RESEARCH ARTICLE SUMMARY

SUSTAINABILITY

Planetary boundaries: Guiding human development on a changing planet

Will Steffen,* Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer, Elena M. Bennett, Reinette Biggs, Stephen R. Carpenter, Wim de Vries, Cynthia A. de Wit, Carl Folke, Dieter Gerten, Jens Heinke, Georgina M. Mace, Linn M. Persson, Veerabhadran Ramanathan, Belinda Reyers, Sverker Sörlin

INTRODUCTION: There is an urgent need for a new paradigm that integrates the continued development of human societies and the maintenance of the Earth system (ES) in a resilient and accommodating state. The planetary boundary (PB) framework contributes to such a paradigm by providing a science-based analysis of the risk that human perturbations will destabilize the ES at the planetary scale. Here, the scientific underpinnings of the PB framework are updated and strengthened.

RATIONALE: The relatively stable, 11,700-year-long Holocene epoch is the only state of the ES that we know for certain can support contemporary human societies. There is increasing evidence that human activities are affecting ES functioning to a degree that threatens the resilience of the ES—its ability to persist in a Holocene-like state in the face of increasing human pressures and shocks. The PB framework is based on critical processes that regulate ES functioning. By combining improved scientific understanding of ES functioning with the precautionary principle, the PB framework identifies levels of anthropogenic perturbations below which the risk of destabilization of the ES is likely to remain low—a "safe operating space" for global societal development. A zone of uncertainty for each PB highlights the area of increasing risk. The current level of anthropogenic impact on the ES, and thus the risk to the stability of the ES, is assessed by comparison with the proposed PB (see the figure).

RESULTS: Three of the PBs (climate change, stratospheric ozone depletion, and ocean acidification) remain essentially unchanged from the earlier analysis. Regional-level boundaries as well as globally aggregated PBs have now been developed for biosphere integrity (earlier "biodiversity loss"), biogeochemical flows, land-system change, and freshwater use. At present, only one regional boundary (south Asian monsoon) can be established for atmospheric aerosol loading. Although we cannot identify a single PB for novel entities (here defined as new substances, new forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects), they are included in the PB framework, given their potential to change the state of the ES. Two of the PBs—climate change and biosphere integrity—are recognized as "core" PBs based on their fundamental importance for the ES. The climate system is a manifestation of the amount, distribution, and net balance of energy at Earth's surface; the biosphere regulates material and energy flows in the ES and increases its resilience to abrupt and gradual change. Anthropogenic perturbation levels of four of the ES processes/features (climate change, biosphere integrity, biogeochemical flows, and land-system change) exceed the proposed PB (see the figure).

CONCLUSIONS: PBs are scientifically based levels of human perturbation of the ES beyond which ES functioning may be substantially altered. Transgression of the PBs thus creates substantial risk of destabilizing the Holocene state of the ES in which modern societies have evolved. The PB framework does not dictate how societies should develop. These are political decisions that must include consideration of the human dimensions, including equity, not incorporated in the PB framework. Nevertheless, by identifying a safe operating space for humanity on Earth, the PB framework can make a valuable contribution to decision-makers in charting desirable courses for societal development. ■

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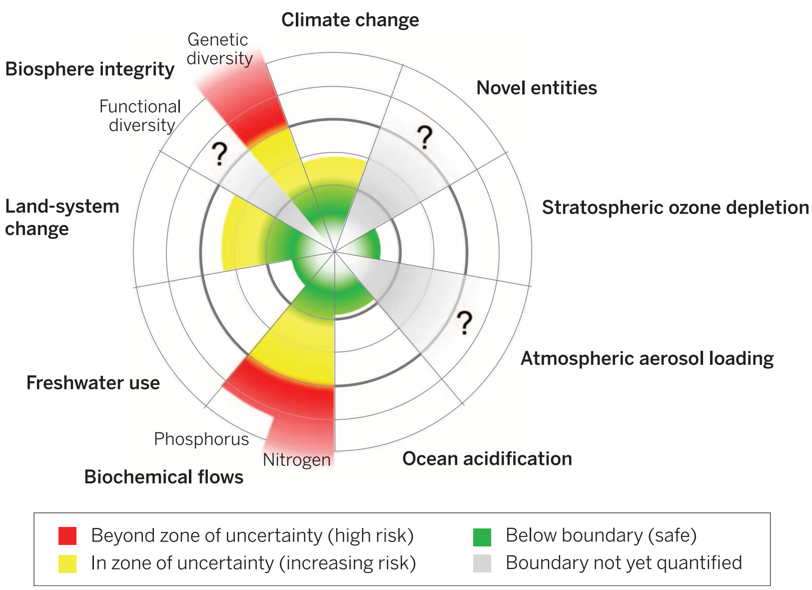

Current status of the control variables for seven of the planetary boundaries. The green zone is the safe operating space, the yellow represents the zone of uncertainty (increasing risk), and the red is a high-risk zone. The planetary boundary itself lies at the intersection of the green and yellow zones. The control variables have been normalized for the zone of uncertainty; the center of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric CO_2 concentration. Processes for which global-level boundaries cannot yet be quantified are represented by gray wedges; these are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity.

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Planetary boundaries: Guiding human development on a changing planet

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The planetary boundaries framework defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the stability of the Earth system. Here, we revise and update the planetary boundary framework, with a focus on the underpinning biophysical science, based on targeted input from expert research communities and on more general scientific advances over the past 5 years. Several of the boundaries now have a two-tier approach, reflecting the importance of cross-scale interactions and the regional-level heterogeneity of the processes that underpin the boundaries. Two core boundaries—climate change and biosphere integrity—have been identified, each of which has the potential on its own to drive the Earth system into a new state should they be substantially and persistently transgressed.

The planetary boundary (PB) approach (*1*, *2*) aims to define a safe operating space for human societies to develop and thrive, based on our evolving understanding of the functioning and resilience of the Earth system. Since its introduction, the framework has been subject to scientific scrutiny [e.g., (*3*–*7*)] and has attracted considerable interest and discussions within the policy, governance, and business sectors as an approach to inform efforts toward global sustainability (*8*–*10*).

In this analysis, we further develop the basic PB framework by (i) introducing a two-tier approach for several of the boundaries to account for regional-level heterogeneity; (ii) updating the quantification of most of the PBs; (iii) identifying two core boundaries; and (iv) proposing a regional-level quantitative boundary for one of the two that were not quantified earlier (*1*).

The basic framework: Defining a safe operating space

Throughout history, humanity has faced environmental constraints at local and regional levels, with some societies dealing with these challenges more effectively than others (*11*, *12*). More recently, early industrial societies often used local waterways and airsheds as dumping grounds for their waste and effluent from industrial processes. This eroded local and regional environmental quality and stability, threatening to undermine the progress made through industrialization by damaging human health and degrading ecosystems. Eventually, this led to the introduction of local or regional boundaries or constraints on what could be emitted to and extracted from the environment (e.g., chemicals that pollute airsheds or waterways) and on how much the environment could be changed by direct human modification (land-use/cover change in natural ecosystems) (*13*). The regulation of some human impacts on the environment—for example, the introduction of chemical contaminants—is often framed in the context of "safe limits" (*14*).

