Mongabay Series: Covering the Commons, Planetary Boundaries

The nine boundaries humanity must respect to keep the planet habitable

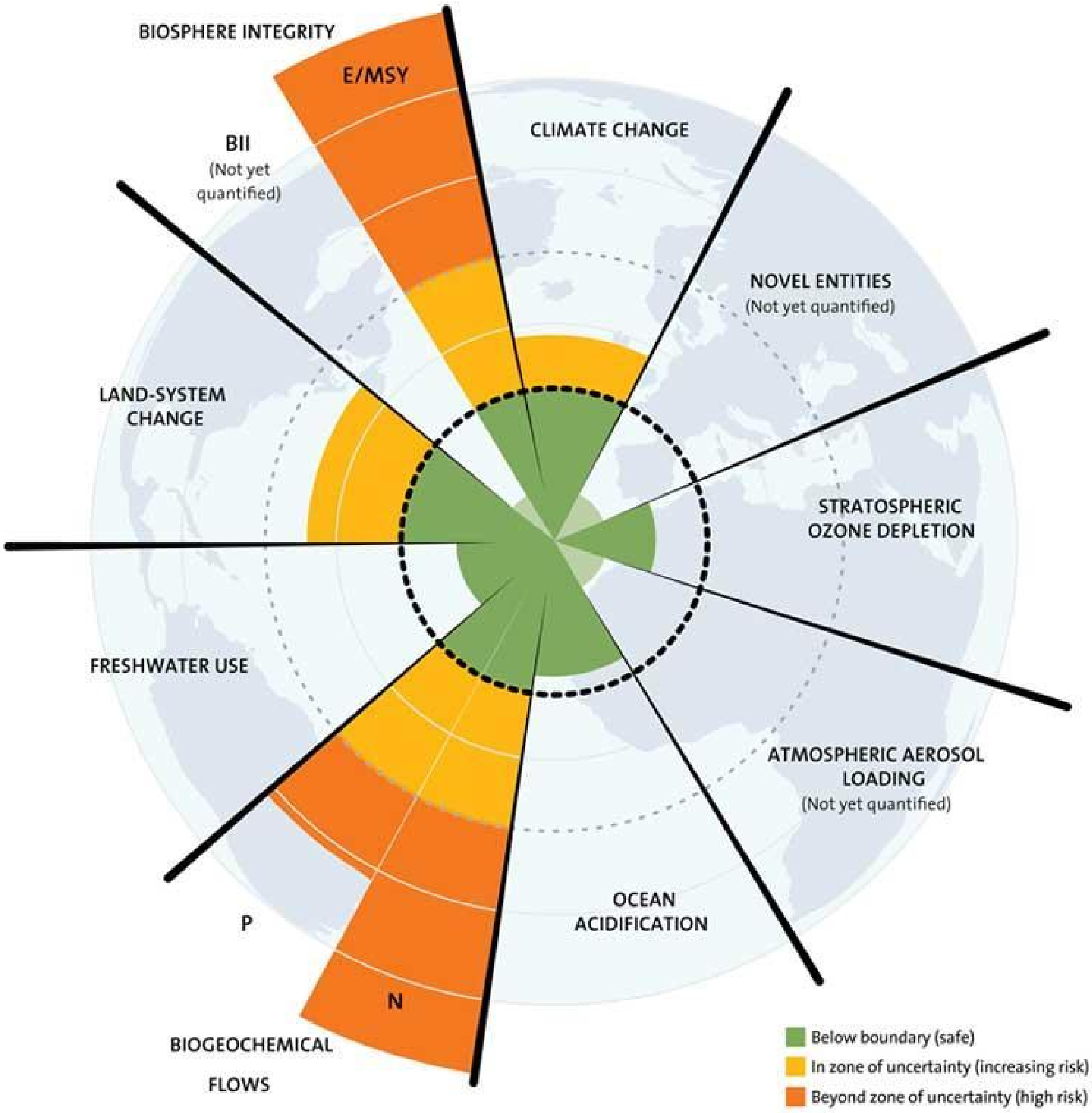
by Claire Asher on 30 March 2021

- *All life on Earth, and human civilization, are sustained by vital biogeochemical systems, which are in delicate balance. However, our species — due largely to rapid population growth and explosive consumption — is destabilizing these Earth processes, endangering the stability of the "safe operating space for humanity."*
- *Scientists note nine planetary boundaries beyond which we can't push Earth Systems without putting our societies at risk: climate change, biodiversity loss, ocean acidification, ozone depletion, atmospheric aerosol pollution, freshwater use, biogeochemical flows of nitrogen and phosphorus, land-system change, and release of novel chemicals.*
- *Humanity is already existing outside the safe operating space for at least four of the nine boundaries: climate change, biodiversity, land-system change, and biogeochemical flows (nitrogen and phosphorus imbalance). The best way to prevent overshoot, researchers say, is to revamp our energy and food systems.*
- *In 2021, three meetings offer chances to avoid planetary boundary overshoot: the Convention on Biological Diversity meeting in Kunming, China; the U.N. Climate Summit (COP26) in Glasgow, U.K.; and the U.N. Food Systems Summit in Rome. Agreements with measurable, implementable, verifiable, timely and binding targets are vital, say advocates.*

Advanced human societies emerged during an unprecedented period of stability on Earth. During the 12,000 years prior to the Industrial Revolution, our planet's surface temperature varied by less than 1° Celsius (1.8° Fahrenheit) above or below the average for that entire period. As a result, life — both human and wild — thrived.

But over the past two centuries, humanity has dramatically increased greenhouse gas concentrations in the atmosphere, pushing us outside this "safe" climate zone; outside the conditions for which civilization has been designed.

Unfortunately for us, climate change represents just one of nine critical planetary boundaries, which the imprudent actions of our species risk dangerously destabilizing and overshooting.



The nine planetary boundaries, counterclockwise from top: climate change, biosphere integrity (functional and genetic), land-system change, freshwater use, biogeochemical flows (nitrogen and phosphorus), ocean acidification, atmospheric aerosol pollution, stratospheric ozone depletion, and release of novel chemicals (including heavy metals, radioactive materials, plastics, and more). Image courtesy of J. Lokrantz/Azote based on Steffen et al. 2015 (via Stockholm Resilience Centre).

A safe operating space for humanity

In the mid-2000s, Johan Rockström, founding director of Sweden's Stockholm Resilience Centre, gathered an international, interdisciplinary team of scientists to unite behind a single goal: define the boundaries for a "safe operating space for humanity" on Earth. They asked themselves: what are the safe operating limits of our planet, and what changes can we force on it before we trigger rapid, catastrophic environmental harm?

