovery increasingly difficult even if individual pressures are reduced.[73,74] Studying the loss of seafloor integrity in the Baltic Sea, and its link to declining ecosystem health, can provide insight into how environmental conditions and marine ecosystems may change more broadly in the Anthropocene, as increasing technological access brings larger parts of the global seafloor within reach of human activities.





● **FIGURE 8:** In bottom-contact fishing, weighted nets are dragged across the seafloor at speed, destroying bottom-dwelling life indiscriminately and swirling up great amounts of sediment. Top left: Photographed from inside a trawl net, which is churning up the sediments as it is being dragged across the seafloor. Right, top: Intact seabed off the island of Arran, Scotland, with juvenile cod swimming over a healthy seagrass meadow. Right, bottom: The same area, recently devastated by scallop dredge fishing. Bottom: Aerial view of churned up sediments from bottom-contact fishing. Top and bottom images as featured in *Ocean with David Attenborough;* credit: Open Planet Studios, Silverback Films, and the Open Planet library. Middle images, credit: Howard Wood/COAST.

2.3 Novel Entities: Known Impacts and Unknown Planetary Threats

Guest article by:
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Can't live without them, but some can't live because of them

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

Novel Entities comprise a very large and diverse basket of "new", human-synthesized chemicals and materials such as pesticides, plasticizers, per- and polyfluorinated alkyl substances (PFASs) and plastics that have become enmeshed in daily use, especially since the 1950s. Depending on the definition, they also include naturally occurring metals and other elements whose natural cycling and chemistry humans have altered,[88,89] as well as genetically modified organisms. In this article, we will focus on human-synthesized or -mobilized chemicals and materials.

To date, hundreds of thousands of chemicals have been registered for use globally, with new ones continuously entering the market. Materials, such as plastics, are diverse and complex as well. The rapid rise in the number and diversity of Novel Entities contributes to the "great acceleration" that is modifying the planet.[1] There is no place on Earth untouched by Novel Entities, from the bottom of the sea to orbiting "space junk".

Too little is known about the vast majority of Novel Entities, even including their identity, let alone their safety. Nevertheless, growing evidence shows that many Novel Entities seriously impact the Earth's biophysical processes at local to planetary scales, with concerns mounting over the extent and irreversibility of those impacts. ● **Fig. 9** summarizes some of the better-known impacts on ecosystems and human populations. It also highlights the considerable unknowns and uncertainties along the pathway from the production of Novel Entities to their presence in the environment, associated exposures, and resulting impacts. Below, we highlight key lessons learned from those impacts to ecosystems and present some solutions for consideration.

Novel Entities are eroding ecosystem health and resilience

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

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

Furthermore, evidence is clear and compelling that pollution from many Novel Entities is toxic to the biosphere, disrupting ecosystem functioning, and reducing the resilience of ecosystems to respond to other assaults from, for example, Climate Change and Ocean Acidification. Chemical pollution has been named as one of the five major drivers of global biodiversity loss[90] by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). Nearly 14% of the 84,000 animal species on the IUCN "Red List" of threatened species have been considered to be affected by pollution.[91] Human populations are also widely exposed to Novel Entities, with mounting evidence of widespread harm.

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

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

Additionally, there is a long list of Novel Entities that are slowly eroding ecosystem integrity and resilience. For example, the widespread use of agricultural pesticides has been linked to declining populations of pollinators, other "non-target" insects, amphibians, and aquatic biota, with cascading effects on insectivorous birds.[92–95] Polychlorinated Biphenyls (PCBs), chemicals that were widely used in electrical transformers and capacitors between the 1940s and 1980s, are now contributing to the slow demise of Orca populations.[96]

Due to the complexity of ecosystem processes, some impacts take decades to become evident. For example, despite early observation of acid rain in the mid 1800s, it took nearly a century for scientists to identify and understand its connection to industrial emissions from mining, mineral processing, and fossil fuel combustion. By then, acid rain had caused large-scale declines and even collapse of some freshwater fish communities, particularly in Northern regions where clear waters lack buffering capacity. Fortunately, many of these declines have now been reversed by concerted efforts to control those industrial emissions. But acid rain from past and continuing emissions is still reducing the growth and resilience of some forests, including reduced carbon sequestration, as acids have depleted nutrients in soils. These changes are taking decades to reverse.[97]

Plastics raise a new set of concerns. Every year, between 19 and 23 million tonnes of plastic waste enter streams, lakes, and oceans.[98] No place on Earth remains untouched by plastic pollution, and this pollution will persist because of the extraordinary longevity of plastics.[99] Most plastics fragment over time, but take hundreds to thousands of years to mineralize into CO_2. Large plastic debris threatens marine birds, turtles, and mammals with entanglement. Small plastic debris can accumulate in the stomachs of some marine birds, impairing feeding, which can lead to starvation. Very small particles, known as micro- and nanoplastics, are now in virtually every organism, including humans. The impacts of micro- and nanoplastics remain insufficiently understood – but this uncertainty is itself a serious concern, given their growing presence and potential risks to ecosystems and human health. This is partly due to the release of many plastic additives and other chemicals therein, only some of which have been well-researched in terms of toxicity. Initial evidence also suggests that plastic debris might interfere with the Earth's natural carbon cycling and the biological carbon "pump",[100] which moves carbon from the surface ocean to deep waters and ultimately to the seafloor. This potential impact is under further investigation.

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

Challenges in reversing the global impacts of Novel Entities

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

Among chemicals infamous for their persistence, global distribution and toxic effects are persistent organic pollutants (POPs). PCBs, among the most prominent examples of POPs, illustrate how long these impacts can endure: Although most production stopped by the 1980s, they remain at high levels in the environment today and continue to contribute to the decline of long-lived whale populations. Soils to which DDT was applied decades ago can still retain high concentrations, which move through the food web to harm bird populations.[101] Many PFASs contaminate surface and groundwater worldwide, with this pollution expected to last for centuries to millennia, risking very long-term harm to exposed ecosystems and human populations.

Toxic metals are inherently persistent and can pose risks. For example, just in Europe, a million wildfowl are estimated to die annually from lead exposure leaching from spent ammunition, with over three million more experiencing sub-lethal effects.[102] Mercury provides another example: Human activities have tripled atmospheric mercury levels since 1850, increasing long-term exposures to global wildlife and causing effects such as lower reproductive success[103] and behavioral changes in some populations.

Even natural materials, subject to chemical alteration by humans, can persist in the environment and pose a long-term source of exposure and potential risk to ecosystems. Human-modified indigo denim fibers from blue jeans are found in the sediment of Arctic waters, thousands of kilometers from their point of release,[104] where they can enter the aquatic food chain and could cause harmful effects,[105] partly due to the chemicals they carry.

Poorly reversible impacts can also come from the evolutionary pressure that chemicals can exert on ecosystems. Biocides and antimicrobials, such as antibiotics used in humans and farm animals, are increasing the abundance of antimicrobial resistant genes in surface water ecosystems receiving treated and untreated wastewater. Globally, antibiotic concentrations exceed safe thresholds in an estimated 6 million kilometers (at low flow) of rivers from human antibiotic consumption alone.[106]

Even the more short-lived Novel Entities provide significant challenges. Economic, political, social and technological factors may be very resistant to change, and "lock-in" continued production, release, and destructive impacts.[107,108]

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

Society can reduce harms from Novel Entities

The Planetary Boundaries are intended to be guardrails that ensure Earth system processes remain in a Holocene-like, civilization-friendly state. Evidence continues to mount that global pollution by Novel Entities is approaching or exceeding these guardrails.[109,110] But it is not inevitable that societies continue to poison themselves and their environment. After over a century of inventing, producing, using, and disposing of chemicals and materials through a largely technology-centered approach, societies must fundamentally rethink their relationship with Novel Entities. This broader rethinking can begin with specific applications, asking where hazardous chemicals and materials are truly necessary and where they can be avoided or replaced.

