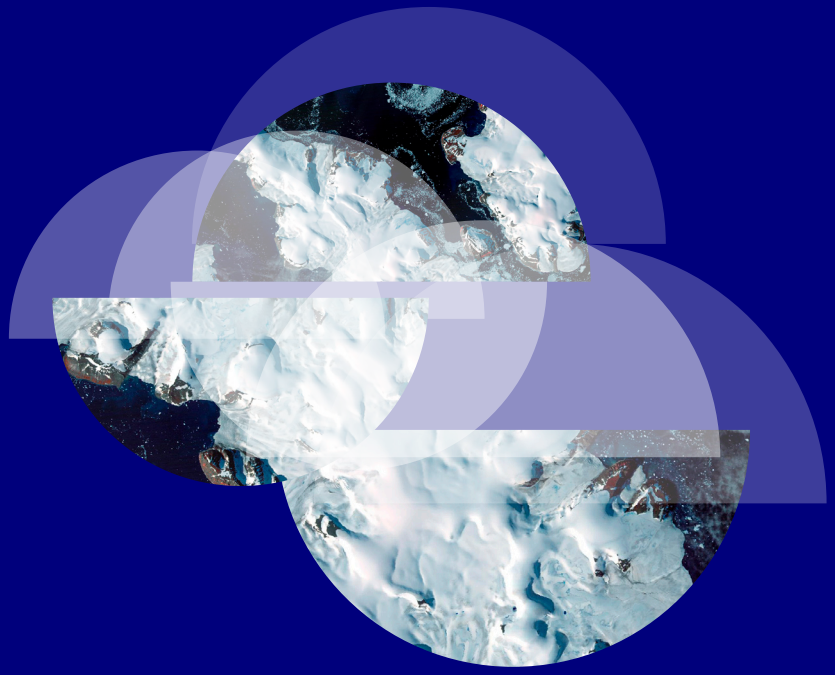
From Planetary Boundaries to

Planetary Politics



CONCITO

Planetary Boundaries

A brief introduction

The Planetary Boundaries framework describes nine, critical, interdependent Earth System processes that contribute to maintaining a stable and resilient Earth System as a whole. Transgressing the boundaries brings the system out of balance, with dire consequences for human health and well-being. The latest update from 2023 showed transgressions for six out of the nine boundaries: climate change, biogeochemical flows, biosphere integrity, land-system change, novel entities, and freshwater. Since the boundaries interact, policies aiming to address climate change will have limited success without addressing the other boundaries as well.

In this brief, we give a short, guided introduction to the planetary boundaries framework. We describe the control variables, the potential impacts of transgressing the boundaries, and the evolution of the planetary boundaries framework itself since its inception in 2009.

Brief 1
Andreas Lind, May 2024

About ”From Planetary Boundaries to Planetary Politics”

The project “From Planetary Boundaries to Planetary Politics” is carried out by the Danish green think tank CONCITO, with a scientific advisory board of researchers from University of Copenhagen, Stockholm Resilience Centre, and Potsdam Institute for Climate Impact Research. The aim of the project is to further, inspire, and support a more holistic approach to climate-, nature-, and environmental policy, using the Planetary Boundaries framework as a reference point.

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Content

Introduction

The climate, environmental, and biodiversity challenges and the crises we face today are inter-connected. By addressing and solving one without regard for the others, we risk exceeding the limits of our planet's carrying capacity.

The recent IPCC synthesis report on climate change (P.R. Shukla et al., 2022) emphasized the urgency of global and system wide action to curb and absorb GHG emissions or face the consequences of a rapidly heating planet. Yet, narrow efforts to solve the climate crisis risk worsening the already looming biodiversity and other environmental crises. This is already happening today, as for example documented by the first Global Assessment of Biodiversity and Ecosystem Services (IPBES 2019).