In 2009, the center published the Planetary Boundaries Framework, which outlined nine key processes, influenced by humanity, that threaten the stability of the entire Earth System. These are: climate change, biodiversity integrity (functional and genetic), ocean acidification, depletion of the ozone layer, atmospheric aerosol pollution, biogeochemical flows of nitrogen and phosphorus, freshwater use, land-system change, and release of novel chemicals (including heavy metals, radioactive materials, plastics, and more).

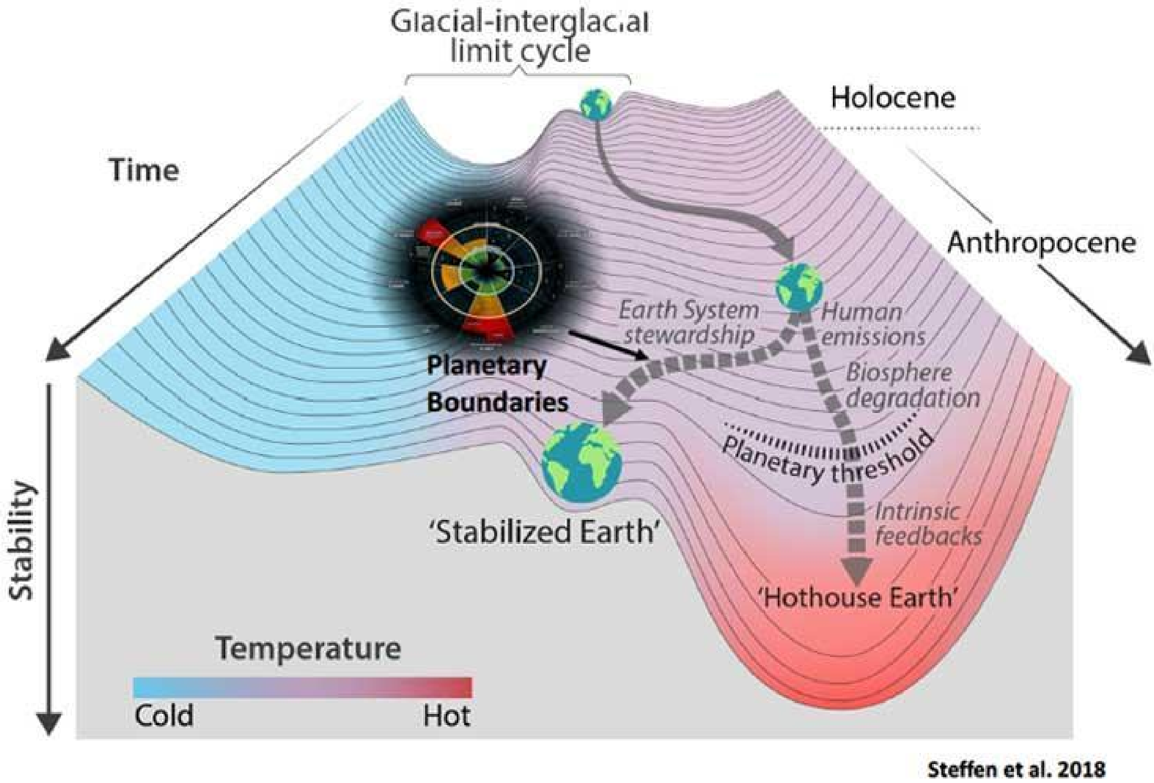
Together, the stability of these nine processes is essential to maintaining the Earth's atmosphere, oceans and ecosystems in the delicate balance that has allowed human civilizations to flourish. However, these are also the processes that human activities have impacted most profoundly.

The researchers then estimated a limit of just how much human activities could exploit and alter each of these processes before the global system would pass a tipping point — a threshold beyond which we risk sending the Earth spiraling into a state that hasn't been experienced for the entirety of human existence, bringing extreme change that could crash civilization and endanger humanity.

"Systems — from the oceans and ice sheets and climate system and ecosystems — can have multiple stable states separated by tipping points," explained Rockström, now the director of the Potsdam Institute for Climate Impact Research. If those "stable" systems are pushed too far, he said, they lose resilience and can transition, abruptly and irreversibly, into a new self-reinforcing state — one that might not support humanity.

The original 2009 Planetary Boundaries report, and its update in 2015, revealed a stark assessment: researchers found that humanity is already existing outside the safe operating space for at least four of the nine planetary boundaries: climate change, biodiversity, land-system change, and biogeochemical flows (Earth's nitrogen and phosphorous cycles, which are being heavily impacted by global agribusiness and industry).

However, the experts warn, these limits are estimates: what we don't know is how long we can keep pushing these key planetary boundaries before combined pressures lead to irreversible change and harm. Think of humanity, blindfolded, simultaneously walking toward nine cliff edges, and you gain some sense of the seriousness and urgency of our situation.



Earth Trajectories: Think of the Earth's climate taking different trajectories through time — pathways weaving between different climate states. Different paths through all the possible climates can be influenced by distinct tipping points. Self-reinforcing feedback processes can lock the planet into a particular trajectory for centuries or millennia. There is no evidence that modern societies can exist, let alone thrive, in conditions substantially different from the Holocene. Image courtesy of Steffen et al. (2018).

Dawn of the Anthropocene

The dynamics of large, complex and interconnected biogeochemical systems like those operating on Planet Earth can be thought of in terms of pathways or trajectories, weaving between different steady states. The Earth's trajectory can be altered by tipping points, which shift us from one steady state to another (something like a car changing gears). A number of complex feedback processes can either reinforce the current steady state, or weaken it, and send the planet spiraling toward a completely new state, like a bowling ball with too much spin careening toward the gutter.

Climate change, the best known of the nine planetary boundaries on which we're encroaching, offers a good example of how this equilibrium process works.

Today, "We are at risk of triggering tipping elements in the Earth System towards a 'Hothouse Earth' from which it would be very difficult to recover to pre-industrial climate," explained Steven Lade, a Stockholm Resilience Centre researcher specializing in social-ecological system modeling.

However, “with rapid decarbonization we could possibly reach a ‘Stabilized Earth,’” he added, maintaining our climate within the safe window of conditions to which humanity has adapted over the last 12,000 years.