These issues remain, but in addition we now face constraints at the planetary level, where the magnitude of the challenge is vastly different. The human enterprise has grown so dramatically since the mid-20th century (*15*) that the relatively stable, 11,700-year-long Holocene epoch, the only state of the planet that we know for certain can support contemporary human societies, is now being destabilized (figs. S1 and S2) (*16*–*18*). In fact, a new geological epoch, the Anthropocene, has been proposed (*19*).

The precautionary principle suggests that human societies would be unwise to drive the Earth system substantially away from a Holocene-like condition. A continuing trajectory away from the Holocene could lead, with an uncomfortably high probability, to a very different state of the Earth system, one that is likely to be much less hospitable to the development of human societies (*17*, *18*, *20*). The PB framework aims to help guide human societies away from such a trajectory by defining a "safe operating space" in which we can continue to develop and thrive. It does this by proposing boundaries for anthropogenic perturbation of critical Earth-system processes. Respecting these boundaries would greatly reduce the risk that anthropogenic activities could inadvertently drive the Earth system to a much less hospitable state.

Nine processes, each of which is clearly being modified by human actions, were originally suggested to form the basis of the PB framework (*1*). Although these processes are fundamental to Earth-system functioning, there are many other ways that Earth-system functioning could be described, including potentially valuable metrics for quantifying the human imprint on it. These alternative approaches [e.g., (*4*)] often represent ways to explore and quantify interactions among the boundaries. They can provide a valuable complement to the original approach (*1*) and further enrich the broader PB concept as it continues to evolve.

The planetary boundary framework: Thresholds, feedbacks, resilience, uncertainties

A planetary boundary as originally defined (*1*) is not equivalent to a global threshold or tipping point. As Fig. 1 shows, even when a global- or continental/ocean basin–level threshold in an Earth-system process is likely to exist [e.g., (*20*, *21*)], the proposed planetary boundary is not placed at the position of the biophysical threshold but rather upstream of it—i.e., well before reaching the threshold. This buffer between the boundary (the end of the safe operating space, the green zone in Fig. 1) and the threshold not only accounts for uncertainty in the precise position of the threshold with respect to the control variable

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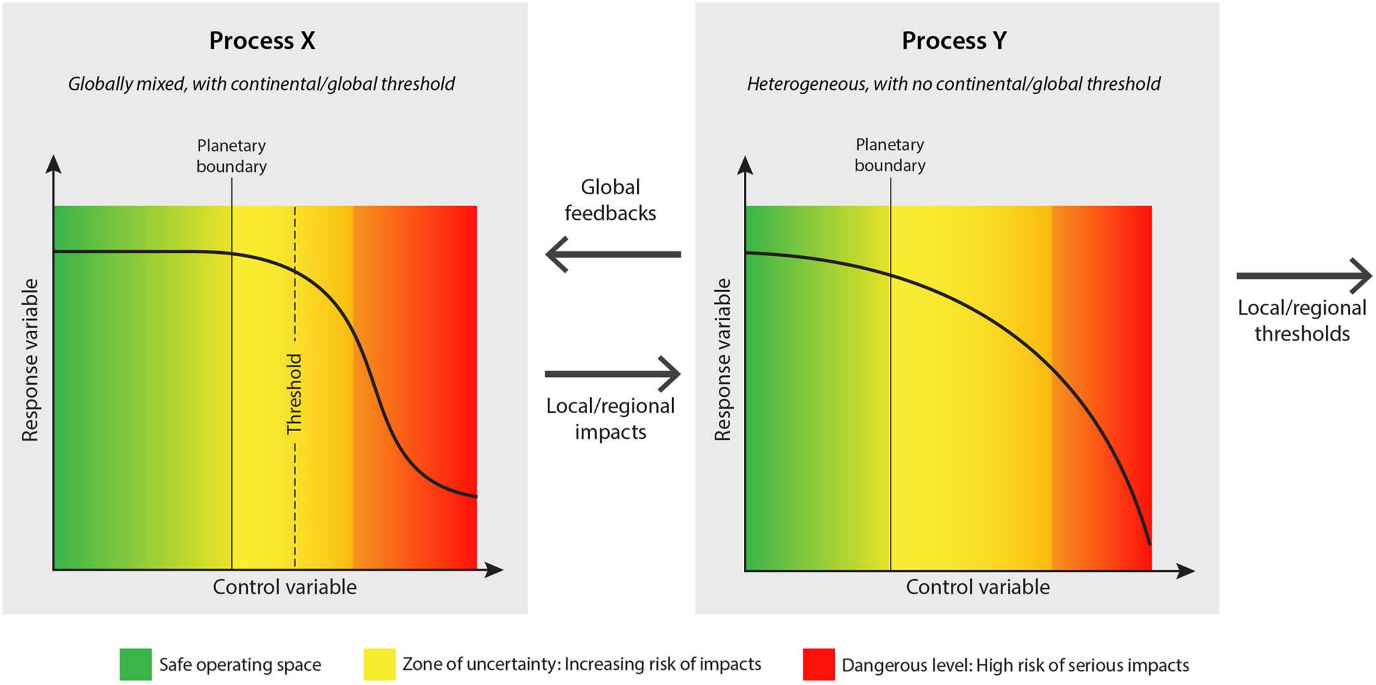

Fig. 1. The conceptual framework for the planetary boundary approach, showing the safe operating space, the zone of uncertainty, the position of the threshold (where one is likely to exist), and the area of high risk. Modified from (*1*).

but also allows society time to react to early warning signs that it may be approaching a threshold and consequent abrupt or risky change.

The developing science of early-warning signs can warn of an approaching threshold or a decrease in the capability of a system to persist under changing conditions. Examples include "critical slowing down" in a process (*22*), increasing variance (*23*), and flickering between states of the system (*24*–*26*). However, for such science to be useful in a policy context, it must provide enough time for society to respond in order to steer away from an impending threshold before it is crossed (*27*, *28*). The problem of system inertia—for example, in the climate system (*18*)—needs to be taken into account in assessing the time needed for society to react to early-warning signs.

Not all Earth-system processes included in the PB approach have singular thresholds at the global/continental/ocean basin level (*1*). Nevertheless, it is important that boundaries be established for these processes. They affect the capacity of the Earth system to persist in a Holocene-like state under changing conditions (henceforth "resilience") by regulating biogeochemical flows (e.g., the terrestrial and marine biological carbon sinks) or by providing the capacity for ecosystems to tolerate perturbations and shocks and to continue functioning under changing abiotic conditions (*29*, *30*). Examples of such processes are land-system change, freshwater use, change in biosphere integrity [rate of biodiversity loss in (*1*, *2*)], and changes in other biogeochemical flows in addition to carbon (e.g., nitrogen and phosphorus). Placing boundaries for these processes is more difficult than for those with known large-scale thresholds (*21*) but is nevertheless important for maintaining the resilience of the Earth system as a whole. As indicated in Fig. 1, these processes, many of which show threshold behavior at local and regional scales, can generate feedbacks to the processes that do have large-scale thresholds. The classic example is the possible weakening of natural carbon sinks, which could further destabilize the climate system and push it closer to large thresholds [e.g, loss of the Greenland ice sheet (*18*)]. An interesting research question of relevance to the PB framework is how small-scale regime shifts can propagate across scales and possibly lead to global-level transitions (*31*, *32*).