The planetary boundaries framework was introduced by a group of scientists in 2009 (Rockström et al., 2009). The framework builds on Earth System Science, a field of science studying the planet as a complex and adaptive system, where biological, physical, chemical and human dynamics interact to produce change (Steffen et al. 2020). The boundaries define the environmental limits within which humanity can safely operate. Since its inception, the concept has been widely taken up in the scientific community and has given rise to a large number of research articles and studies, as well as increasingly policy-oriented reports.

In this brief we give a short, guided introduction to the planetary boundaries framework. The brief consists of two short sections with more detailed information in the appendixes and references to key studies:

1. The Planetary Boundaries (as of 2023)

This section introduces the planetary boundaries, as well as its foundation in Earth System Science. It briefly describes the status of the boundaries based on the latest update of the framework (Richardson et al., 2023). Appendix 1 contains a more detailed description of each boundary, the consequences of transgressing them, and their control variables.

2. Planetary Boundaries – 2009-2023

The second section presents a rundown of the development the framework has undergone since its inception in 2009. Appendix 2 contains a summary table with more detail.

The Planetary Boundaries (as of 2023)

The Planetary Boundaries (PB) framework (Rockström et al., 2009), describes nine critical Earth System processes that contribute to maintaining a stable and resilient Earth System as a whole. When functioning as they did in (most of) the Holocene epoch, these processes together contribute to a "safe operating space" for humanity.

The Holocene is the name for the interglacial period that began approximately 11,700 years ago and that since have provided a relatively stable environment in which human societies could develop and thrive. However, since the beginning of the Industrial Revolution, humanity's influence on the Earth's system functions has increased rapidly to the extent that Earth System scientists have coined the term "the Anthropocene"[1] to emphasize the consequences of human activities on the biosphere (life on Earth) and the geosphere (the Earth's climate, energy balance, and resources) (Crutzen 2006). This is the core of PB science – to recognize and understand the pressures that humans are putting on the planet.

As such, the PB framework is the answer to an important question: "*What are the non-negotiable planetary preconditions that humanity needs to respect in order to avoid the risk of deleterious or even catastrophic environmental change at continental to global scales?*" (Rockström et al., 2009).

Figure 1 shows the latest status of the PB assessment (2023). It illustrates the nine Earth system processes (boundaries), the limit for a safe operating space, and the degree of transgression. Six out of the nine boundaries relate to processes of waste accumulation – namely climate change, novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, and biogeochemical flows – while the remaining three are related to human appropriation of limited Earth resources – freshwater change, land system change, and biosphere integrity.