The period of Earth climate stability in which our societies have thrived is known as the Holocene epoch. Beginning some 12,000 years ago, it marked the end of more than 100,000 years of alternating glacial and interglacial periods that saw the planet’s temperature fluctuate by as much as 6°C (10.8°F).

Modern humans have existed for about 200,000 years, but it was “only in the last 10,000 years that we were able to develop civilization as we know it,” Rockström said. “The very origins of modern civilization, namely domestication of animals and plants and the establishment of agriculture, happened in the Holocene.”

The world’s crops will need to feed 8 billion people by 2023, putting incredible pressure on Earth Systems. Image by Albert Aschl via Flickr (CC BY-NC-SA 2.0).

Yet these very same hallmarks of our extraordinary success — agriculture, sedentary living, industrial manufacturing — are today fundamentally altering many Earth System processes responsible for keeping conditions on Earth stable.

In fact, our transgressions of the nine planetary boundaries have been so severe that geologists believe we have entered a new epoch in the Earth’s history. The start of the Anthropocene — a human-influenced period that scientists say was initiated somewhere between 10,000 and 70 years ago — has been marked by rapid, human-triggered increases in greenhouse gas emissions, large-scale land-use change, extreme biodiversity loss, and massive global consumption and pollution brought on by rapidly advancing technology and a booming *Homo sapiens* population.

The dawn of the Anthropocene, a new epoch, needs to serve as a warning, Rockström said, that "we're starting to hit the ceiling of the biophysical coping capacity of the whole Earth System."

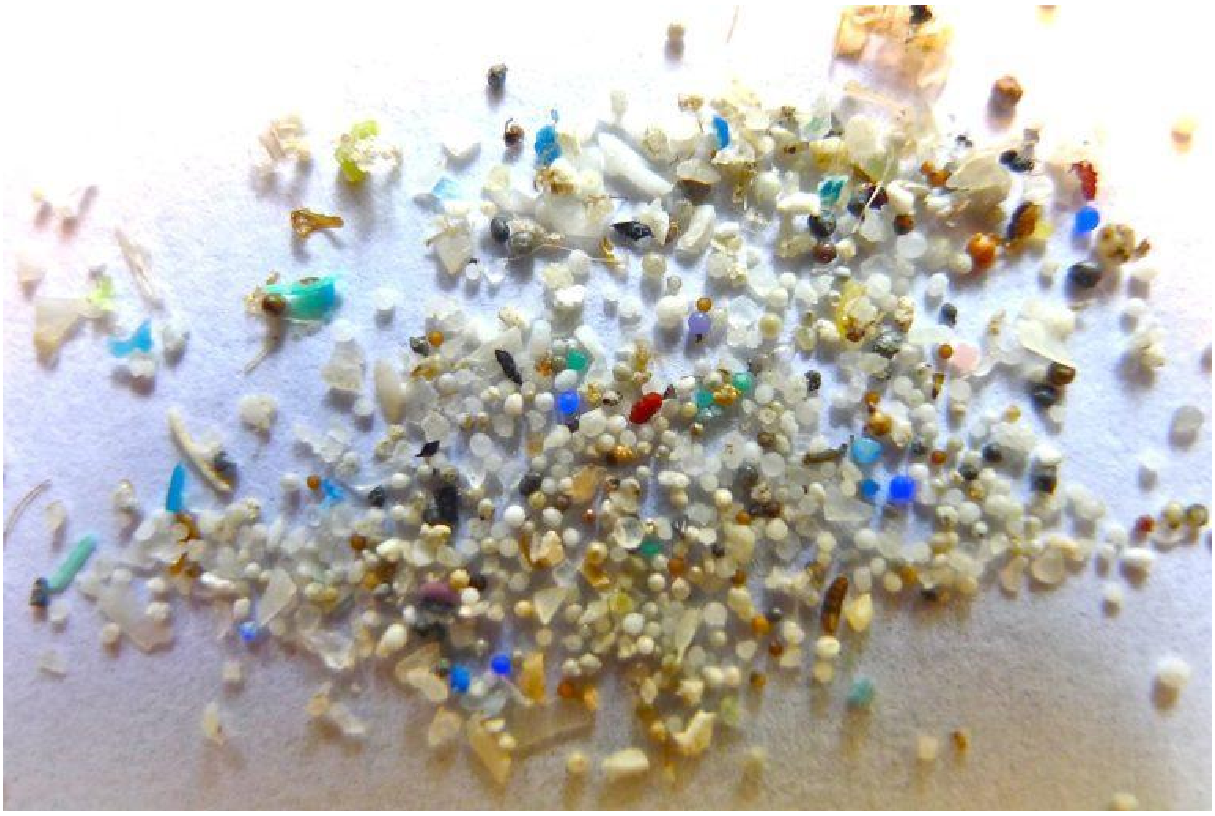
Ocean abundance: As important as biodiversity is, scientists say that measuring total species populations — abundance — is a more informative basis for assessing biosphere health. Image by Olivier Roux via Flickr (CC BY-NC 2.0).

On a path to climate and biodiversity overshoot

Six years on from the last Stockholm Resilience Centre update (another is due this year), Rockström noted there is little evidence we've reversed course to avoid looming tipping points. "If anything, we are even deeper into the transgression of climate, on biodiversity, on land-use, and on nitrogen and phosphorus. So we have not turned around the [2015] trends."

Of the four boundaries that researchers say we have already exceeded, climate change and biosphere integrity are considered "core" planetary boundaries because either one, on its own, could change the course of Earth's trajectory and endanger humanity.

"There's enough science today to say that [human-induced climate change] on its own can knock the planet away from the Holocene state," Rockström said. "Similarly, if we just continue our mass extinction, losing more and more species, from phytoplankton to top predators, you will come to a point where the whole planet [system] collapses."



What we can't see can hurt us: Microplastics like these are an example of novel entities — materials, chemicals, nanotech particles, even new life forms, created by humans and released into the environment, often with unknown effects. Novel entities may represent a third core boundary, in addition to climate and biodiversity, because of the potential for a global disaster resulting from a human-made substance that, for example, influenced animal and human fertility. Image by Oregon State University via Flickr (CC BY-SA 2.0).

There is strong evidence we're already in the midst of a global mass extinction. A 2019 assessment by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) reported that 25% of plants and animals assessed — totaling 1 million species worldwide — are threatened with extinction. A separate study found that more than 500 vertebrate species are on the brink, each with fewer than a thousand individuals remaining in the wild.

Importantly, researchers say we are flying blind when it comes to both the quantity or quality of biodiversity loss that can be tolerated by ecosystems before triggering irreversible change.