A zone of uncertainty, sometimes large, is associated with each of the boundaries (yellow zone in Fig. 1). This zone encapsulates both gaps and weaknesses in the scientific knowledge base and intrinsic uncertainties in the functioning of the Earth system. At the "safe" end of the zone of uncertainty, current scientific knowledge suggests that there is very low probability of crossing a critical threshold or substantially eroding the resilience of the Earth system. Beyond the "danger" end of the zone of uncertainty, current knowledge suggests a much higher probability of a change to the functioning of the Earth system that could potentially be devastating for human societies. Application of the precautionary principle dictates that the planetary boundary is set at the "safe" end of the zone of uncertainty. This does not mean that transgressing a boundary will instantly lead to an unwanted outcome but that the farther the boundary is transgressed, the higher the risk of regime shifts, destabilized system processes, or erosion of resilience and the fewer the opportunities to prepare for such changes. Observations of the climate system show this principle in action by the influence of increasing atmospheric greenhouse gas concentrations on the frequency and intensity of many extreme weather events (*17*, *18*).

Linking global and regional scales

PB processes operate across scales, from ocean basins/biomes or sources/sinks to the level of the Earth system as a whole. Here, we address the subglobal aspects of the PB framework. Rockström *et al.* (*1*) estimated global boundaries only, acknowledging that the control variables for many processes are spatially heterogeneous. That is, changes in control variables at the subglobal level can influence functioning at the Earth-system level, which indicates the need to define subglobal boundaries that are compatible with the global-level boundary definition. Avoiding the transgression of subglobal boundaries would thus contribute to an aggregate outcome within a planetary-level safe operating space.

We focus on the five PBs that have strong regional operating scales: biosphere integrity, biogeochemical flows [earlier termed "phosphorus (P) and nitrogen (N) cycles" (*1*, *2*)], land-system change, freshwater use, and atmospheric aerosol loading. Table S1 describes how transgression of any of the proposed boundaries at the subglobal level affects the Earth system at the global level.

For those processes where subglobal dynamics potentially play a critical role in global dynamics, the operational challenge is to capture the importance of subglobal change for the functioning of the Earth system. To do this, we propose the development of a two-level set of control variables and boundaries. The subglobal-level units of analysis for these six boundaries are not identical; they vary according to the role that the processes play in the Earth system: (i) changes in biosphere integrity occur at the level of land-based biomes, large freshwater ecosystems, or major marine ecosystems as the largest subglobal unit; (ii) the role of direct, human-driven land-system change in biophysical climate regulation is primarily related to changes in forest biomes; (iii) freshwater flows and use occur at the largest subglobal level in the major river basins around the world; and (iv) changes in biogeochemical flows, exemplified by phosphorus and nitrogen cycling, aggregate from relatively localized but very severe perturbations in intensive agricultural zones to affect global flows of nutrients. We recognize these as critical regions for Earth-system functioning. Where appropriate, the updates of the individual boundaries (see below) (*33*) now contain both the globally aggregated boundary value of the control variable and its regional distribution function. Figure 2 shows the distributions and current status of the control variables for three of the boundaries where subglobal dynamics are critical: biogeochemical cycles, land-system change, and freshwater use.

We emphasize that our subglobal-level focus is based on the necessity to consider this level to understand the functioning of the Earth system as a whole. The PB framework is therefore meant to complement, not replace or supersede, efforts to address local and regional environmental issues.

Updates of the individual boundaries

Brief updates of all nine of the PBs are given in this section, and more detailed descriptions of the updates for three of the PBs that have undergone more extensive revision can be found in (*33*). The geographical distribution issues discussed above are particularly important for five of the PBs, and their control variables and boundaries have been revised accordingly (Table 1). Figure 3 shows the current status of the seven boundaries that can be quantified at the global level.

Climate change

We retain the control variables and boundaries originally proposed—i.e., an atmospheric CO_2 concentration of 350 parts per million (ppm) and an increase in top-of-atmosphere radiative forcing of +1.0 W m^{-2} relative to preindustrial levels (*1*). The radiative forcing control variable is the more inclusive and fundamental, although CO_2 is important because of its long lifetime in the atmosphere and the very large human emissions. Human-driven changes to radiative forcing include all anthropogenic factors: CO_2, other greenhouse gases, aerosols, and other factors that affect the energy balance (*18*). Radiative forcing is generally the more stringent of the two boundaries, although the relationship between it and CO_2 can vary through time with changes in the relative importance of the individual radiative forcing factors.

Evidence has accumulated to suggest that the zone of uncertainty for the CO_2 control variable should be narrowed from 350 to 550 ppm to 350 to 450 ppm CO_2 (*17*, *18*), while retaining the current zone of uncertainty for radiative forcing of +1.0 to 1.5 W m^{-2} relative to preindustrial levels. Current values of the control variables are 399 ppm CO_2 (annual average concentration for 2014) (*34*) and +2.3 W m^{-2} (1.1 to 3.3 W m^{-2}) in 2011 relative to 1750 (*18*). Observed changes in climate at current levels of the control variables confirm the original choice of the boundary values and the narrowing of the zone of uncertainty for CO_2. For example, there has already been an increase in the intensity, frequency, and duration of heat waves globally (*35*); the number of heavy rainfall