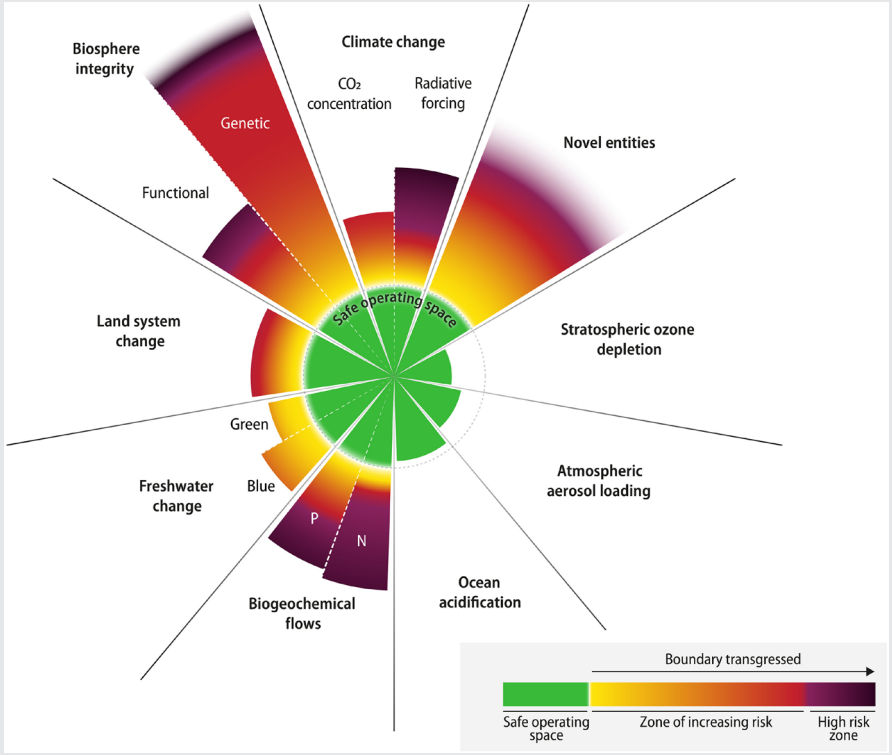

Figure 1. The Planetary Boundaries framework 2023 (Richardson et al., 2023)

[2] Recently, a majority of the international Subcommission on Quaternary Stratigraphy (SQS) voted against the proposal to create an Anthropocene epoch (https://www.nature.com/articles/d41586-024-00675-8).

Transgressing the boundaries brings the system out of balance. This has dire consequences for human health and well-being. In the 2015-update of the PBs, the authors argued that Climate change & Biosphere integrity should be "recognized as core planetary boundaries through which the other boundaries operate" (Steffen et al., 2015).

This implies that transgressions in the climate change and biosphere boundaries is likely to push the Earth system out of the Holocene state. For the other seven boundaries even though serious transgression will affect the conditions for human well-being, it does not by itself (necessarily) push us out of the safe operating space. Overall, however, the boundaries are interdependent and transgression of one boundary might very well contribute to transgression of the others increasing the risk of pushing the Earth system to a new state. An important lesson from PB science is therefore that we will have limited or no success on climate change without also addressing the other boundaries in parallel.

The PB framework provides a snapshot of the current state of the Earth system, measured through one or two proxy variables, called "control variables", for each boundary. For example, the Climate Change boundary is measured through two control variables: Atmospheric CO2 concentration (ppm CO2) and radiative forcing (W m-2).

Despite scientific advances, there is still much uncertainty surrounding the complexity of the Earth System processes. This uncertainty is reflected in the PB framework with a "zone of increasing risk" for each boundary threshold. The zone of increasing risk has previously been referred to as the "zone of uncertainty" (Steffen et al., 2015). To limit the risks of potentially catastrophic overshooting, the boundaries often referred to for each of the nine Eart system processes correspond to crossing from the safe operating space into the zone of increasing risk, as shown in Figure 1 and detailed in this quote:
"*Planetary boundaries are proxy boundaries based on a precautionary principle that are set at the lower end of a scientifically defined uncertainty zone about tipping points or thresholds of large-scale change. The precaution is motivated by the highly uncertain, but non-negligible probability of catastrophic welfare damages in the wake of a shift of the Earth system to a new state.*" (Rockström et al 2023, welfare economics)

For example, transgression of the Climate Change boundary, e.g. by emitting too much CO2, already today leads to regional climate disruptions, and loss of glacial freshwater supplies. Closely connected, ocean acidification is also a consequence of too much CO2 absorbed by the oceans. Although it keeps the level of atmospheric CO2 down, this balancing act e.g. leads to coral bleaching, with severe consequence for the communities who depend on the coral reefs for food and income. Emissions, particularly the burning of fossil fuels, also contribute to the number of aerosols in the air. Aerosols have multiple impacts on the Earth system, and a large negative impact on human health.

The next page contains the results from the latest revision (Richardson et al., 2023) – mirroring Figure 1. The control variables are explained in Appendix 1.

Note that only the boundary value for crossing from the safe operating space into the zone of increasing risk is reported in the table above. The PB framework also sets values for the upper end of the zone of increasing risk (before entering the high risk zone).

Table 1. Status of planetary boundaries, 2023.