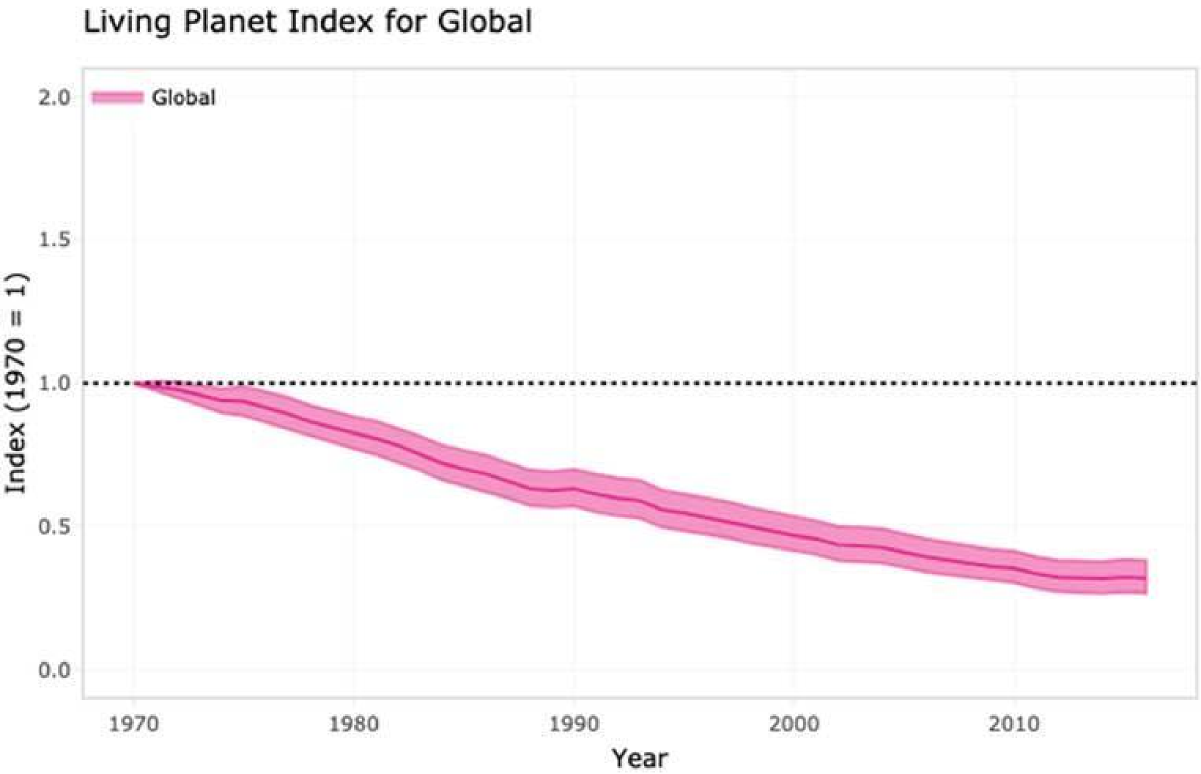
Securing genetic diversity: Scientists say metrics designed to monitor our position regarding the biosphere planetary boundary must consider both genetic and functional diversity of species, populations and ecosystems. Tropical forests contain huge amounts of untapped genetic diversity, which scientists are trying to protect using vast gene banks, such as the CIAT gene bank in Colombia. Image courtesy of N. Palmer/CGIAR.

"IPBES made it clear that we have really high extinction rates right now and they're getting higher," said Rebecca Shaw, chief scientist and senior vice president of WWF. However, data not on extinctions, but on total population declines, are actually more informative for assessing biosphere health, she said, noting, "By the time species are moving to extinction there's very little you can do."

"We should really be looking at population [abundance] declines around the world, and nest that with ecosystem integrity measures, and nest that in [measures of] the way ecosystems are functioning to deliver services to humans," Shaw explained.

According to WWF and the Zoological Society of London's (ZSL) 2020 Living Planet Report, population sizes of mammals, birds, amphibians, reptiles and fish declined by 68% on average between 1970 and 2016 — a strong alarm call.

As cities spread across the landscape, they consume and pollute, pushing Earth Systems toward destabilization and the overshoot of planetary boundaries. Image courtesy of NASA.



Living Planet Index: Diverse ecosystems deliver an astonishing array of natural services, from pollination and pest control to flood regulation, erosion prevention, and clean air and water, and they provide us with food, biofuels, materials, and medicine — benefits that could start to degrade and disappear if we push the biosphere boundary too far. The Living Planet Index (LPI) is a measure of the state of the world's biodiversity produced annually by WWF and the Zoological Society of London (ZSL), based on assessments of populations of vertebrate species. It shows that populations of mammals, birds, amphibians, reptiles, and fish have declined by 68% since 1970. Image courtesy of Living Planet Report 2020, WWF/ZSL.

Early warnings

Scientists are now detecting the first flashing warning lights on the Earth System dashboard, telling us humanity is already pushing beyond our world's safe operating space for multiple planetary boundaries and approaching tipping points.

"We have changed the planet so much that it is very likely that there will be significant impacts, and we're seeing those impacts in the last five years," Shaw said.

An example: melting of the Greenland and West Antarctic ice sheets has accelerated since the early 1990s, suggesting these colossal ice deposits may have now entered a new state of sustained and escalating retreat, after many centuries of stability. Contained within these now vulnerable ice sheets is enough water to raise the global sea level by more than 65 meters (213 feet).