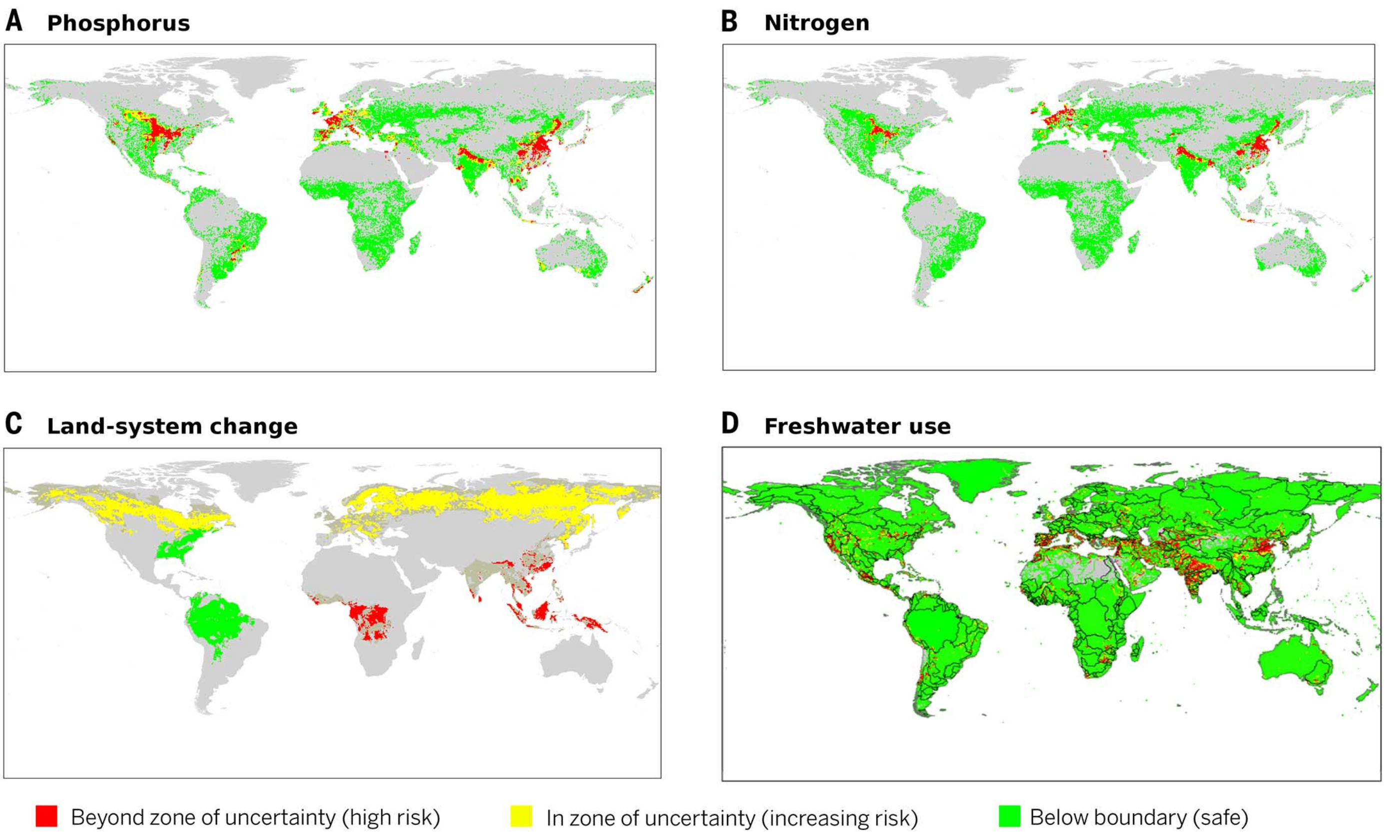

Fig. 2. The subglobal distributions and current status of the control variables for (**A**) biogeochemical flows of P; (**B**) biogeochemical flows of N; (**C**) land-system change; and (**D**) freshwater use. In each panel, green areas are within the boundary (safe), yellow areas are within the zone of uncertainty (increasing risk), and red areas are beyond the zone of uncertainty (high risk). Gray areas in (A) and (B) are areas where P and N fertilizers are not applied; in (C), they are areas not covered by major forest biomes; and in (D), they are areas where river flow is very low so that environmental flows are not allocated. See Table 1 for values of the boundaries and their zones of uncertainty and (*33*) for more details on methods and results.

Table 1. The updated control variables and their current values, along with the proposed boundaries and zones of uncertainty, for all nine planetary boundaries. In the first column, the name for the Earth-system process used in the original PB publication (R2009, reference 1) is given for comparison.

Earth-system process	Control variable(s)	Planetary boundary (zone of uncertainty)	Current value of control variable
Climate change (R2009: same)	Atmospheric CO_2 concentration, ppm	350 ppm CO_2 (350–450 ppm)	398.5 ppm CO_2
	Energy imbalance at top-of-atmosphere, W m^{-2}	+1.0 W m^{-2} (+1.0–1.5 W m^{-2})	2.3 W m^{-2} (1.1–3.3 W m^{-2})
Change in biosphere integrity (R2009: Rate of biodiversity loss)	*Genetic diversity:* Extinction rate	< 10 E/MSY (10–100 E/MSY) but with an aspirational goal of ca. 1 E/MSY (the background rate of extinction loss). E/MSY = extinctions per million species-years	100–1000 E/MSY
	Functional diversity: Biodiversity Intactness Index (BII) Note: These are interim control variables until more appropriate ones are developed	Maintain BII at 90% (90–30%) or above, assessed geographically by biomes/large regional areas (e.g. southern Africa), major marine ecosystems (e.g., coral reefs) or by large functional groups	84%, applied to southern Africa only
Stratospheric ozone depletion (R2009: same)	Stratospheric O_3 concentration, DU	<5% reduction from pre-industrial level of 290 DU (5%–10%), assessed by latitude	Only transgressed over Antarctica in Austral spring (~200 DU)
Ocean acidification (R2009: same)	Carbonate ion concentration, average global surface ocean saturation state with respect to aragonite (Ω_{arag})	≥80% of the pre-industrial aragonite saturation state of mean surface ocean, including natural diel and seasonal variability (≥80%– ≥70%)	~84% of the pre-industrial aragonite saturation state
Biogeochemical flows: (P and N cycles) (R2009: Biogeochemical flows: (interference with P and N cycles))	*P Global*: P flow from freshwater systems into the ocean	11 Tg P yr^{-1} (11–100 Tg P yr^{-1})	~22 Tg P yr^{-1}
	P Regional: P flow from fertilizers to erodible soils	6.2 Tg yr^{-1} mined and applied to erodible (agricultural) soils (6.2-11.2 Tg yr^{-1}). Boundary is a global average but regional distribution is critical for impacts.	~14 Tg P yr^{-1}
	N Global: Industrial and intentional biological fixation of N	62 Tg N yr^{-1} (62–82 Tg N yr^{-1}). Boundary acts as a global 'valve' limiting introduction of new reactive N to Earth System, but regional distribution of fertilizer N is critical for impacts.	~150 Tg N yr^{-1}

Earth-system process	Control variable(s)	Planetary boundary (zone of uncertainty)	Current value of control variable
Land-system change (R2009: same)	*Global:* Area of forested land as % of original forest cover	*Global:* 75% (75–54%) Values are a weighted average of the three individual biome boundaries and their uncertainty zones	62%
	Biome: Area of forested land as % of potential forest	*Biome*: Tropical: 85% (85–60%) Temperate: 50% (50–30%) Boreal: 85% (85–60%)	
Freshwater use (R2009: Global freshwater use)	*Global:* Maximum amount of consumptive blue water use (km^3yr^{-1})	*Global:* 4000 km^3 yr^{-1} (4000–6000 km^3 yr^{-1})	~2600 km^3 yr^{-1}
	Basin: Blue water withdrawal as % of mean monthly river flow	*Basin:* Maximum monthly withdrawal as a percentage of mean monthly river flow. For low-flow months: 25% (25–55%); for intermediate-flow months: 30% (30–60%); for high-flow months: 55% (55–85%)	
Atmospheric aerosol loading (R2009: same)	*Global:* Aerosol Optical Depth (AOD), but much regional variation		
	Regional: AOD as a seasonal average over a region. South Asian Monsoon used as a case study	*Regional*: (South Asian Monsoon as a case study): anthropogenic total (absorbing and scattering) AOD over Indian subcontinent of 0.25 (0.25–0.50); absorbing (warming) AOD less than 10% of total AOD	0.30 AOD, over South Asian region
Introduction of novel entities (R2009: Chemical pollution)	No control variable currently defined	No boundary currently identified, but see boundary for stratospheric ozone for an example of a boundary related to a novel entity (CFCs)	

events in many regions of the world is increasing (*17*); changes in atmospheric circulation patterns have increased drought in some regions of the world (*17*); and the rate of combined mass loss from the Greenland and Antarctic ice sheets is increasing (*36*).