Boundary	Status (2023-update)	Planetary boundary
Climate change Transgressed	417 ppm CO2 +2.91 W m-2	350 ppm CO2 +1 W m-2
Novel entities Transgressed	Transgressed (Estimated >0%)	0%
Stratospheric ozone depletion In safe operating space	284.6 DU	~276 DU
Atmospheric aerosol loading In safe operating space	0.1	0.076
Ocean acidification In safe operating space	2.8 Ωarag	≥ ~2.75 Ωarag
Biogeochemical flows Transgressed	P: Global: 22.6 Tg of P year−1; regional: 17.5 Tg of P year−1 N: 190 Tg of N year−1	P: Global: 11 Tg of P year−1; regional: 6.2 Tg of P year−1 N: 62 Tg of N year−1
Freshwater change Transgressed	Blue water: 18.2% Green water: 15.8%	Blue water: 10.2% Green water: 11.1%
Land system change Transgressed	Boreal: Americas, 56.6%; Eurasia: 70.3% Temperate: Americas, 51.2%; Europe, 34.2%; Asia, 37.9% Tropical: Americas, 83.9%; Africa, 54.3%; Asia, 37.5%	Boreal: 85% Temperate: 50% Tropical: 85%
Biosphere integrity Transgressed	Estimated >100 E/MSY Estimated 30% HANNP	<10 E/MSY <10% HANNP

Source: (Richardson et al., 2023)

If you want to read more:

- *Planetary Boundaries: Exploring the Safe Operating Space for Humanity (Rockström et al., 2009)*
- *Planetary boundaries: Guiding human development on a changing planet (Steffen et al., 2015)*
- *Outside the Safe Operating Space of the Planetary Boundary for Novel Entities (Persson et al., 2022)*
- *A planetary boundary for green water (Wang-Erlandsson et al., 2022)*
- *Earth beyond six of nine planetary boundaries (Richardson et al., 2023)*

The Planetary Boundaries 2009-2023

The planetary boundaries framework has been debated, challenged, and undergone significant revisions since 2009. A quick search on Web of Science (an academic literature search database) results in more than 1,100 entries (more than 800 articles[2]).

Currently, all larger assessments of country performance in a planetary boundary framework lens use the original 2009 or the updated 2015-edition of the framework. To understand the conclusions and decisions made in these assessments, one must understand the framework used at that time and how it differs from the most recent edition of the framework. The aim of this section is to provide this understanding.

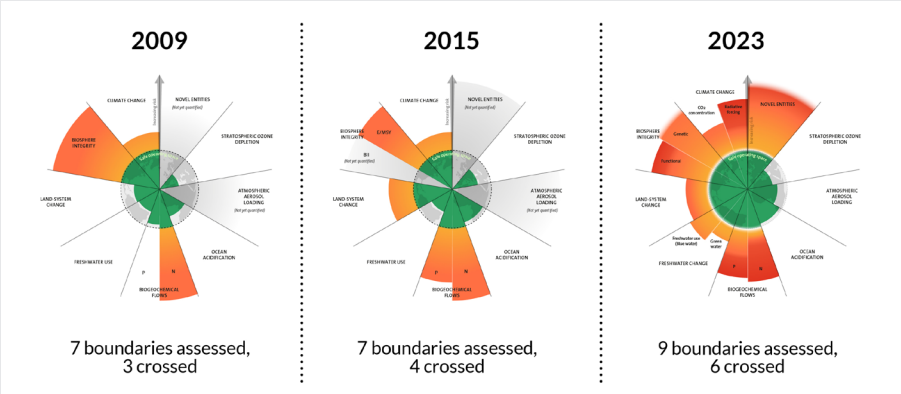

Figure 2. Planetary Boundaries over time. Credit: Azote for Stockholm Resilience Centre, Stockholm University. Based on Richardson et al. 2023, Steffen et al. 2015, and Rockström et al. 2009.