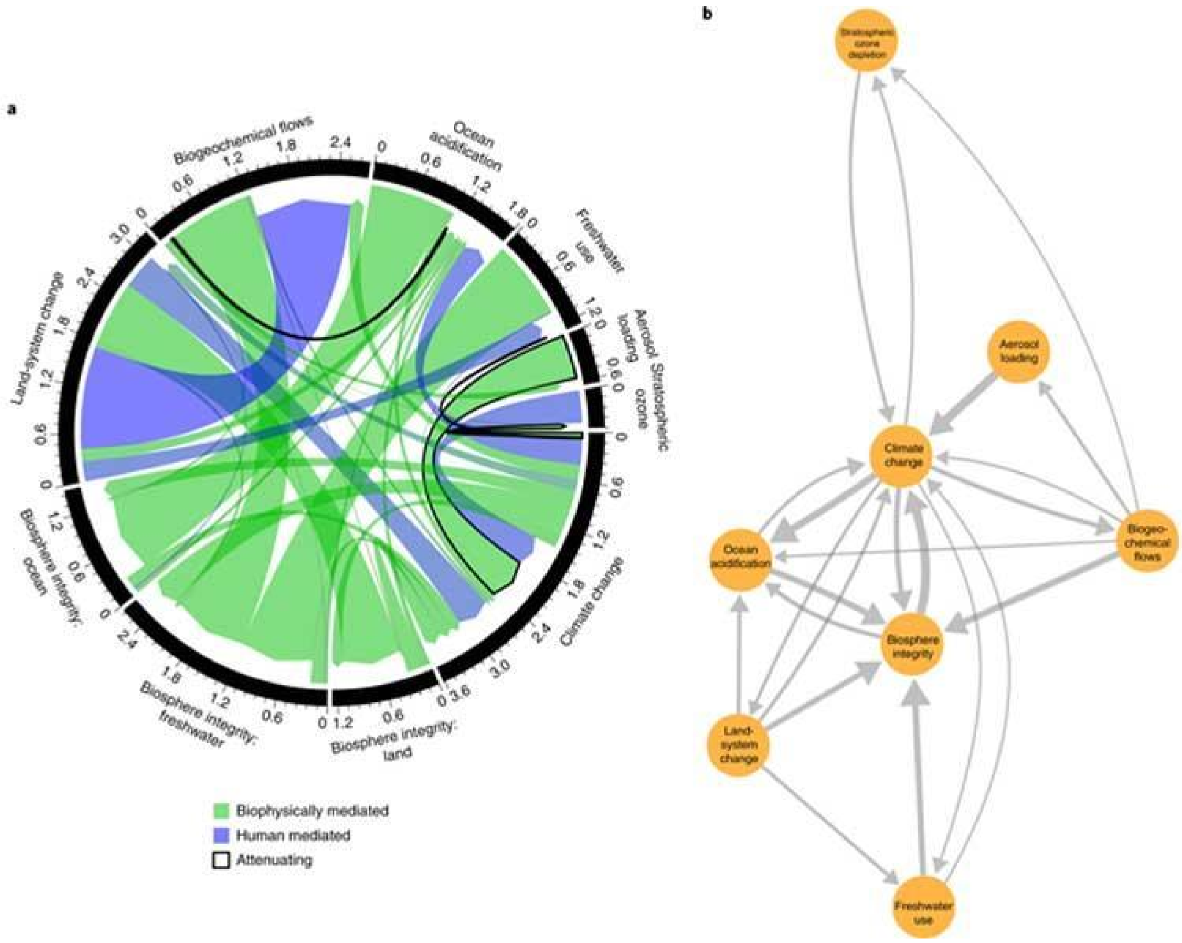
Greenland ice sheet: This great icebound northern island lost 3.8 trillion metric tons of ice between 1992 and 2017, contributing 10 millimeters to global sea-level rise so far. Future ice loss is certain to accelerate as the globe warms. The flow of melting ice into the oceans is not only raising sea levels, but the influx of freshwater could alter global ocean currents and even the world's climate. This image of northwest Greenland was captured by the Copernicus Sentinel-3 satellite. Image by the European Space Agency via Flickr (CC BY-SA 2.0).

Similarly, Arctic sea ice is retreating and scientists predict the region could be mostly ice-free in the summer as early as 2035 — with no certainty of what extreme changes this might bring.

Other early warning signs that we are approaching a climate change tipping point include increasingly frequent and severe droughts, heat waves, storms, and tropical cyclones.

“The number of climate-related natural disasters is climbing at an alarming rate, with significant economic and health impacts, especially for the most vulnerable,” said Ana María Loboguerrero Rodríguez, head of Global Policy Research for the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

No one knows how much stress civilization can withstand before it starts to collapse.



Earth Systems and the nine planetary boundaries do not exist separately. They form a vast web of interrelated processes and functions — unbalance one, and the stability of others is impacted. Image courtesy of Steffen et al. (2015) via Stockholm Resilience Centre.

Feedback loops upon feedback loops

These early changes are signs of an impending shift from once stable Holocene conditions, say scientists. More concerning: many of these changes are expected to create positive feedback loops that further accelerate change.

For example, the continued melting of the Greenland ice sheet will not only cause major sea level rise, but also could alter ocean surface temperature and salinity, potentially triggering a transition in ocean circulation systems like the Atlantic Meridional Ocean Circulation (AMOC), which in turn could drastically alter global climate, and even accelerate the loss of the East Antarctic Ice Sheet.

However, it's not all likely to be bad news: some feedback loops may have a balancing effect on the climate and on other planetary boundaries. "Which of these feedback loops wins, and when, is one of the big questions about our future climate," Lade said.

Still, these reinforcing loops could trigger more complicated cascades of change. "The whole Earth System is a complex self-regulating system," Rockström said, "if you push one [planetary boundary] too far it can cascade like a domino and impact the others."