Pulling back from current unsustainable practices to safer conditions will require ambitious changes. Fortunately, some solutions are available today. Actions can start with reversing the trend of ever-increasing rates of Novel Entity production, which currently exceed the rate of population growth. For example, the production of basic petrochemicals, from which many industrial chemicals and plastics are derived, doubled between 1990 and 2010. Continuing business as usual, production of these basic petrochemicals could more than triple by 2030 compared with 2010.[111] However, global production has recently stagnated because of structural overcapacity,[112] highlighting the potential to reduce production to better align with actual demand. Part of the demand can be further reduced by addressing overconsumption in high-income countries. For example, the material footprint of high-income countries is six times higher than that of low-income countries. Notably,[113] this overconsumption among high-income countries comes with disproportionate environmental impacts in lower-income countries.[114,115]

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

Next, the rate of Novel Entities proliferation needs to be tamed. Currently, more than 350,000 individ-

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

ual chemicals and mixtures have been registered for large-scale production and use in different parts of the world,[116] with new chemicals and materials continually introduced to the market. This proliferation could be addressed through simplification, i.e., using fewer and less diverse Novel Entities to achieve the same functions. One potential pathway is to advance the development of Novel Entities that are *Safe and Sustainable by Design* (SSbD),[117] coupled with effective mechanisms to phase out other chemicals and materials used for the same applications, particularly those that are known to be problematic.

Determining which Novel Entities may continue to be used, and for which applications, will be challenging. However, we take inspiration by seeing the progress with POPs listed under the Stockholm Convention – through dedicated restriction/elimination efforts, levels of these chemicals are declining worldwide.[118] This approach needs to be taken further to reduce, or better yet, eliminate the non-essential use of other hazardous Novel Entities. The concept of "essential use" was first introduced in the 1970s during discussions about restricting the use of ozone-depleting substances. It was then incorporated into the Montreal Protocol that has effectively reduced the production of ozone-depleting substances. Recently, the essential use concept has been introduced to guide the phase-out of PFASs,[119] and could be applied to other hazardous chemicals and materials.

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

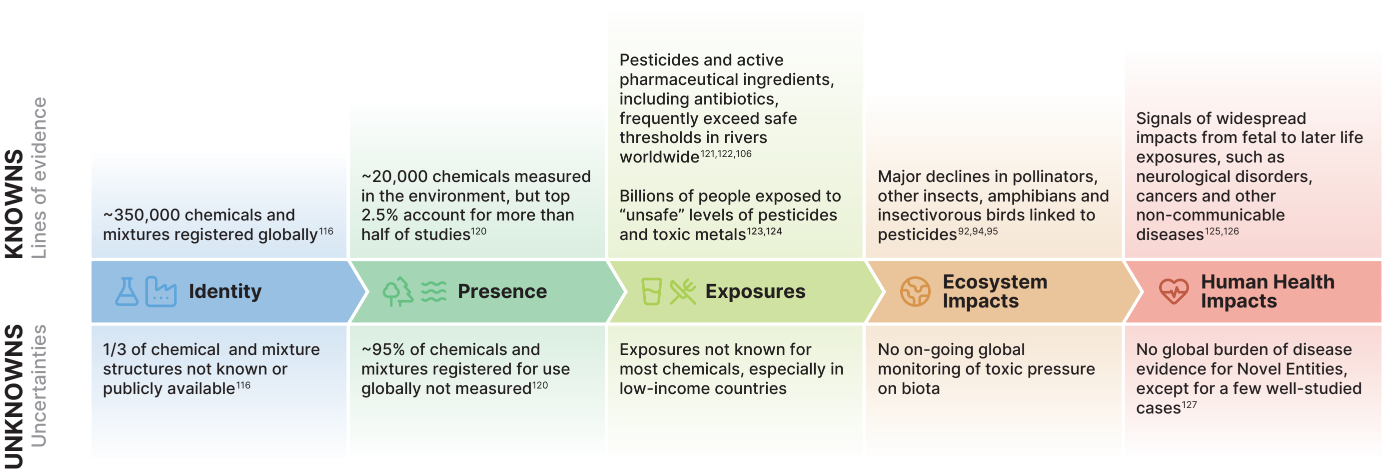


FIGURE 9: Novel Entities pose significant threats to the functioning of the Planet, as well as for human well-being. Much is already known about widespread contamination with various substances, and observations of additional destructive impacts are emerging. However, some of the greatest risks lie in the "unknowns": impacts of pollution that we are not yet aware of, but which may already be causing grave harm, or may do so in the future. By the time these effects become widely recognized and understood, it may be too late to reverse them.

3 | Planetary Boundary Information Sheets

Photography by Mattias Klum

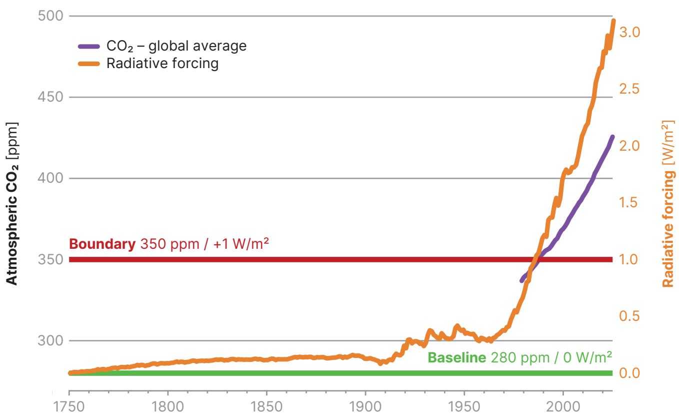
3.1 Climate Change

Human activities are trapping more heat in the climate system and driving long-term changes in temperature, weather patterns, oceans, ice sheets, and ecosystems. The Climate Change boundary is already transgressed, increasing the risk of severe impacts and irreversible shifts in the Earth system.

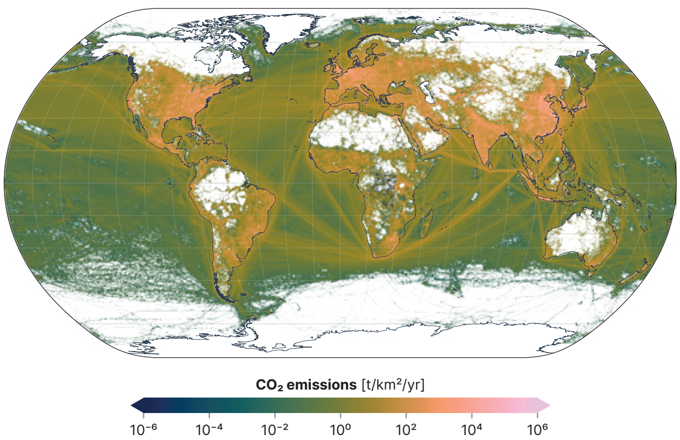
What is changing?

Climate Change concerns the stability of Earth's climate: the balance between incoming and outgoing energy. Human activities are disrupting this balance mainly by releasing greenhouse gases that trap additional heat in the atmosphere.

The main driver is carbon dioxide from burning coal, oil and gas, cement production, and deforestation. Methane from agriculture, fossil fuel extraction and landfills, and nitrous oxide from fertilizer use also contribute. Land-use change, aerosols, urbanization, and changes in Earth's reflectivity further affect the climate.



● Historical trends of atmospheric CO_2 concentration and radiative forcing (disturbance of Earth's energy balance). Both have left the Safe Operating Space, with trends continuing to worsen.



● Global patterns of CO_2 emissions: highly concentrated in heavily populated areas, with further hotspots such as industrial operations, resource extraction, and shipping.

Why does this matter?