Assessed boundaries and status

The 2009-paper assessed seven boundaries[3] and found transgressions for three of them (climate change, biogeochemical flows, and biosphere integrity). In 2015, the same seven boundaries were assessed, and land-system change was added to the list of transgressed boundaries. Finally, the 2023-update saw all nine boundaries assessed, resulting in six transgressed boundaries, with novel entities and freshwater change added to the four transgressions from the 2015-update, confer Figure 2 below.

In early 2024, Potsdam Institute for Climate Impact Research announced the beginning of "The Planetary Boundary Science Initiative"[4] – PBScience in short – a scientific effort to provide more up-to-date knowledge on the health of the planet. The initiative has two overarching goals: 1) to provide annual updates to the planet's health (as opposed to the current 6-8 years between PB framework updates) and 2) to improve the measurements and modelling of how the Earth system functions and evolves under the pressure of human activity. This initiative is a promising addition to the PB framework and the science behind it.

Boundaries and control variables

In 2015, several boundaries received an update to include a two-tier approach with a regional and a global perspective, and climate change and biosphere integrity were, as previously mentioned, designated as "core boundaries", underlining their importance for the functioning of the Earth system processes. The 2023-edition saw further changes, particularly with regards to novel entities (now assessed), biosphere integrity (assessment of both genetic and functional biosphere diversity), atmospheric aerosol loading (assessed with new

[2] Per January 2024.
[3] Climate change, stratospheric ozone depletion, ocean acidification, biogeochemical flows, freshwater use, land-system change, and biosphere integrity.
[4] https://www.pik-potsdam.de/en/institute/departments/earth-system-analysis/research/pbscience

control variable for global PB), and freshwater change (new control variable). The most notable, recent changes concern freshwater change and biosphere integrity. Freshwater change is now considered in terms of both blue water (surface and groundwater) and green water (plant-available water). This change, combined with the new control variables measuring deviations from the preindustrial state, puts more emphasis on how the freshwater change boundary interacts with and impacts the other boundaries, e.g. through reduced carbon sequestration capacity, climate regulation, and biodiversity loss (Richardson et al., 2023).

For biosphere integrity, the recent update introduced a new control variable for functional diversity. The new variable, so-called human-appropriated net primary production (HANNP), replaces the Biodiversity Intactness Index used in the 2015-edition. This is better proxy for the integrity of the ecological functions of the biosphere.

See Appendix 2 for the detailed description of the changes to the framework over time.

If you want to read more:

- *Matching scope, purpose and uses of planetary boundaries science (Downing et al., 2019)*
- *Human impacts on planetary boundaries amplified by Earth system boundaries (Lade et al., 2019)*
- *The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a "Safe Operating Space" for Humanity (Biermann & Kim, 2020)*

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Appendix 1: The planetary boundaries framework

The nine boundaries, examples of consequences of transgression, and their control variables are described in the table below.

Table 2: The nine planetary boundaries, consequences of transgression, and control variables

Process	Description and examples of consequences of transgression	Control variable(s)
Climate change	The climate change boundary concerns Earth's energy budget, heavily impacted by anthropogenic drivers. It is one of the two core boundaries. Transgression of this boundary would lead to loss of polar ice sheets, regional climate disruptions, loss of glacial freshwater supplies, and weakening of carbon sinks, among other consequences.	The boundary is measured through two control variables: 1. Annual averages of atmospheric CO_2 concentration (ppm). The boundary is set at 350 ppm. 2. Radiative forcing (W m^{-2}). The boundary is set at 1 W m^{-2}.
Novel entities	Novel entities are defined as truly novel anthropogenic introductions to the Earth system, for example synthetic chemicals, nuclear waste, and genetically modified organisms. The impacts of novel entities on the Earth system are less researched than the other boundaries but could entail unacceptable impacts on human health and ecosystem functioning.	The share of released chemicals with adequate safety assessment and monitoring has been suggested as a candidate control variable (Persson et al., 2022). The boundary is set at 0% (i.e. no release of untested synthetics into the Earth system).
Stratospheric ozone depletion	Stratospheric ozone protects the Earth from ultraviolet radiation from the Sun. Transgression of this boundary would lead to severe and irreversible radiation effects on human health and ecosystems.	The boundary is measured in Dobson units (DU) and is set at 276 DU, corresponding to a less than five percent reduction from preindustrial levels.
Atmospheric aerosol loading	The boundary on atmospheric aerosol loading is complex and encompasses a multitude of different particles, both natural (e.g. dust) and human-caused (e.g. pollution from cars/factories). So far, biogenic aerosols have not been considered in the PB framework. Aerosols have multiple impacts on the Earth system, including scattering incoming radiation back to space and influencing hydrological cycles. Moreover, aerosols have a large negative impact on human health.	The control variable for the boundary for atmospheric aerosol loading is the mean interhemispheric difference in aerosol optical depth (AOD). AOD is a measure of the overall reduction in sunlight reaching Earth's surface. The planetary boundary value is set at 0.1.