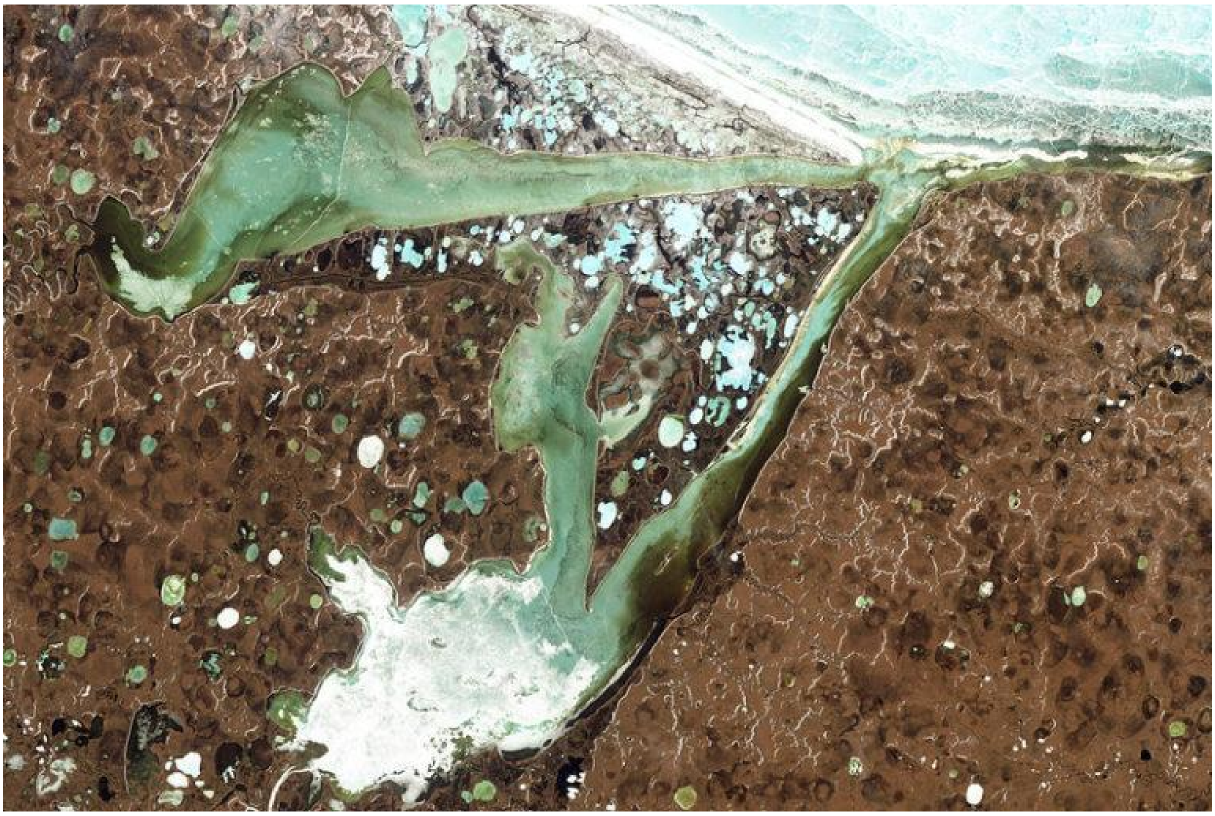
For example, land-use change due to agriculture is the leading cause of deforestation worldwide; it reduces the amount of water released to the air from plant leaves. In the Amazon Basin, this transpiration is a major source of rainfall. But signs are strong that rapid Amazon deforestation — combined with global climate change — may be triggering more extreme drought, leading to an abrupt shift from rainforest to degraded savanna, with profound implications for the entire planet. That biome-wide shift would release a vast store of ancient sequestered carbon, exacerbating climate change, leading to more drought and more tree die-off — a vicious, self-multiplying cycle.

Roads penetrating the Brazilian Amazon are followed by illegal loggers, then by cattle ranchers, then by soy growers in a vicious cycle that is ravaging the tropical nation's greatest, most biodiverse biome — potentially leading to a catastrophic rainforest-to-degraded-savanna tipping point. Image courtesy of NASA.

"There is growing concern that, with the recent increase in deforestation rates under Brazil's [Jair] Bolsonaro government, we may be approaching a tipping point for the Amazon rainforest," said Will Steffen, emeritus professor at the Australian National University, Canberra, who was part of the team that developed the original planetary boundaries framework. "The three [Earth System tipping points] of greatest concern in my view are the Amazon rainforest, the Greenland ice sheet, and Siberian permafrost."

The Amazon Rainforest example shows how disruptions to regional processes — such as the cycling of water by trees — can add up and push us toward planet-wide tipping points.

Another tipping point example: the devastating wildfires striking Australia and California in 2019 and 2020. They arose from multiple factors — intensifying drought due to climate change, accumulated leaf litter, unusual wind patterns — that built up slowly. Then, a small human intervention, such as a spark from a utility company power transformer as happened in California, was enough to "change a forest to a shrubland overnight because of climate change," potentially altering biodiversity, Shaw said. "Climate change really manifests itself in these bursts of catastrophes."