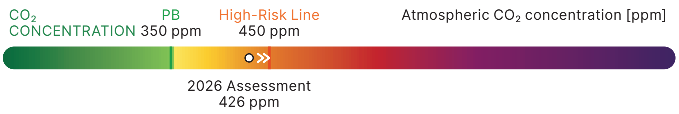
The global climate sets the background conditions for life on Earth: temperature ranges, rainfall patterns, ocean circulation, ice cover, growing seasons, and the frequency of extreme events. When this system is pushed out of balance, risks can spread through many connected parts of the Earth system at once.

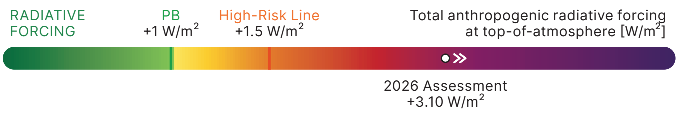
Continued warming can create feedback effects. Melting ice sheets and glaciers contribute to sea-level rise and reduce Earth's reflectivity, which can amplify further warming. Oceans absorb much of the excess heat and CO_2, driving marine heatwaves, acidification, coral reef decline, and disruption of food webs. On land, heat, drought, fire, and shifting rainfall can degrade forests and other ecosystems, weakening biodiversity and reducing their ability to store carbon.

For people, these Earth system changes translate into rising risks to health, food production, water availability, infrastructure, coastal settlements, livelihoods, and economic stability. The greatest danger is that impacts do not simply add up one by one: They can compound and cascade, especially if tipping points are crossed and long-lasting changes become difficult or impossible to reverse.

How is this boundary assessed?

The Climate Change boundary is assessed using two control variables: atmospheric carbon dioxide concentration, and total human-caused radiative forcing, which describes how strongly human activities are adding heat to the Earth system.





Where are we now?

The boundary is **transgressed** for both control variables, which are both trending in the wrong direction. Atmospheric CO_2 has reached 426 ppm, and is thus above the safe level of 350 ppm. Human-caused radiative forcing is +3.10 W/m², more than three times the safe level of +1.0 W/m². This means the Earth system is already well beyond the Safe Operating Space for climate stability.

Impacts are already visible in rising global temperatures, more frequent and intense heatwaves, heavy rainfall, droughts and floods, melting land ice, sea-level rise, ocean warming and acidification, ecosystem stress, and growing risks to health, food security, water availability, and infrastructure.

3.2 Change in Biosphere Integrity

The living biosphere is being depleted and reorganized: Species are disappearing, habitats are being transformed, and a growing share of nature's energy is being diverted to human use. This weakens the living foundation of the Earth system, reducing its capacity to sustain the flows of energy, water, carbon, and nutrients that make the planet habitable.

What is changing?

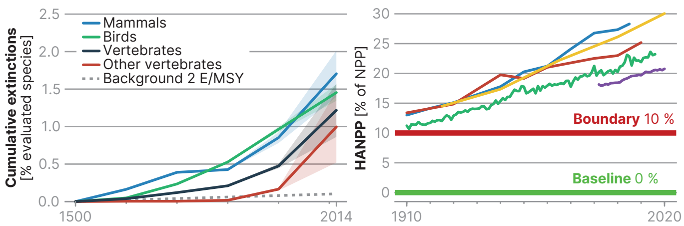
Biosphere Integrity concerns the diversity, functioning, and interactions of life across land, freshwater, and ocean. Earth's biosphere is under great pressure: Natural habitats are being converted, degraded, and fragmented, especially through agriculture, grazing, forestry, infrastructure, and urban expansion. Species and ecosystems are being directly depleted through activities such as logging, fishing, and other forms of resource extraction. These pressures are amplified by climate change, pollution, invasive species, and nutrient overload.

Why does this matter?

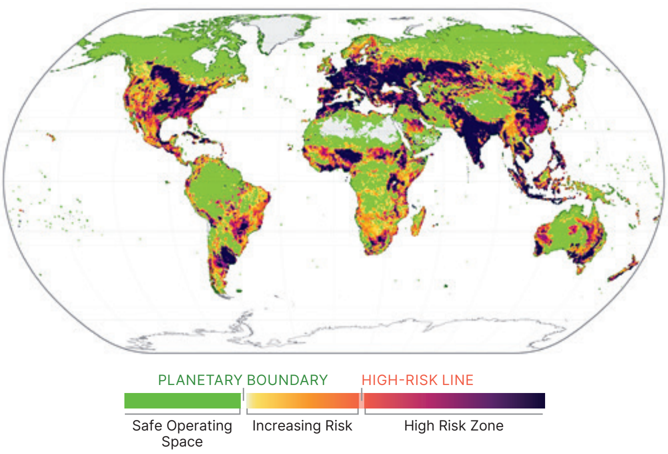
The biosphere is not just one component of the Earth system; it is one of its central organizing forces. Living organisms shape the atmosphere, soils, rivers, oceans, and climate through photosynthesis, respiration, decomposition, predation, pollination, nutrient cycling, and countless other ecological processes.

As Biosphere Integrity declines, these biological processes lose diversity and complexity and become less effective. Ecosystems and their inhabitants lose their ability to absorb shocks (such as droughts, fires, pests, heatwaves, and disease), acclimate, adapt, or migrate. Forests, wetlands, soils, grasslands, and marine ecosystems can become less effective in storing carbon, regulating freshwater, maintaining soil fertility, supporting food webs, and buffering climate extremes.

For people, this can undermine the biological foundations of food security, clean water access, health, and livelihoods. Consequences are grave: increasing risk of crop failure and fishery losses, pest and disease outbreaks, and reduced protection from floods, heat, and erosion.



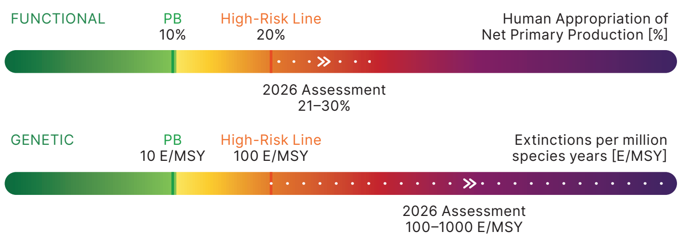
● Historical trends of global species extinction rates (top), and several estimates of human appropriation of net primary production (HANPP; the energy we take from nature). Both have left the Safe Operating Space, with worsening trends.



● Global risk map of Change in Biosphere Integrity – HANPP. The boundary is most strongly breached in regions with high land-use intensity; areas without boundary transgressions are primarily in (semi-)natural regions such as the Amazon, Congo Basin, and boreal forests.

How is this boundary assessed?

To assess Change in Biosphere Integrity, the Planetary Boundaries framework uses two proxies. The first evaluates nature's remaining *genetic diversity*, measuring the rate at which species are going extinct in extinctions per million species-years (E/MSY). The second, *functional integrity*, tracks whether ecosystems retain enough energy and complexity to perform their Earth system roles. *Functional integrity* is measured through the Human Appropriation of Net Primary Production (HANPP): the percentage of plant-based energy that humans harvest, consume, or prevent ecosystems from using.



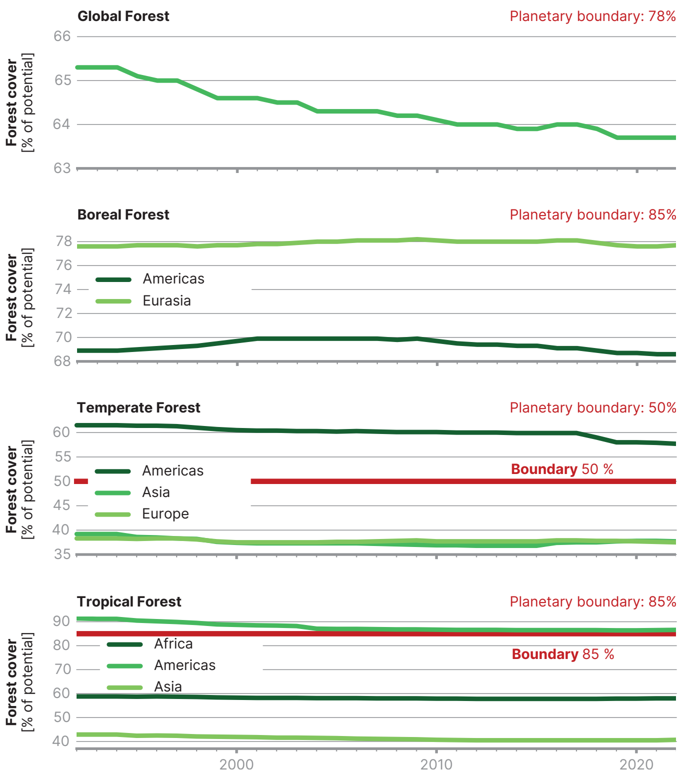
Where are we now?