Ocean acidification	The oceans play an important role in the Earth system as a CO_2 sink and as an integral part of the biosphere. This boundary is thus closely linked with the climate change boundary. Ocean acidification has serious impacts on coral reefs and associated ecosystems, with severe consequence for the portion of humanity depending on coral reefs and their ecosystems for food, income, and (storm) protection.	The control variable is carbonate ion concentration in surface seawater, measured as the average global surface ocean saturation state with respect to aragonite (an important mineral component of coral reefs susceptible to dissolution in acidic waters). The boundary is set at ≥ ~2.75 (≥80% of the preindustrial averaged global Ω_{arag} of 3.44).
Biogeochemical flows	Many biogeochemical flows are important for life on Earth and for Earth system functions. For now, the PB framework only encompasses two elements in the biogeochemical flows: nitrogen and phosphorus. Other elements, e.g. silicon, might be included in future updates (Richardson et al., 2023). All living things need nutrients. But exceeding the boundaries for nutrient flows has severe impacts on ecosystems, the climate, and biodiversity. Too much nitrogen leads to acidification of terrestrial ecosystems and eutrophication of coastal and freshwater systems. Similarly, an excess of phosphorus can lead to algal blooms and coastal “dead zones”.	There are both global and regional boundaries for phosphorus. The global boundary for phosphorus is set at 11 Tg of P per year from freshwater systems to the oceans. The global boundary is set to avoid a large-scale ocean anoxic event. The regional level boundary is set at a flow of 6.2 Tg of P per year from fertilizers to erodible soils. The planetary boundary for nitrogen is the application rate of intentionally fixed N (industrial and intentional biological) to the agricultural system of 62 Tg of N per year.
Freshwater change	The boundary for freshwater change contains two elements: blue water (surface and groundwater) and green water (plant-available water). Transgressing the freshwater change boundary could affect regional climate patterns (e.g. the monsoon), biomass production, carbon uptake, and biodiversity. Many of these with a direct impact on human livelihoods, through water supply or precipitation patterns.	Streamflow is used as a proxy for blue water and root-soil moisture is used as a proxy for green water. The control variables are thus defined as the percentage of annual global ice-free land area with streamflow/rootzone soil moisture deviations from preindustrial variability (1661-1860). Boundaries are set at ~10% for blue water and at ~11% for green water.
Land system change	The land-system change boundary focuses on the biogeophysical processes in land systems that directly regulate the climate (Steffen et al., 2015). It recognizes that the three major forest biomes have a large influence on the climate (and the other boundaries), also beyond the region in which the land-system change occurs. As such, transgression of the land system boundary can trigger irreversible and widespread conversion of biomes to undesired states, affecting e.g. carbon storage and biodiversity.	The control variable for the boundary is forest cover remaining compared to the potential area of forest in the Holocene. The boundary is set at 85% for boreal forests, 50% for temperate forest, and 85% for tropical forests.