Changes in biosphere integrity

We propose a two-component approach, addressing two key roles of the biosphere in the Earth system. The first captures the role of genetically unique material as the "information bank" that ultimately determines the potential for life to continue to coevolve with the abiotic component of the Earth system in the most resilient way possible. Genetic diversity provides the long-term capacity of the biosphere to persist under and adapt to abrupt and gradual abiotic change. The second captures the role of the biosphere in Earth-system functioning through the value, range, distribution, and relative abundance of the functional traits of the organisms present in an ecosystem or biota (*7*).

For the first role, the concept of phylogenetic species variability (PSV) (*7*, *33*, *37*) would be an appropriate control variable. However, because global data are not yet available for PSV, we retain the global extinction rate as an interim control variable, although it is measured inaccurately and with a time lag. There may be a considerable risk in using extinction rate as a control variable, because phylogenetic (and functional) diversity may be more sensitive to human pressures than species-level diversity (*38*). In principle, the boundary should be set at a rate of loss of PSV no greater than the rate of evolution of new PSV during the Holocene. Because that is unknown, we must fall back on the (imperfectly) known extinction rate of well-studied organisms over the past several

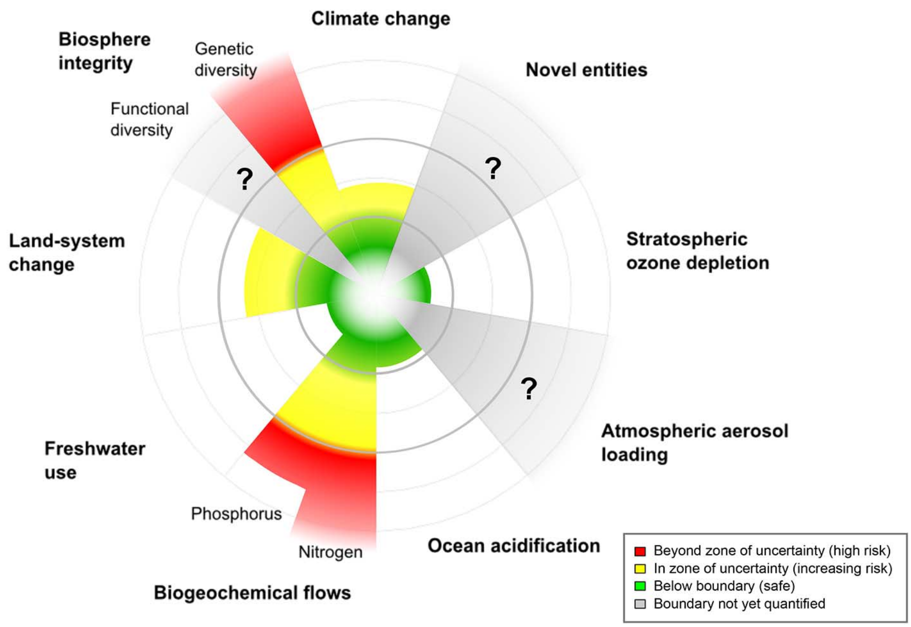

Fig. 3. The current status of the control variables for seven of the nine planetary boundaries. The green zone is the safe operating space (below the boundary), yellow represents the zone of uncertainty (increasing risk), and red is the high-risk zone. The planetary boundary itself lies at the inner heavy circle. The control variables have been normalized for the zone of uncertainty (between the two heavy circles); the center of the figure therefore does not represent values of 0 for the control variables. The control variable shown for climate change is atmospheric CO_2 concentration. Processes for which global-level boundaries cannot yet be quantified are represented by gray wedges; these are atmospheric aerosol loading, novel entities, and the functional role of biosphere integrity. Modified from (1).

million years—about 1 per million species-years (39)—and add a large uncertainty bound, raising the boundary to 10 per million species-years. The risk is that, although the Earth system can tolerate a higher-than-background level of extinctions for a time, we do not know what levels of, or types of, biodiversity loss may possibly trigger nonlinear or irreversible changes to the Earth system.

The second control variable aims to capture the role of the biosphere in Earth-system functioning and measures loss of biodiversity components at both global and biome/large ecosystem levels. Although several variables have been developed at local scales for measuring functional diversity [e.g., (40)], finding an appropriate control variable at regional or global levels is challenging. For the present, we propose an interim control variable, the Biodiversity Intactness Index (BII) (41). BII assesses change in population abundance as a result of human impacts, such as land or resource use, across a wide range of taxa and functional groups at a biome or ecosystem level using preindustrial era abundance as a reference point. The index typically ranges from 100% (abundances across all functional groups at preindustrial levels) to lower values that reflect the extent and degree of human modification of populations of plants and animals. BII values for particular functional groups can go above 100% if human modifications to ecosystems lead to increases in the abundance of those species.

Due to a lack of evidence on the relationship between BII and Earth-system responses, we propose a preliminary boundary at 90% of the BII but with a very large uncertainty range (90 to 30%) that reflects the large gaps in our knowledge about the BII–Earth-system functioning relationship (42, 43). BII has been so far applied to southern Africa's terrestrial biomes only (see fig. S3 for an estimation of aggregated human pressures on the terrestrial biosphere globally), where the index (not yet disaggregated to functional groups) was estimated to be 84%. BII ranged from 69 to 91% for the seven countries where it has been applied (41). Observations across these countries suggest that decreases in BII adequately capture increasing levels of ecosystem degradation, defined as land uses that do not alter the land-cover type but lead to a persistent loss in ecosystem productivity (41).

In addition to further work on functional measures such as BII, in the longer term the concept of biome integrity—the functioning and persistence of biomes at broad scales (7)—offers a promising approach and, with further research, could provide a set of operational control variables (one per biome) that is appropriate, robust, and scientifically based.

Stratospheric ozone depletion

We retain the original control variable [O_3 concentration in DU (Dobson units)] and boundary (275 DU). This boundary is only transgressed over Antarctica in the austral spring, when O_3 concentration drops to about 200 DU (44). However, the minimum O_3 concentration has been steady for about 15 years and is expected to rise over the coming decades as the ozone hole is repaired after the phasing out of ozone-depleting substances. This is an example in which, after a boundary has been transgressed regionally, humanity has taken effective action to return the process back to within the boundary.

Ocean acidification

This boundary is intimately linked with one of the control variables, CO_2, for the climate change PB. The concentration of free H^+ ions in the surface ocean has increased by about 30% over the past 200 years due to the increase in atmospheric CO_2 (45). This, in turn, influences carbonate chemistry in surface ocean waters. Specifically, it lowers the saturation state of aragonite (Ω_{arag}), a form of calcium carbonate formed by many marine organisms. At $\Omega_{arag} < 1$, aragonite will dissolve. No new evidence has emerged to suggest that the originally proposed boundary (≥80% of the preindustrial average annual global Ω_{arag}) should be adjusted, although geographical heterogeneity in Ω_{arag} is important in monitoring the state of the boundary around the world's oceans (fig. S4). Currently, Ω_{arag} is approximately equal to 84% of the preindustrial value (46). This boundary would not be transgressed if the climate-change boundary of 350 ppm CO_2 were to be respected.