The boundary is strongly **transgressed**. Species are going extinct at more than 100 extinctions per million species-years, far above the safe level of 10 E/MSY. Humans appropriate 21–30% of potential natural plant productivity on land, above the safe level of 10%.

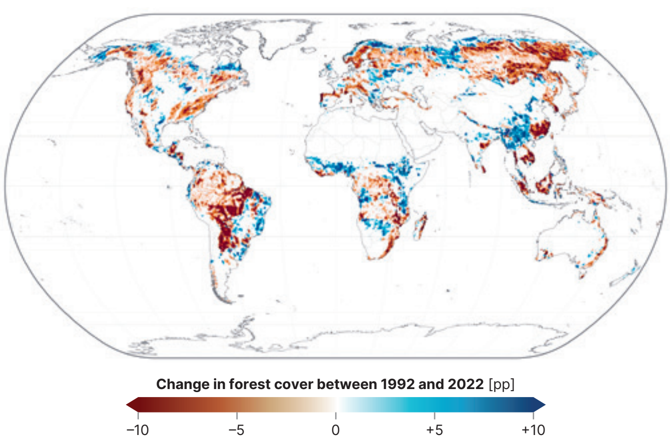
Impacts are visible in widespread habitat loss, shrinking species populations, extinction of evolutionary lineages, reduced pollination and pest regulation, ecosystem degradation, and declining carbon uptake and storage. The deeper risk is that continued biosphere degradation could reduce the Earth system's capacity to self-regulate, increasing the likelihood of cascading change.

3.3 Land System Change

Forests and other land systems stabilize the climate, regulate the freshwater cycle, and support biodiversity. Forest loss is ongoing at alarming rates, driven by a number of complex factors including expanding agriculture, logging, and Climate Change.



● Annual mean forest cover (as a percentage of potential forest cover), globally and for three different biomes (temperate, boreal, and tropical). As a result of land-use change and, increasingly, climate change, forests across all major forest biomes have been steadily declining over the last few decades.



● Change in forest cover between 1992 and 2022 (absolute change of the percentage of forest cover, i.e., a change from 60% to 50% is shown as -10). Contiguous pristine forests in the tropics and boreal zones, in particular, have suffered losses of primary forest, while temperate forests, often reflecting managed forestry, have mostly suffered from climate change impacts.

What is changing?

Land System Change concerns the transformation of land through direct or indirect human actions. Particularly concerning is the loss and degradation of forests, since they are central to carbon storage, biodiversity, water cycling, and climate regulation.

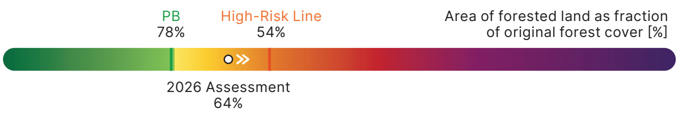
The main direct drivers are a complex mix of agricultural expansion (cropland and grazing) and timber extraction, as well as the expansion of infrastructure. Climate Change and Freshwater Change increasingly amplify Land System Change through heat, drought, fire, flooding, and pest outbreaks.

Why does this matter?

Land systems are active parts of the Earth system. Forests store carbon, recycle moisture, cool land surfaces, recharge groundwater, protect soils, and provide habitat for much terrestrial life. When forests are cleared or degraded, all these functions are weakened. Stored carbon is released. Moisture recycling declines, reducing rainfall and water availability locally and downwind. Runoff, erosion, and soil degradation increase. Habitat loss fragments ecosystems and reduces their ability to recover from shocks.
For people, these changes mean less reliable water supplies, lower soil fertility, less environmental cooling, higher fire and flood exposure, and increased disease risks. The largest risks arise where land degradation interacts with climate change and freshwater stress, potentially pushing ecosystems such as the Amazon toward tipping points.

How is this boundary assessed?

Land System Change is assessed by measuring remaining forest area, compared with the forest cover that would exist without human land-use change. The global safe level is 78% of potential forest cover. Additionally, thresholds have been defined for large regions (biomes) on different continents.



Where are we now?

The boundary is **transgressed**. Only 64% of potential global forest cover remains, below the 78% safe level. Most major forest biomes have crossed their thresholds, and their forest cover is continuing to decline.

Impacts are already visible in the form of biodiversity loss, carbon emissions from deforestation, disrupted rainfall, soil degradation, altered water flows, wildfire damage, and pest outbreaks. Continued forest loss would make these impacts much more severe, and increase the risk of large-scale ecosystem shifts.

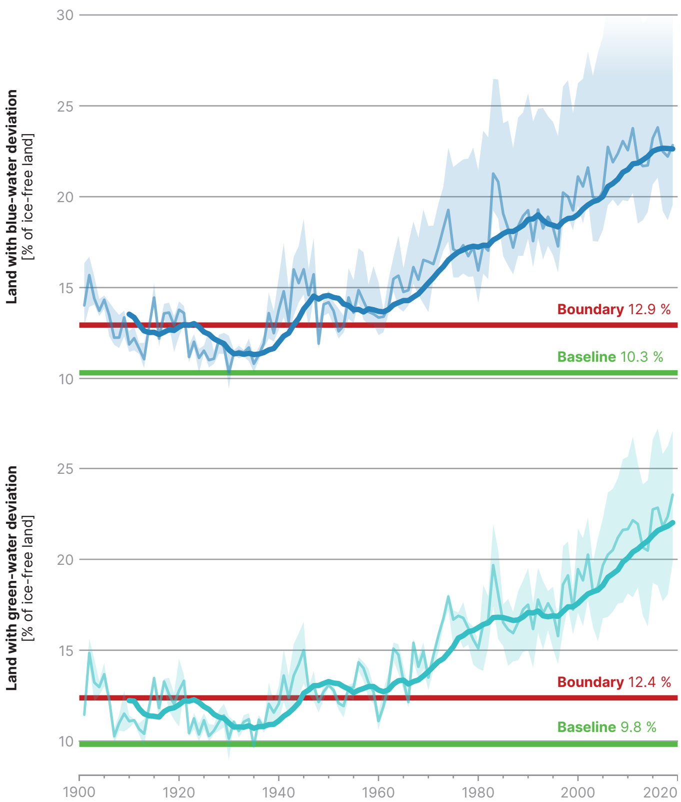
3.4 Freshwater Change

Human activities are disrupting the global water cycle, making river flows and soil moisture increasingly unstable across large parts of the planet. The Freshwater Change boundary is already transgressed for both blue water and green water, increasing risks to ecosystems, food and water security, carbon storage, and regional climate stability.

What is changing?

Freshwater Change concerns the global water cycle on land: water flowing through rivers, lakes, wetlands, reservoirs and groundwater, often called blue water, and water held in soils and available to plants, known as green water. Together, these freshwater flows and stores support ecosystems, regulate climate, sustain food production, and provide water for people.

Human activities are altering both parts of the system. Climate Change is intensifying and redistributing rainfall, evaporation, droughts, and floods. At the same time, irrigation, water withdrawals, dams, river regulation, deforestation, agriculture, and urbanization directly change how water moves through landscapes.