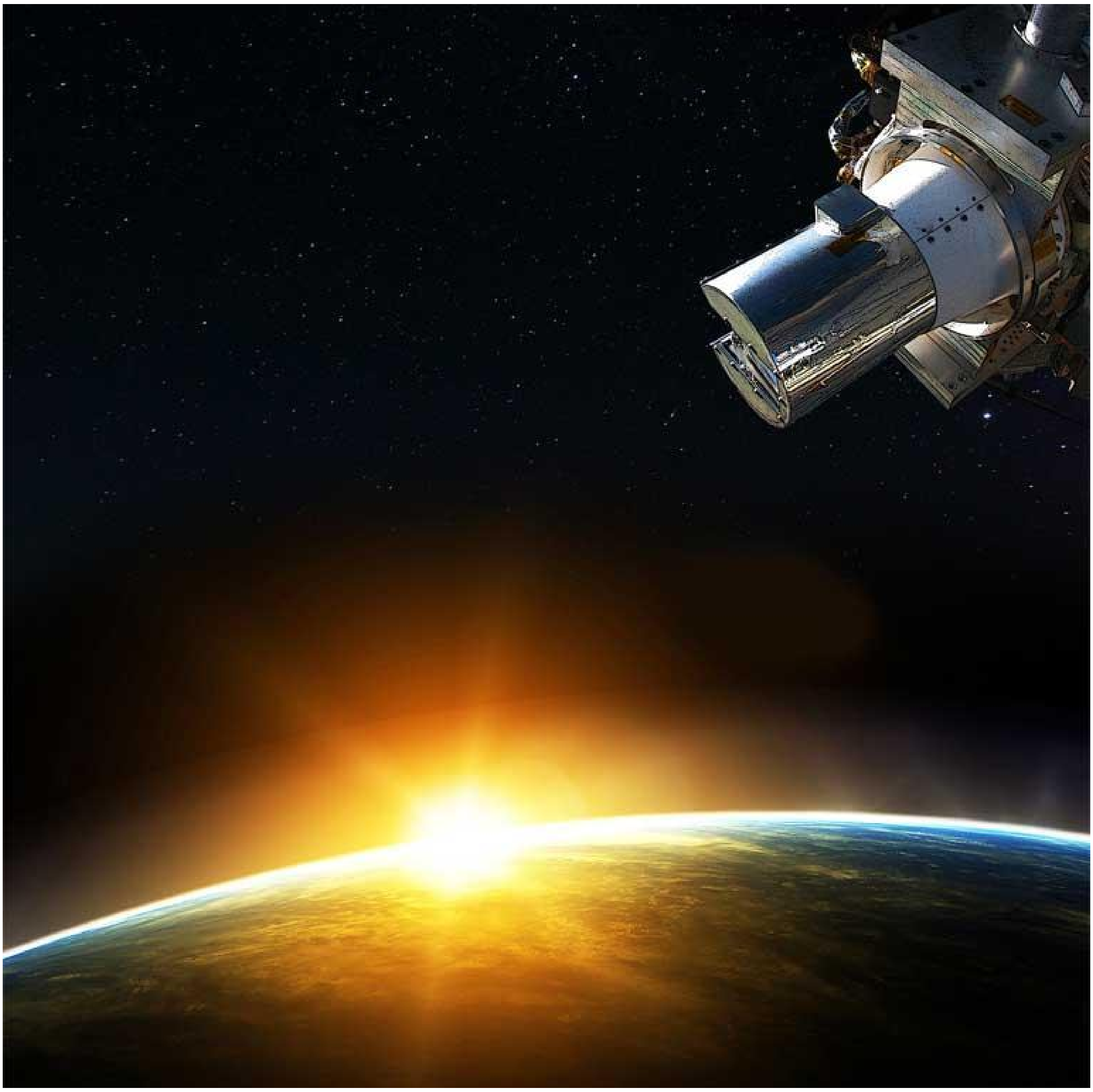


Omulyakhskaya and Khromskaya bays, northern Siberia, an Arctic region where permafrost melt and methane release to the atmosphere is rapidly escalating, contributing to climate change. Image by NASA Goddard Space Flight Center via Flickr (CC BY-SA 2.0).

Regional interactions between planetary boundaries may already be accelerating our trajectory away from a safe Earth operating space. “At a planet scale, you don’t [yet clearly] see these types of things; [but] at the regional scale, it’s really phenomenal how [the interaction between] climate change and biodiversity loss [for example] is manifesting itself,” Shaw noted. “We never thought we’d see [biodiversity] collapse like we’re seeing at the regional scale this early.”

As regional and global change intensifies, scientists warn that it’s what we don’t know about the vast complexity of interactions between Earth System processes — only a fraction of which have been well studied — that concerns them most.

“It is quite frustrating to have to admit that we don’t yet fully understand the fundamental interactions between planetary boundaries,” Rockström said. Even if we are able to bring the climate system back into a safe operating space, he added, “we may by that time have triggered so much forest dieback and so much permafrost thawing and so much ice melt … that the planet has already chosen another route” — another trajectory and steady state not conducive to human civilization.



Monitoring air pollution with SAGE III: The release of aerosol pollutants into the atmosphere threatens human health and could alter ocean-atmosphere circulation systems. The Stratospheric Aerosol and Gas Experiment III (SAGE III) was launched to the International Space Station in 2017 to monitor atmospheric aerosol pollution. Image by NASA's Marshall Space Flight Center via Flickr (CC BY-NC 2.0).

Food systems key to conserving a habitable Earth

If we are to steer our planet away from a devastating new trajectory, phasing out fossil fuels to reach a net-zero greenhouse gas emissions world economy is a key priority. But even more pressing, experts say, is a change to our food systems.

Food production accounts for nearly 25% of climate-changing greenhouse gas emissions, is the biggest driver of biodiversity loss, the primary cause of land-use change, one of the largest sources of nitrogen and phosphorus pollution, and it generates huge freshwater demand. Because food production generates big carbon emissions, it adds to ocean acidification too. That covers six of the nine planetary boundaries.

Together, “a food-system transformation and an energy transformation would take us a long way back into the safe space,” Rockström said.

“Nothing short of a systemic transformation of food systems is required to feed the world’s current and future population sustainably under climate change,” said CGIAR’s Loboguerrero. Making that sweeping change would not only reduce emissions, but improve health and food security, “providing multiple incentives for behavior change.”

Oil palm plantations in Malaysia. Humanity’s food systems, along with energy production, contribute most to destabilizing planetary boundaries. Image by Rhett A. Butler/Mongabay.

Setting ambitious policy priorities

The next 12 months offer golden opportunities for the global community to come together and agree on policy priorities to set Earth on a trajectory for long-term stability.

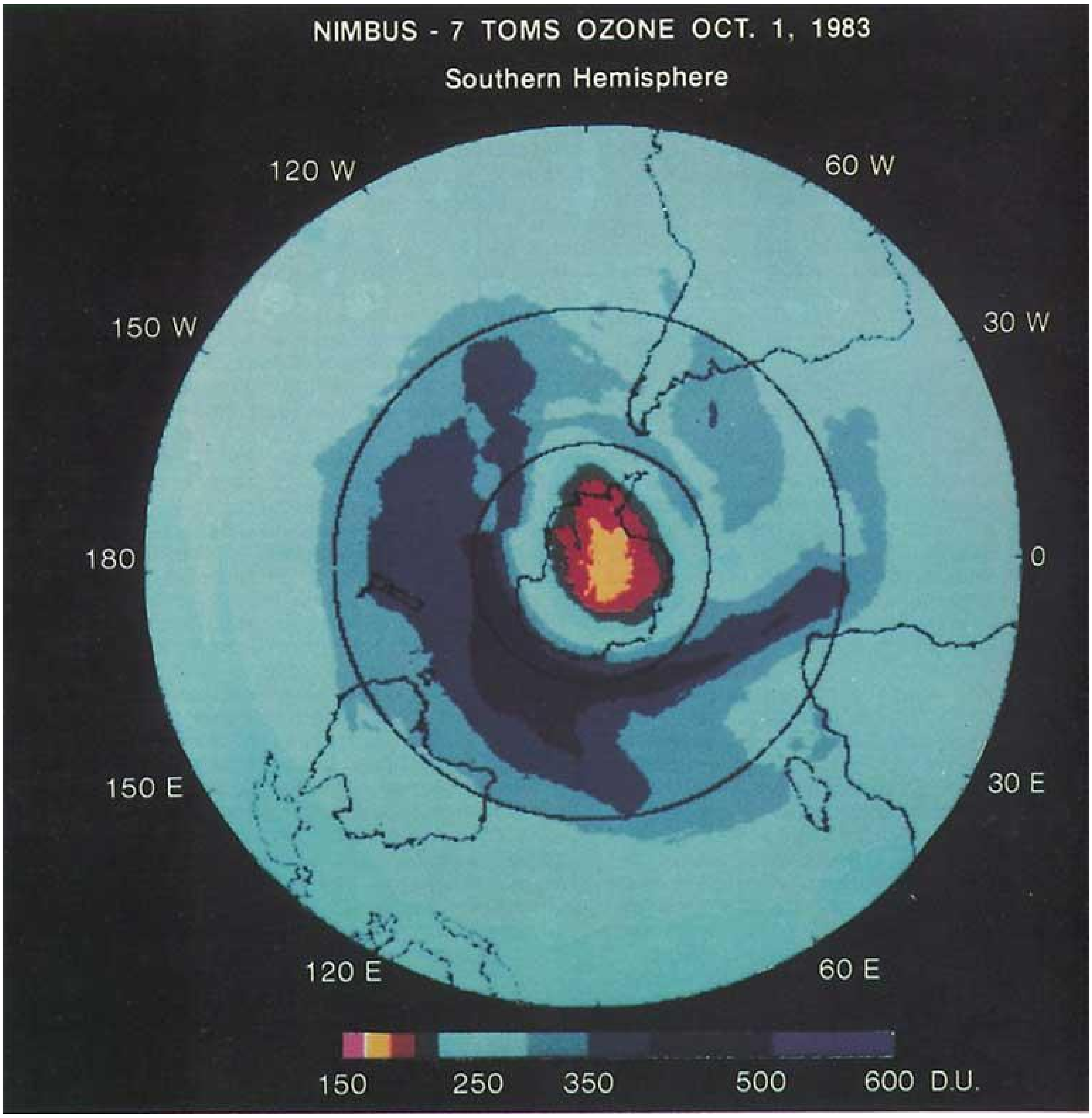
Three major international meetings are scheduled for 2021: the Convention on Biological Diversity’s (CBD) 15th meeting of the Conference of the Parties in