Biogeochemical flows

The original boundary was formulated for phosphorus (P) and nitrogen (N) only, but we now propose a more generic PB to encompass human influence on biogeochemical flows in general. Although the carbon cycle is covered in the climate-change boundary, other elements, such as silicon (47, 48), are also important for Earth-system functioning. Furthermore, there is increasing evidence that ratios between elements in the environment may have impacts on biodiversity on land and in the sea (49–51). Thus, we may ultimately need to develop PBs for other elements and their ratios, although for now we focus on P and N only.

A two-level approach is now proposed for the P component of the biogeochemical flows boundary (see also the supplementary materials). The original global-level boundary, based on the prevention of a large-scale ocean anoxic event, is retained, with the proposed boundary set at a sustained flow of 11 Tg P $year^{-1}$ from freshwater systems into the ocean. Based on the analysis of Carpenter and Bennett (3), we now propose an additional regional-level P boundary, designed to avert widespread eutrophication of freshwater systems, at a flow of 6.2 Tg P $year^{-1}$ from fertilizers (mined P) to erodible soils.

Given that the addition of P to regional watersheds is almost entirely from fertilizers, the regional-level boundary applies primarily to the world's croplands. The current global rate of application of P in fertilizers to croplands is 14.2 Tg P $year^{-1}$ (52, 53). Observations point toward a few agricultural regions of very high P application rates as the main contributors to the transgression of this boundary (Fig. 2 and fig. S5A) and suggest that a redistribution of P from areas where it is currently in excess to areas where the soil is naturally P-poor may simultaneously boost global crop production and reduce the transgression of the regional-level P boundary (3, 52, 54).

The N boundary has been taken from the comprehensive analysis of de Vries *et al.* (5), which proposed a PB for eutrophication of aquatic ecosystems of 62 Tg N year^{-1} from industrial and intentional biological N fixation, using the most stringent water quality criterion. As for the P boundary, a few agricultural regions of very high N application rates are the main contributors to the transgression of this boundary (Fig. 2 and fig. S5B). This suggests that a redistribution of N could simultaneously boost global crop production and reduce the transgression of the regional-level boundary.

Because the major anthropogenic perturbation of both the N and P cycles arises from fertilizer application, we can analyze the links between the independently determined N and P boundaries in an integrated way based on the N:P ratio in the growing plant tissue of agricultural crops. Applying this ratio, which is on average 11.8 (55), to the P boundary (6.2 Tg P year^{-1}) gives an N boundary of 73 Tg N year^{-1}. Conversely, applying the ratio to the N boundary (62 Tg N year^{-1}) gives a P boundary of 5.3 Tg P year^{-1}. The small differences between the boundaries derived using the N:P ratio and those calculated independently, which are likely nonsignificant differences given the precision of the data available for the calculations, show the internal consistency in our approach to the biogeochemical boundaries.

More detail on the development of the P and N boundaries is given in (33), where we also emphasize that the proposed P and N boundaries may be larger for an optimal allocation of N (and P) over the globe.

Land-system change

The updated biosphere integrity boundary provides a considerable constraint on the amount and pattern of land-system change in all terrestrial biomes: forests, woodlands, savannas, grasslands, shrublands, tundra, and so on. The land-system change boundary is now focused more tightly on a specific constraint: the biogeophysical processes in land systems that directly regulate climate—exchange of energy, water, and momentum between the land surface and the atmosphere. The control variable has been changed from the amount of cropland to the amount of forest cover remaining, as the three major forest biomes—tropical, temperate and boreal—play a stronger role in land surface–climate coupling than other biomes (56, 57). In particular, we focus on those land-system changes that can influence the climate in regions beyond the region where the land-system change occurred.

Of the forest biomes, tropical forests have substantial feedbacks to climate through changes in evapotranspiration when they are converted to nonforested systems, and changes in the distribution of boreal forests affect the albedo of the land surface and hence regional energy exchange. Both have strong regional and global teleconnections. The biome-level boundary for these two types of forest have been set at 85% (Table 1 and the supplementary materials), and the boundary for temperate forests has been proposed at 50% of potential forest cover, because changes to temperate forests are estimated to have weaker influences on the climate system at the global level than changes to the other two major forest biomes (56). These boundaries would almost surely be met if the proposed biosphere integrity boundary of 90% BII were respected.

Estimates of the current status of the land-system change boundary are given in Figs. 2 and 3 and fig. S6 and in (58).

Freshwater use

The revised freshwater use boundary has retained consumptive use of blue water [from rivers, lakes, reservoirs, and renewable groundwater stores (59)] as the global-level control variable and 4000 km^3/year as the value of the boundary. This PB may be somewhat higher or lower depending on rivers' ecological flow requirements (6). Therefore, we report here a new assessment to complement the PB with a basin-scale boundary for the maximum rate of blue water withdrawal along rivers, based on the amount of water required in the river system to avoid regime shifts in the functioning of flow-dependent ecosystems. We base our control variable on the concept of environmental water flows (EWF), which defines the level of river flows for different hydrological characteristics of river basins adequate to maintain a fair-to-good ecosystem state (60–62).

The variable monthly flow (VMF) method (33, 63) was used to calculate the basin-scale boundary for water. This method takes account of intra-annual variability by classifying flow regimes into high-, intermediate-, and low-flow months and allocating EWF as a percentage of the mean monthly flow (MMF). Based on this analysis, the zones of uncertainty for the river-basin scale water boundary were set at 25 to 55% of MMF for the low-flow regime, 40 to 70% for the intermediate-flow regime, and 55 to 85% for the high-flow regime (table S2). The boundaries were set at the lower end of the uncertainty ranges that encompass average monthly EWF. Our new estimates of the current status of the water use boundary—computed based on grid cell–specific estimates of agricultural, industrial, and domestic water withdrawals—are shown in Figs. 2 and 3, with details in figs. S7 and S8.

Atmospheric aerosol loading

Aerosols have well-known, serious human health effects, leading to about 7.2 million deaths per year (64). They also affect the functioning of the Earth system in many ways (65) (fig. S9). Here, we focus on the effect of aerosols on regional ocean-atmosphere circulation as the rationale for a separate aerosols boundary. We adopt aerosol optical depth (AOD) (33) as the control variable and use the south Asian monsoon as a case study, based on the potential of widespread aerosol loading over the Indian subcontinent to switch the monsoon system to a drier state.

The background AOD over south Asia is ~0.15 and can be as high as 0.4 during volcanic events (66). Emissions of black carbon and organic carbon from cooking and heating with biofuels and from diesel transportation, and emission of sulfates and nitrates from fossil fuel combustion, can increase seasonal mean AODs to as high as 0.4 (larger during volcanic periods), leading to decreases of 10 to 15% of incident solar radiation at the surface (fig. S9). A substantial decrease in monsoon activity is likely around an AOD of 0.50, an increase of 0.35 above the background (67). Taking a precautionary approach toward uncertainties surrounding the position of the tipping point, we propose a boundary at an AOD of 0.25 (an increase due to human activities of 0.1), with a zone of uncertainty of 0.25 to 0.50. The annual mean AOD is currently about 0.3 (66), within the zone of uncertainty.