● Disturbance of Earth's freshwater systems of blue water (streamflow) and green water (soil moisture) flows from 1901 to 2019. Both have significantly increased since the early 20th century, surpassing the Planetary Boundary around 1940 and continuing to rise since then.

Why does this matter?

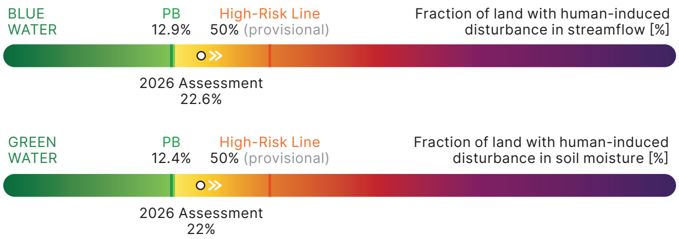
Freshwater is essential for the functioning of the Earth system. It shapes vegetation, rivers, wetlands, soils, biodiversity, regional climates, and the carbon cycle. When freshwater conditions become too dry or too wet, ecosystems can lose resilience, and the likelihood of droughts, floods, fires, heatwaves, and long-term degradation increases.

Reduced streamflow can shrink wetlands, deplete lakes and reservoirs, and degrade freshwater habitats and connected ecosystems. Dry soils can stress forests as well as crops, increase wildfire risk, weaken carbon uptake, and trigger carbon emissions from ecosystem disturbance. Wet deviations can increase flooding, disrupt natural river-flow patterns, cause waterlogging, and contribute to permafrost thaw.

For people, the impacts often arrive earlier through water scarcity, crop losses, flood damage, wildfire exposure, infrastructure stress, and pressure on drinking water, irrigation, hydropower, and food production.

How is this boundary assessed?

To assess the Freshwater Change boundary, scientists compare current streamflow (blue water) and root-zone soil moisture (green water) conditions with a pre-industrial-like baseline. The measure is the percentage of global ice-free land area experiencing unusually wet or dry conditions.



Where are we now?

The boundary is **transgressed** for both control variables. Significant streamflow deviations now affect 22.6% of global ice-free land area, above the safe level of 12.9%. Significant soil-moisture deviations affect 22.0%, above the safe level of 12.4%.

Both blue water and green water deviations have increased strongly since the early 20th century, crossed their boundaries around the 1940s, and have continued to rise. Impacts already visible include more frequent droughts and floods, disrupted river flows, groundwater depletion, drying soils, ecosystem stress, and growing pressure on food and water security. Continued transgression could further weaken ecosystem resilience, reduce carbon storage, intensify fire and flood risks, and lead to large-scale die-offs in significant ecosystems such as the Amazon.

3.5 Modification of Biogeochemical Flows

Human activities have massively increased nitrogen and phosphorus flows through soils, waters, and the atmosphere, mainly through fertilizers, livestock manure, and wastewater. These nutrients are essential for life, but when their cycles are overloaded, they can destabilize ecosystems, deoxygenate waters, and disrupt life in rivers, lakes, and coastal seas.

What is changing?

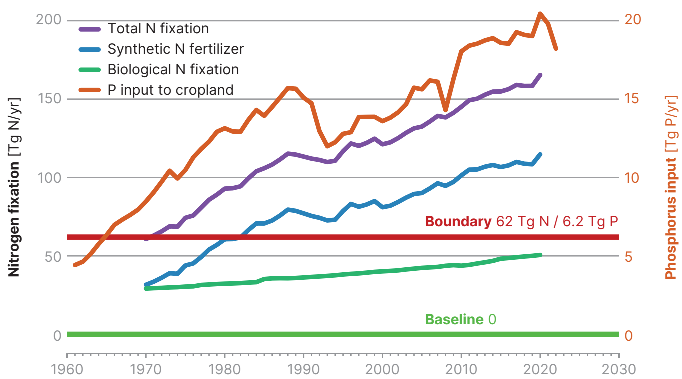
Biogeochemical Flows describe how elements vital to life cycle through the Earth system. Especially relevant are nitrogen and phosphorus, two nutrients essential for plant growth. In natural conditions, their limited availability helps shape ecosystems.

Industrial nitrogen fixation, nitrogen-fixing crops, and mined phosphate rock have changed this balance. Food production is the main driver: Large amounts of nitrogen and phosphorus are added to fields and pastures as fertilizers. Runoff from fields, erosion, sewage, and manure carry nutrients into streams and oceans. Over-fertilization, food waste, limited recycling, and poor sewage treatment increase nutrient losses to the environment.

Why does this matter?

Nitrogen and phosphorus are necessary for life, but too much in the wrong place can destabilize ecosystems. Freshwater, marine, and terrestrial systems are adapted to specific nutrient levels and ratios. Excess nutrients can shift species composition, reduce biodiversity, and weaken resilience.

In water bodies, nutrient pollution can trigger eutrophication: Algae grow rapidly, then decay and consume oxygen. This can create dead zones in lakes, rivers and coastal seas, harming aquatic life and food webs. Nitrogen pollution also contributes to Atmospheric Aerosol Loading, Stratospheric Ozone Depletion, and Climate Change.

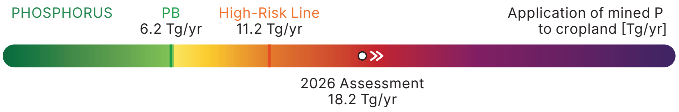


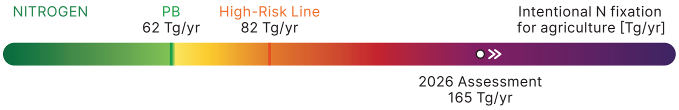
● Phosphorus and nitrogen inputs to agricultural lands from 1961 until 2022. The significant increase over time in both nutrients reflects the growing demand for agricultural productivity.

For people, impacts include unsafe drinking water, fishery and tourism losses, and health damage from nitrogen-related air pollution.

How is this boundary assessed?

The boundary for Modification of Biogeochemical Flows is assessed using two control variables: mined phosphorus applied to cropland each year, and nitrogen intentionally fixed for agriculture each year. Both are expressed in teragrams (million metric tons) per year.

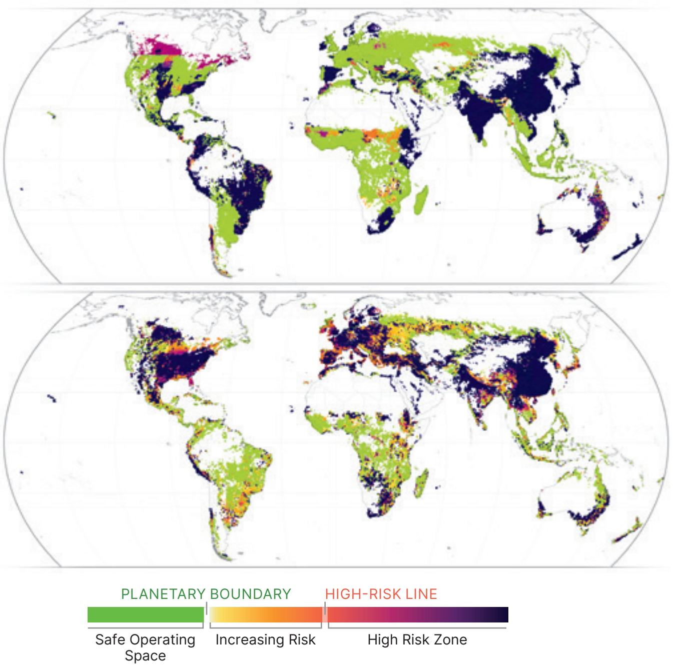




Where are we now?

The boundary is **transgressed** for both nutrients. Mined phosphorus application is around 18.2 Tg P/year, nearly three times the safe level of 6.2 Tg P/year. Agricultural nitrogen fixation is around 165 Tg N/year, far above the safe level of 62 Tg N/year.