Kunming, China, from Oct. 11-24; the U.N. Climate Change Conference (COP26) in Glasgow, U.K., from Nov. 1-12; and the U.N. Food Systems Summit in Rome from July 19-21. Measurable, implementable, verifiable, time sensitive, and most importantly, binding targets and agreements are vital.

“It’s a big year for outcomes and for commitments for the next 10 years that will determine whether or not we stay within these planetary boundaries,” Shaw said. At WWF, she added, “we’re looking to work with other stakeholders through those three meetings to get actions to stay within the safe operating zone at both the regional scale and planetary scale.”

In a paper published in *Science* last October, Shaw joined an international team of scientists calling for the CBD to set “ambitious goals” for biodiversity and sustainability, such as no net loss of biodiversity by 2030.

What makes this year’s meetings more crucial than ever: reminders of past failed global summits, and a clear understanding that time is fast running out.



Repairing the ozone layer: The first evidence for degradation of the ozone layer over Antarctica was presented in 1985 and ultimately led to the international adoption in 1987 of the Montreal Protocol on Substances that Deplete the Ozone Layer. Now, more than 30 years later, the ozone layer is showing signs of recovery. Image by NASA Goddard Space Flight Center via Flickr (CC BY 2.0).

Cause for hope

Experts are calling for a transformative, holistic approach to avoid risky tipping points, seeing the entire Earth System as a shared global commons, with humans as stewards. “The intertwisted nature of this framework calls for the development of a novel governance approach at global, regional, and local scales,” Loboguerrero said.

One such framework is the Global Commons Alliance, which brings together more than 50 international NGOs, multinational corporations, and city policymakers to promote the adoption of science-based targets to operate within planetary boundaries. But that partnership will need to grow geometrically if we are to act effectively.

That's a daunting global goal. But there is one planetary boundary — the first we ever realized we were in danger of crossing — that offers hope: the depletion of the ozone layer. In 1987, the world's nations recognized the urgency and validity of the science, and embraced the politically binding requirements of the Montreal Protocol. We stepped back from the brink, shrinking the ozone hole, which could now be healed by 2050.

If nations can come together to address climate change, biodiversity loss, and pollution, as they did to address the threat to the ozone layer, then there is a chance we can reverse current trends and steer Earth's trajectory back toward a stable Holocene state. That chance is growing dimmer — but it is an effort we absolutely need to make.

A young orangutan in the wild. If we fail to prevent the overshoot of planetary boundaries not only does humanity risk oblivion, but so do many of the world's species. Image by Rhett A. Butler /Mongabay.

The Nine Planetary Boundaries: A closer look

The Planetary Boundaries Framework (last updated in 2015) defines nine key Earth System processes and sets safe boundaries for human activities. They are:

Climate change: Rising concentrations of greenhouse gases in the atmosphere are leading to increasing global temperatures. We passed the safe boundary of 350 parts per million of CO_2 in 1988. By 2020, levels were 417ppm.

Novel entities: One of the more elusive planetary boundaries, novel entities refers to harmful chemicals, materials, and other new substances (such as plastics), as well as naturally-occurring substances such as heavy metals and radioactive materials released by human activities. We release tens of thousands of synthetic substances into the environment every day, often with unknown effects. These risks are exemplified by the danger posed by CFCs to the ozone layer, or of DDT to biodiversity.

Stratospheric ozone depletion: The depletion of O_3 in the stratosphere as a result of chemical pollutants was first discovered in the 1980s and led to the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer. The ozone layer is now showing signs of recovery.

Atmospheric aerosols: Atmospheric aerosol pollution is a bane to human health and can also influence air and ocean circulation systems that affect the climate. For example, severe aerosol pollution over the Indian subcontinent may cause the monsoon system to abruptly switch to a drier state.

Ocean acidification: Rising atmospheric CO_2 levels are increasing the acidity of the world's oceans, posing a severe risk to marine biodiversity and particularly invertebrates whose shells dissolve in acidic waters.

Biogeochemical flows: We have profoundly altered the planet's natural nitrogen and phosphorus cycles by applying these vital nutrients in large quantities to agricultural land, leading to runoff into neighboring ecosystems.

Freshwater use: Agriculture, industry and a growing global population are putting ever greater strain on the freshwater cycle, while climate change is altering weather patterns, causing drought in some regions and flooding in others.

Land-system change: Changes in land-use, particularly the conversion of tropical forests to farmland, have a major effect on climate because of the impact on atmospheric carbon dioxide concentrations, on biodiversity, freshwater, and the reflectivity of the Earth's surface.

Biosphere Integrity: The functional integrity of ecosystems is a core planetary boundary because of the many ecoservices they provide, from pollination to clean air and water. Scientists are concerned about rapid declines in plant and animal populations, the degradation of ecosystems, and the loss of genetic diversity which could disrupt essential biosphere services.

Image and explanations courtesy of J. Lokrantz/Azote based on Steffen et al. (2015) via Stockholm Resilience Centre.

Banner image: Monitoring ice sheet melt: A WWF-sponsored research expedition to monitor melting of the Greenland ice sheet in 2009, led by Marco Tedesco of the City University of New York. Contained within the Greenland ice sheet is enough water to raise the global sea level by more than 65 meters (213 feet). Image by James Balog/Extreme Ice Survey.

Citations:

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