Introduction of novel entities

We define novel entities as new substances, new forms of existing substances, and modified life forms that have the potential for unwanted geophysical and/or biological effects. Anthropogenic introduction of novel entities to the environment is of concern at the global level when these entities exhibit (i) persistence, (ii) mobility across scales with consequent widespread distributions, and (iii) potential impacts on vital Earth-system processes or subsystems. These potentially include chemicals and other new types of engineered materials or organisms [e.g., (68–71)] not previously known to the Earth system, as well as naturally occurring elements (for example, heavy metals) mobilized by anthropogenic activities. The risks associated with the introduction of novel entities into the Earth system are exemplified by the release of CFCs (chlorofluorocarbons), which are very useful synthetic chemicals that were thought to be harmless but had unexpected, dramatic impacts on the stratospheric ozone layer. In effect, humanity is repeatedly running such global-scale experiments but not yet applying the insights from previous experience to new applications (72, 73).

Today there are more than 100,000 substances in global commerce (74). If nanomaterials and plastic polymers that degrade to microplastics are included, the list is even longer. There is also a "chemical intensification" due to the rapidly increasing global production of chemicals, the expanding worldwide distribution as chemical products or in consumer goods, and the extensive global trade in chemical wastes (75).

In recent years, there has been a growing debate about the global-scale effects of chemical pollution, leading to calls for the definition of criteria to identify the kinds of chemical substances that are likely to be globally problematic (76, 77). Persson *et al.* (73) proposed that there are three conditions that need to be fulfilled for a chemical to pose a threat to the Earth system: (i) the chemical has an unknown disruptive effect on a vital Earth-system process; (ii) the disruptive effect is not discovered until it is a problem at the global scale; and (iii) the effect is not readily reversible. The challenge to the research community is to develop the knowledge base that allows the screening of chemicals, before they are released into the environment, for properties that may predispose them toward becoming global problems.

As a first step toward meeting this challenge, the three conditions outlined above have been used as the basis for identifying scenarios of chemical pollution that fulfill the conditions and as a next step for pinpointing chemical profiles that fit the scenarios (*28*). This proposal constitutes a first attempt at adding the Earth-system perspective when assessing hazard and risk of chemicals and offers a vision for a systematic approach to a complex management situation with many unknowns.

Despite this progress in developing an Earth-system–oriented approach, there is not yet an aggregate, global-level analysis of chemical pollution on which to base a control variable or a boundary value. It may also serve little purpose to define boundary values and control variables for a planetary boundary of this complexity. Nevertheless, there is a potential threat from novel entities to disrupt the functioning of the Earth-system and society needs to learn how to mitigate these unknown risks and manage chemicals under uncertainty (*28*, *73*).

Some precautionary and preventive actions can be considered. These may include a stronger focus on green chemistry (*78*), finding synergies with risk-reducing interventions in other fields such as occupational health (*79*), paying more attention to learning from earlier mistakes (*80*, *81*), and investing in science to better understand and monitor vital Earth-system processes in order to be able to detect disruptive effects from novel entities as early as possible.

Hierarchy of boundaries

An analysis of the many interactions among the boundaries (table S3 and fig. S10) suggests that two of them—climate change and biosphere integrity—are highly integrated, emergent system-level phenomena that are connected to all of the other PBs. They operate at the level of the whole Earth system (*7*) and have coevolved for nearly 4 billion years (*82*). They are regulated by the other boundaries and, on the other hand, provide the planetary-level overarching systems within which the other boundary processes operate. Furthermore, large changes in the climate or in biosphere integrity would likely, on their own, push the Earth system out of the Holocene state. In fact, transitions between time periods in Earth history have often been delineated by substantial shifts in climate, the biosphere, or both (*82*, *83*).

These observations suggest a two-level hierarchy of boundaries, in which climate change and biosphere integrity should be recognized as core planetary boundaries through which the other boundaries operate. The crossing of one or more of the other boundaries may seriously affect human well-being and may predispose the transgression of a core boundary(ies) but does not by itself lead to a new state of the Earth system. This hierarchical approach to classifying the boundaries becomes clearer by examining in more detail the roles of climate and biosphere integrity in the functioning of the Earth system.

The climate system is a manifestation of the amount, distribution, and net balance of energy at Earth's surface. The total amount of energy sets the overall conditions for life. In Earth's current climate, a range of global surface temperatures and atmospheric pressures allows the three phases of water to be present simultaneously, with ice and water vapor playing critical roles in the physical feedbacks of the climate system. The distribution of energy by latitude, over the land and sea surfaces, and within the ocean plays a major role in the circulation of the two great fluids, the ocean and the atmosphere. These systemic physical characteristics are key spatial determinants of the distribution of the biota and the structure and functioning of ecosystems and are controllers of biogeochemical flows.

Biosphere integrity is also crucial to Earth-system functioning, where the biosphere is defined as the totality of all ecosystems (terrestrial, freshwater, and marine) on Earth and their biota (*32*). These ecosystems and biota play a critical role in determining the state of the Earth system, regulating its material and energy flows and its responses to abrupt and gradual change (*7*). Diversity in the biosphere provides resilience to terrestrial and marine ecosystems (*83*, *84*). The biosphere not only interacts with the other planetary boundaries but also increases the capacity of the Earth system to persist in a given state under changes in these other boundaries. The ultimate basis for the many roles that the biosphere plays in Earth-system dynamics is the genetic code of the biota, the basic information bank that defines the biosphere's functional role and its capacity to innovate and persist into the future.

Planetary boundaries in a societal context

A proposed approach for sustainable development goals (SDGs) (*85*) argues that the stable functioning of the Earth system is a prerequisite for thriving societies around the world. This approach implies that the PB framework, or something like it, will need to be implemented alongside the achievement of targets aimed at more immediate human needs, such as provision of clean, affordable, and accessible energy and the adequate supply of food. World development within the biophysical limits of a stable Earth system has always been a necessity [e.g., (*86*, *87*)]. However, only recently, for a number of reasons, has it become possible to identify, evaluate, and quantify risks of abrupt planetary- and biome-level shifts due to overshoot of key Earth-system parameters: (i) the emergence of global-change thinking and Earth-system thinking (*88*); (ii) the rise of "the Planetary" as a relevant level of complex system understanding (*89*–*92*); and (iii) observable effects of the rapid increase in human pressures on the planet (*16*).

The PB approach is embedded in this emerging social context, but it does not suggest how to maneuver within the safe operating space in the quest for global sustainability. For example, the PB framework does not as yet account for the regional distribution of the impact or its historical patterns. Nor does the PB framework take into account the deeper issues of equity and causation. The current levels of the boundary processes, and the transgressions of boundaries that have already occurred, are unevenly caused by different human societies and different social groups. The wealth benefits that these transgressions have brought are also unevenly distributed socially and geographically. It is easy to foresee that uneven distribution of causation and benefits will continue, and these differentials must surely be addressed for a Holocene-like Earth-system state to be successfully legitimated and maintained. However, the PB framework as currently construed provides no guidance as to how this may be achieved [although some potential synergies have been noted (*54*)], and it cannot readily be used to make choices between pathways for piecemeal maneuvering within the safe operating space or more radical shifts of global governance (*93*).