Impacts are already visible as eutrophication, algal blooms, oxygen loss, polluted waters, biodiversity impacts, and nitrogen-related air pollution. A key risk is persistence: Phosphorus in soils and nitrogen in groundwater can keep causing damage for decades, even after inputs are reduced.



● Global risk maps for phosphorus (above) and nitrogen (below) cycles. Boundary transgressions are particularly notable in parts of South America and Asia for phosphorus, and in parts of Asia and Europe for nitrogen.

3.6 Ocean Acidification

The ocean absorbs a large share of the carbon dioxide released by human activities. This helps slow climate change, but it also changes seawater chemistry, making the ocean more acidic and less supportive of many forms of marine life.

What is changing?

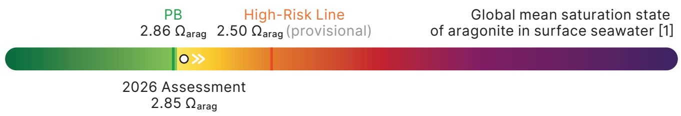
Ocean acidification concerns the chemistry of seawater. When carbon dioxide enters the ocean, it forms carbonic acid. This lowers pH and impedes growth and survival for organisms that are sensitive to acidification. The main global driver is human-caused CO_2 emissions, while coastal waters can also be affected by nutrient runoff, upwelling, freshwater input, and other local pressures.

Why does this matter?

Ocean acidification threatens the stability and functioning of marine ecosystems. Tropical corals, shellfish, pteropods, and deep-water corals need more energy to build and maintain shells or skeletons, leaving less energy for growth, reproduction, and survival. Many non-calcifying organisms can also be affected through changes to their internal physiology. As sensitive species are harmed, impacts can cascade through marine food webs, degrade habitats, and alter the biological processes that help move carbon from the surface ocean to the deep sea. This makes acidification a risk not only to marine biodiversity, fisheries, and coastal communities, but also to the ocean's role in regulating climate and maintaining Earth system stability.

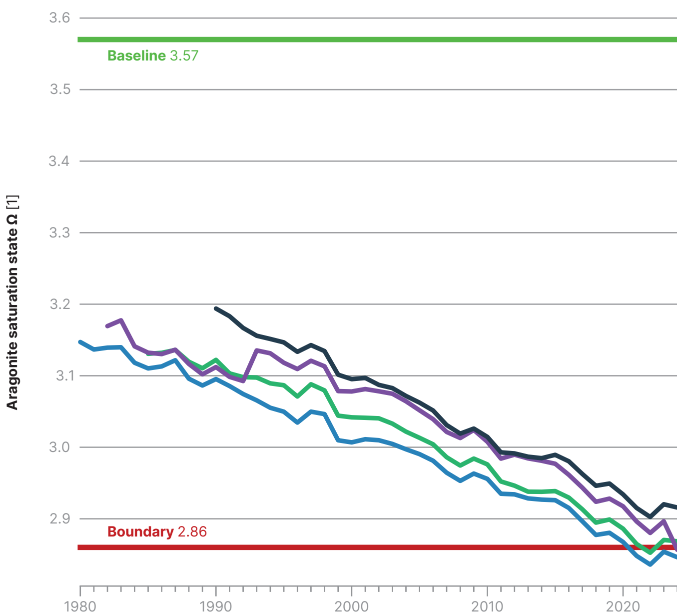
How is this boundary assessed?

The Ocean Acidification boundary is assessed using the global mean surface aragonite saturation state. Aragonite is a form of calcium carbonate used by many marine organisms. Lower aragonite saturation indicates that seawater conditions are becoming less favorable for organisms that build and maintain calcium carbonate structures.

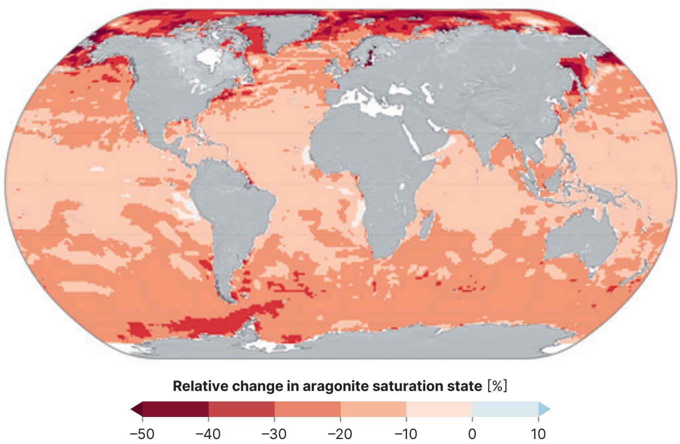


Where are we now?

The boundary is **transgressed**. The level defined as safe is a global surface aragonite saturation state of 2.86 (80% of pre-industrial levels); the current best estimate is 2.85, just below this threshold. The Arctic and Southern Oceans are seeing the strongest changes. Harmful conditions are already affecting vulnerable species and ecosystems: Pteropods show signs of shell damage and dissolution; tropical reefs face reduced recovery capacity alongside warming-driven bleaching; and deep-water corals are increasingly exposed to corrosive conditions. These observed impacts indicate declining ecosystem resilience and growing risks of wider food-web disruption and habitat loss. In addition, acidification tends to weaken the ocean carbon sink.



● Global surface aragonite saturation state from several datasets. The aragonite saturation state has breached the Planetary Boundary, increasingly endangering marine ecosystems.



● Change of Ocean Acidification (via the indicator *surface aragonite saturation state*), between 1750 and 2024. Nearly all regions have become significantly more acidic; this is especially pronounced at high latitudes.

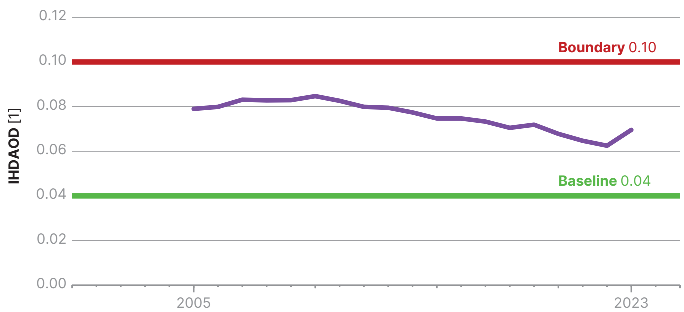
3.7 Increase in Atmospheric Aerosol Loading

Tiny particles suspended in the atmosphere are changing how sunlight, clouds, and rainfall behave. Globally, aerosol loading is within the Safe Operating Space and improving, but regional aerosol loading – especially over South Asia – remains hazardous and can disrupt monsoon rainfall.

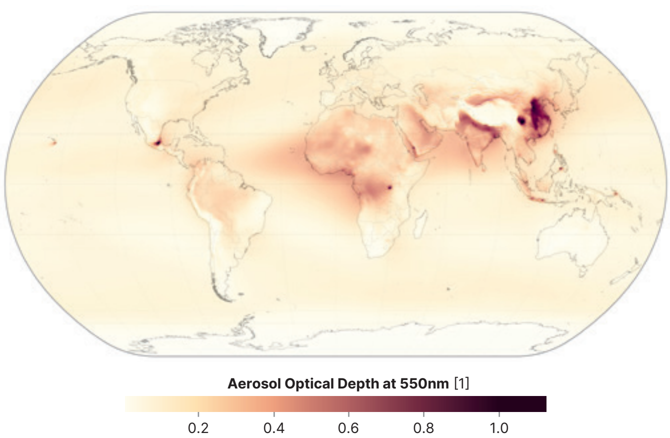
What is changing?

Atmospheric Aerosol Loading concerns particles in the air: sulfates, black carbon, organic particles, dust, and smoke. Depending on their type, aerosols can have heating or cooling effects on the planet. They also influence cloud formation and rainfall, making their effects complex and regionally varied.