Biosphere integrity	The biosphere is the part of Earth where life can exist and grow. It is one of the two core boundaries. The biosphere integrity boundary is set to preserve the overall dynamic and adaptive character of the biosphere and its functions that impact a range of the other boundaries. Transgression of the biosphere integrity boundary has impacts on especially the freshwater-, biogeochemical-, climate-, and land system boundaries. Moreover, large biodiversity losses are also unacceptable for ethical reasons.	There are two components of the biosphere integrity boundary: Genetic and functional. 1. The control variable for the genetic component is extinctions per million species per year (E/MSY). The boundary is set at 10 E/MSY (10 times the average background extinction rate). 2. The control variable for the functional component is the human appropriation of the biosphere's net primary production (HANNP). This is in essence the energy available to ecosystems. The boundary is set at 10% of preindustrial Holocene mean net primary production, meaning that >90% of the energy remains in the ecosystems for supporting biosphere functions.

Sources: Adapted from (Rockström et al., 2009), (Steffen et al., 2015), and (Richardson et al., 2023).

Appendix 2: The development of the planetary boundaries framework

The table below summarizes the conceptual changes the boundaries have undergone from 2009 to 2023:

Table 3: Planetary Boundaries framework development, 2009-2023

Boundary	2009-edition	2015-update	2023-update
Climate change	Unchanged		
Novel entities	Originally called "Chemical pollution" which included *radioactive compounds, heavy metals, and a wide range of organic compounds of human origin* Not assessed	Renamed as "Novel entities". Introduced as *new substances, new forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects* Not assessed	Redefined as *truly novel anthropogenic introductions to Earth system* Assessed as transgressed
Stratospheric ozone depletion	Unchanged		
Atmospheric aerosol loading	Not assessed	Introduced "AOD" as control variable. Suggested regional planetary boundary for South Asia (the South Asian Monsoon as a case study). Global boundary not yet quantified	Control variable for global boundary proposed as *mean interhemispheric difference in AOD*. Assessed as within safe operating space (globally).

Ocean acidification	Unchanged		
Biogeochemical flows	Originally called “Interference with the global phosphorus and nitrogen cycles”. Control variables defined as: • P: *inflow of phosphorus to ocean, increase compared with natural background weathering.* • N: *amount of N2 removed from atmosphere for human use, Mt N yr^{-1}*	Renamed as “Biogeochemical flows” to encompass human influence on biogeochemical flows in general (not just P and N flows). Introduced a two-level approach for phosphorus, with a regional-level boundary defined as *flow from fertilizers to erodible soils*. Control variables updated to: • P (global): *P flow from freshwater systems into the Ocean*. • N*: Industrial and intentional biological fixation of N*.	Unchanged from 2015.
Freshwater change	Originally called “Global freshwater use”. Control variable (only global) was *consumptive blue water use (km^3 yr^{-1})*.	Renamed as “Freshwater use”. Introduced *blue water withdrawal as % of mean monthly river flow* as a basin-level control variable to complement the global PB.	Revised to consider changes across the entire water cycle over land and differentiates between blue and green water. Control variables are redefined as *the variability of the percentage of global land area with deviations from the preindustrial state*
Land system change	Control variable was *percentage of global land cover converted to cropland*.	Control variable changed to (global) *area of forested land as % of original forest cover*, and (biome) a*rea of forested land as % of potential forest*. Assessed as a global, weighted average and per biome (boreal, temperate, tropical).	Unchanged from 2015.
Biosphere integrity	Originally called “Rate of biodiversity loss”. Did not distinguish between the functional and genetic component of biosphere integrity.	Renamed as “Biosphere integrity”. Introduced a two-component approach with genetic and functional biosphere diversity. Only genetic diversity was assessed (as transgressed). Proposed to use the Biodiversity Intactness Index (BII) as control variable for functional diversity.	Introduced a new control variable (*HANNP*) for functional diversity, replacing the proposed BII from the 2015-edition. Both biosphere integrity components assessed as transgressed