Human-driven aerosol loading mainly comes from fossil fuel combustion, industry, transport, and biomass burning (e.g., from agriculture and forest fires). Emissions have declined in many higher-income regions, but remain high or increasing in Asia and Africa.



● 5-year running mean of the difference in the aerosol optical depth (AOD) between the Northern and Southern Hemispheres for the period from 2003–2025. This boundary process is within the Safe Operating Space and continuing to recover, despite a slight uptick in the most recent data point.



● Global aerosol concentration (measured as optical depth at 550nm from all aerosol types), time-averaged over 2010–2020. High aerosol concentrations occur over major dust source regions (such as the Sahara and Arabian Peninsula), biomass-burning zones (such as Central Africa and the Amazon), and industrially polluted areas (such as India and Eastern China). While the boundary is not transgressed globally, some regions show unsafe aerosol concentrations, impacting both monsoon formation and human health.

Why does this matter?

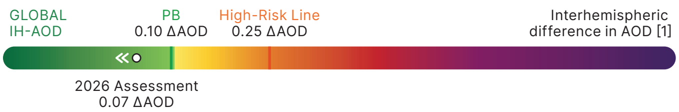
Aerosols affect the Earth system by changing how energy and water move through the atmosphere. Because aerosol pollution is concentrated mainly in the Northern Hemisphere, it can make one hemisphere absorb more solar energy than the other, shifting circulation patterns and altering where rainfall forms.

Aerosols also complicate climate change. Some particles, such as sulfates, reflect sunlight and have a cooling effect; others, such as black carbon, absorb sunlight and warm the atmosphere. Reducing aerosol pollution is essential for human health and ecosystems, but it can also reveal some greenhouse-gas warming that was previously masked by cooling aerosols.

For people, aerosols are an immediate health risk, especially through fine particulate matter that damages lungs and the cardiovascular system. They can also reduce crop productivity and threaten water availability where societies depend on seasonal rainfall.

How is this boundary assessed?

The global boundary uses the difference in aerosol optical depth (AOD) between the Northern and Southern Hemispheres. Aerosol optical depth indicates how strongly particles block or scatter light. Current studies propose an additional regional boundary over South Asia.



Where are we now?

At the global scale, Atmospheric Aerosol Loading is **within the Safe Operating Space**. The difference in aerosol optical depth between the Northern and Southern Hemispheres is about 0.07, below the global boundary of 0.10, and has declined since around 2010.

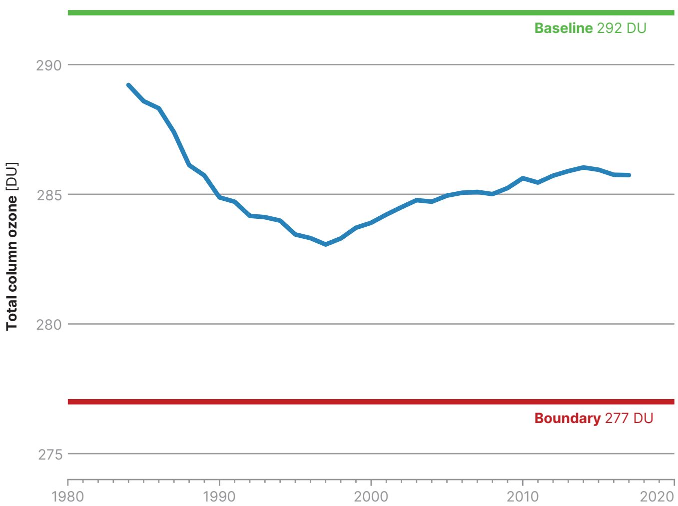
Regional risks remain significant. Over South Asia, aerosol concentrations are beyond safe levels, with recent trends moving in the wrong direction. This matters because high aerosol loading in the region is linked to risks of weakened or delayed monsoon rainfall, as well as severe air pollution.

3.8 Stratospheric Ozone Depletion

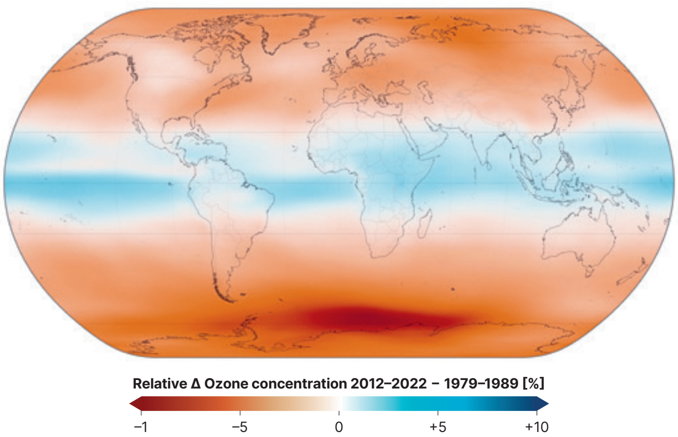
The stratospheric ozone layer shields life from harmful ultraviolet radiation. Human-made ozone-depleting substances damaged this protective layer in the late 20th century, but international action has brought the boundary back within the safe zone, although recovery remains incomplete.

What is changing?

This boundary concerns ozone in the stratosphere: the upper-atmosphere layer where ozone absorbs much of the Sun's harmful UV radiation before it reaches Earth's surface. When stratospheric ozone declines, more UV radiation penetrates the atmosphere. Changes in ozone also affect atmospheric temperature gradients and circulation.



● Mean stratospheric ozone concentration (as 11-year running mean to filter out variation related to solar cycles; measured in Dobson Units (DU)) for 1979–2022. This boundary is within the Safe Operating Space, and has recovered since the mid-1990s – although this recovery may have plateaued in recent years.



● Global changes in stratospheric ozone concentration between the periods 1979–1989 and 2012–2022. Regional trends are mixed; the persistent Antarctic ozone hole highlights ongoing recovery challenges.

The main historical drivers of ozone depletion were chlorofluorocarbons, or CFCs, formerly used in refrigeration, aerosols, fire suppression, and solvents. Once released, these long-lived substances can reach the stratosphere, where sunlight breaks them down and releases chlorine that destroys ozone. Their emissions have been strongly reduced under the Montreal Protocol. Remaining concerns include nitrous oxide from agriculture and uncertain effects from rocket launches and re-entering space debris.

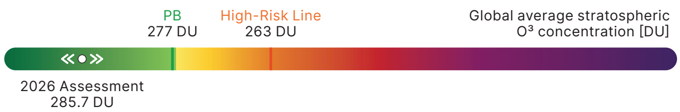
Why does this matter?

Stratospheric ozone forms a life-essential global protective layer which absorbs much of the UV radiation coming from the sun. Increased UV radiation can damage plants, reduce crop productivity, affect forest health, and disrupt aquatic ecosystems.

Ozone depletion also changes the structure and dynamics of the atmosphere. Antarctic ozone loss cooled the lower stratosphere, strengthened the Antarctic polar vortex, and shifted Southern Hemisphere winds and rainfall patterns. This makes ozone depletion a risk to both the biosphere and to atmospheric circulation, with consequences for ecosystems, climate patterns and, more directly, human exposure to harmful UV radiation.

How is this boundary assessed?

The Ozone Depletion boundary is assessed as average stratospheric ozone concentration outside the polar regions, expressed in Dobson Units. One Dobson Unit represents the amount of ozone that would form a layer 0.01 millimeters thick under standard temperature and pressure. The Planetary Boundary is set at 277.4 DU, a maximum 5% decline from the reference level.



Where are we now?

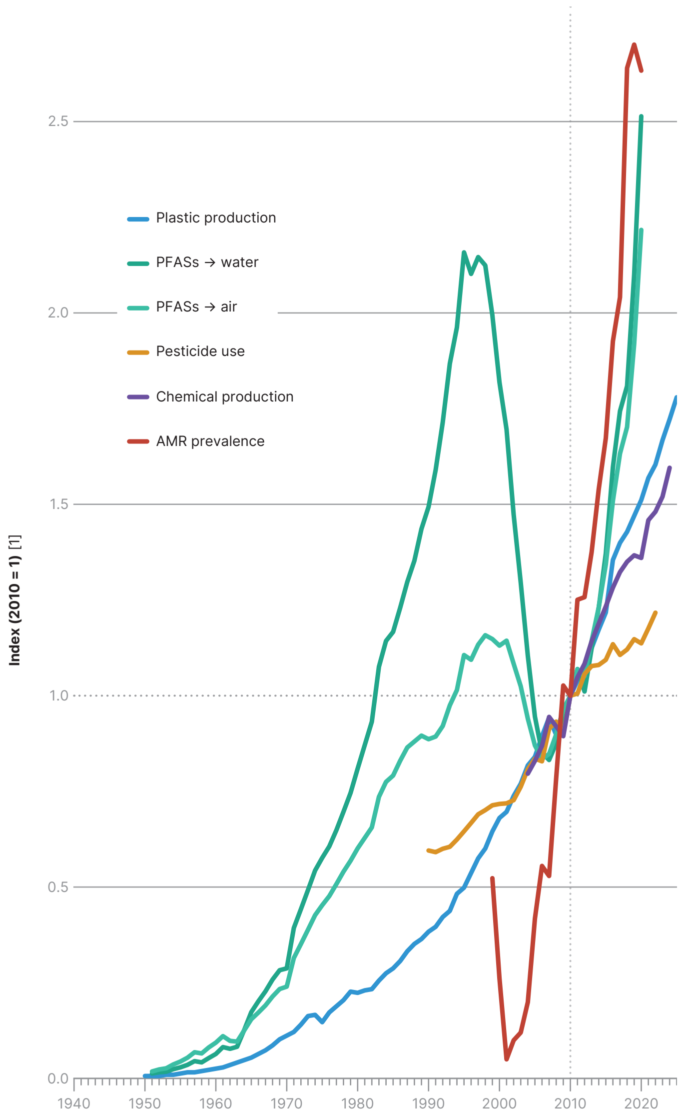
The boundary is currently **within the Safe Operating Space**. Current stratospheric ozone is around 286 DU, above the Planetary Boundary of 277 DU. After severe depletion in the late 20th century, ozone levels began recovering from the mid-1990s as ozone-depleting substances were phased out. However, recovery may have plateaued recently, and levels remain below mid-20th-century conditions. The main risks now are incomplete recovery and emerging pressures that could slow or complicate further recovery.

3.9 Introduction of Novel Entities

Human societies are creating chemicals, materials, and other substances faster than they can be assessed, monitored, or controlled. Many such novel entities can persist, spread globally, accumulate in ecosystems, and interact in ways that may disrupt Earth system processes.

What is changing?

Novel Entities refer to human-made substances introduced into the Earth system. These include synthetic chemicals, plastics and microplastics, pesticides, per- and polyfluoroalkyl substances (PFASs), persistent organic pollutants, radioactive materials, and antimicrobial agents.



● Illustration of trends across the life cycle of different kinds of novel entities, including production of plastics and chemicals, use of pesticides, emissions of PFASs, and impacts such as antimicrobial resistance (AMR). Production, use, release, and impacts of many novel entities are increasing, posing threats to the Earth System as well as to environmental and human health.

The boundary is being pushed by rapid growth in the volume and diversity of chemical and material production. Substances are produced, used, and released through industry, agriculture, consumer products, healthcare, infrastructure, and waste systems. Testing, regulation, and monitoring have not kept pace, especially for mixtures, transformation products, and long-term effects across air, water, soils, sediments, and living organisms.

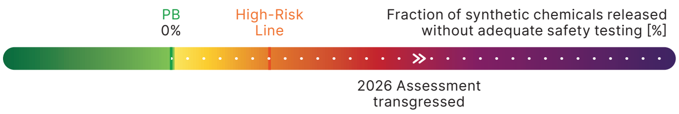
Why does this matter?

Novel Entities can erode ecosystem resilience and amplify pressures on other Planetary Boundaries. Their gravest risk, however, lies in the unknown: Many substances are released at scale before their long-term, combined Earth system effects are understood. Some persist for millennia, travel far from their sources, accumulate in organisms and food webs, or transform into new compounds with different properties. By the time harmful effects are clearly proven, contamination may already be widespread and difficult or impossible to reverse.

For people, risks can arise through contaminated food and water, chemical exposure, reduced ecosystem services, threats to crop production, and rising antimicrobial resistance.

How is this boundary assessed?

The current boundary for Novel Entities uses a precautionary proxy: the share of novel entities released into the environment without adequate safety testing. The safe level is set at 0% inadequately tested release.



Where are we now?

The boundary is **transgressed**. Production, use, and release of many novel entities – including plastics, synthetic chemicals, pesticides, and PFASs – continue to increase, while safety testing, monitoring, and regulation lag behind. Observed impacts already show the scale of concern: PFASs are detected globally in water, soil, wildlife, and humans; PCBs still affect marine mammals decades after bans; plastics and microplastics are widespread across environments; pesticides contribute to insect and pollinator decline; and antimicrobial use has helped drive antimicrobial resistance.

Many of these effects are irreversible on human timescales. Continued growth could amplify biodiversity loss, further disrupt food webs, and generate new risks faster than societies can respond to them.

4 | Solutions and Outlook

Photography by Mattias Klum

The Planetary Health Check is designed as a diagnostic tool. It identifies where human pressure on the planet is already too high, where risks are increasing, and where continued transgression could undermine Earth's stability and resilience. Such a diagnosis does not define a single policy program, but it does set a clear benchmark for action: Societies need to return to, and remain within, the Safe Operating Space.

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

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

Countries need stronger institutional capacity to interpret these risks nationally. We recommend establishing a **Chief Planetary Scientist**, or an equivalent independent advisory role, in every country. Such a position would translate global Earth system science into national risk assessment, support coordination across ministries and agencies, and help ensure that climate, biodiversity, water, land, pollution, and resilience are considered together.

The Planetary Boundaries should also inform **macroeconomic thinking** more broadly. Climate policy has already introduced the idea of a remaining carbon budget. Comparable limit and budget approaches are needed for other boundaries. Such budgets translate physical constraints into economic information. They reveal where risks are underpriced and clarify the economic value of intact forests, resilient ecosystems, clean water, stable soils, and functioning oceans. This could represent a powerful driver of innovation, directing investment and technological development toward solutions that reduce pressure on the Earth system while supporting long-term prosperity. In this context, Planetary Commons[128] such as the Amazon rainforest highlight the need to account for Earth system elements of planetary importance, no matter where they are located.

International efforts are slowly moving in this direction. The High Seas Treaty marks progress for biodiversity beyond national jurisdiction, while debates over deep-sea mining show that seafloor integrity remains an unresolved frontier. Negotiations on a global plastics agreement show growing recognition that novel entities require international control across their life cycle.

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

To support the enormous societal challenge of returning to the Safe Operating Space, the Planetary Boundaries Initiative (PBI) is being developed as a global, collaborative platform to advance the Planetary Boundaries framework and translate it into real-world impact. It brings together science, solutions, and communication to better assess planetary risks, track their development, and support responses across science, policy, business, and civil society. The PBI will strengthen the scientific basis of the framework, support participatory expert processes, integrate diverse knowledge systems, and improve how global thresholds are connected to practical decisions. To make this possible, it will build shared analytical workflows, reproducible data systems, and accessible decision-support formats that help turn complex Earth system knowledge into clear, usable insights. Overall, the PBI seeks to create a transparent, actionable, and globally connected foundation for helping societies return to and remain within Earth's Safe Operating Space.

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