The nature of the PB framework implies that two important cautions should be observed when application of the framework to policy or management is proposed: boundary interactions and scale.

Boundary interactions

The planetary boundaries framework arises from the scientific evidence that Earth is a single, complex, integrated system—that is, the boundaries operate as an interdependent set [e.g., (*94*)] (table S1 and fig. S10). Although a systematic, quantitative analysis of interactions among all of the processes for which boundaries are proposed remains beyond the scope of current modeling and observational capacity, the Earth system clearly operates in well-defined states in which these processes and their interactions can create stabilizing or destabilizing feedbacks (*16*, *90*, *95*). This has profound implications for global sustainability, because it emphasizes the need to address multiple interacting environmental processes simultaneously (e.g., stabilizing the climate system requires sustainable forest management and stable ocean ecosystems).

Scale

The PB framework is not designed to be "downscaled" or "disaggregated" to smaller levels, such as nations or local communities. That said, the PB framework recognizes the importance of changes at the level of subsystems in the Earth system (e.g., biomes or large river basins) on the functioning of the Earth system as a whole. Also, there are strong arguments for an integrated approach coupling boundary definitions at regional and global levels with development goals to enable the application of "PB thinking" at levels (nations, basins, and regions) where policy action most commonly occurs [e.g., (*85*, *96*)].

This update of the PB framework is one step on a longer-term evolution of scientific knowledge to inform and support global sustainability goals and pathways. This evolution is needed more than ever before; there are severe implementation gaps in many global environmental policies relating to the PB issues, where problematic trends are not being halted or reversed despite international consensus about the urgency of the problems. The prospect of tighter resource constraints and rising environmental hazards is also unavoidably turning the focus onto global social equity and the planetary stewardship of Earth's life-support system. There is a need for a truly global evidence base, with much greater integration among issues, in order to respond to these global challenges. New research initiatives [e.g., Future Earth (www.futureearth.org)] provide evidence that science can respond to this need by applying Earth-system research to advance a new generation of integrated global analyses and to explore options for transformations toward sustainability. This is a clear sign that, as the risks of the Anthropocene to human well-being become clearer, research is maturing to a point where a systemic step-change is possible—and necessary—in exploring and defining a safe and just planetary operating space for the further development of human societies.

Methods summary

Our approach to building the planetary boundaries framework is described above. We have implemented the framework through an expert assessment and synthesis of the scientific knowledge of intrinsic biophysical processes that regulate the stability of the Earth system. Our precautionary approach is based on the maintenance of a Holocene-like state of the Earth system and on an assessment of the level of human-driven change that would risk destabilizing this state. For the climate change PB, there is already much literature on which to base such an assessment. For others, such as stratospheric ozone, ocean acidification, extinction rates, and P and N cycles, we have used estimates of preindustrial values of the control variable as a Holocene baseline. Where large, undesirable thresholds exist and have been studied (e.g., polar ice sheets, Amazon rainforest, aragonite dissolution, atmospheric aerosols, and the south Asian monsoon), quantitative boundaries can be readily proposed. For others, where the focus is on erosion of Earth-system resilience, the boundaries are more difficult (but not impossible) to quantify, as reflected in larger uncertainty zones.

We used large-scale assessments of the impacts of human activities on Earth-system functioning [e.g., Intergovernmental Panel on Climate Change (*17*, *18*), the International Geosphere-Biosphere Programme synthesis (*16*), and chemicals (*75*, *80*)] as sources of community-level understanding on which to propose PBs. Our update has also relied on post-2009 assessments of individual boundaries by the relevant expert research communities; examples include phosphorus (*3*), nitrogen (*5*), biosphere integrity (*7*), freshwater use (*5*, *63*), and novel entities [with a focus on chemicals (*28*, *73*)]. Finally, some new analyses have been undertaken specifically for this paper: (i) a freshwater-use PB based on the EWF approach (*33*, *63*); (ii) the linkage of the phosphorus and nitrogen boundaries via the N:P ratio in growing crop tissue (*33*); and (iii) the use of major forest biomes as the basis for the land-system change PB (*33*).

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SUPPLEMENTARY MATERIALS

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Methods

Biogeochemical flows: phosphorus

Control variables

Ocean anoxia (global): For this component of the P boundary we retain as the control variable the inflow of P to the ocean, as compared to the natural background weathering rate.

Freshwater eutrophication (regional/croplands): Carpenter and Bennett (3) proposed three possible control variables: the flow of P from land to freshwater, the flow of P to erodible soils, and the total mass of erodible P on the continents. They computed the planetary boundary and its sensitivities to different water quality criteria and to a range of assumed flow rates of P to the sea. The water quality criterion they propose is based on a relationship (Carlson's index) that connects several metrics of water quality, including P concentration, to phytoplankton biomass (97). A water quality criterion of 160 mg m^{-3} is appropriate for rivers, while a level of 24 mg P m^{-3} avoids the eutrophication of freshwater lakes and reservoirs.

We adopt a flow rate of P to the sea consistent with the ocean anoxia boundary. We then adopt the flow of P to erodible soil as the control variable. It would arguably be more appropriate to use the flow of P from soil to the freshwater system as the control variable, as this is more directly related to eutrophication, but this component is more difficult to measure than the application of P to soils and is also less amenable to management control. However, a drawback of using P application rate to soil is that the estimated boundary is based on an assumed and constant flow rate of P to the sea. This is unlikely to be the case as erosion rates have changed dramatically since pre-historic times (98). Also, we assume here that all cropland soils are in principle "erodible" in terms of flow of P from soil to freshwater, but that actual erodibility will, in practice, vary considerably depending on the nature of the soil and the tillage practice.

Proposed boundary values

Ocean anoxia (global): We assume a relatively low natural background rate of P inflow to the ocean of about 1.1 Tg P yr^{-1}, which implies a boundary of about 1.2 to 1.3 Tg P yr^{-1}(1). However, even larger increases would have to be maintained for 10,000 years or more to double the amount of P in the oceans. Approaching a human-induced threshold for an ocean anoxic event would probably be at least 1000 years in the future at present rates of P inflow (8 or 9 Tg P yr^{-1}), and much longer at inflows of about 1.3 Tg P yr^{-1}. Given these very long timeframes, the original P boundary was set at about 10 times the natural background weathering rate, or 11 Tg P yr^{-1}, with a zone of uncertainty of 11 to 100 Tg P yr^{-1} (1).

Freshwater eutrophication (regional/croplands): Based on the Carpenter and Bennett (3) analysis, we adopt the riverine water quality criterion of 160 mg m^{-3} and a flow rate to the ocean of 9 Tg P yr^{-1}. For this water quality criterion to be appropriate, we assume that sedimentation will reduce the P concentration in lakes below the lake water quality criterion of 24 mg m^{-3}. That is, we are ***not*** proposing a lake and reservoir water quality criterion of 160 mg m^{-3}.

These parameters give a boundary of 26.2 Tg P yr^{-1} (Table A.1 in (3)). This boundary also includes the fluxes from natural and human-induced weathering, which are estimated to be 15-20 Tg P yr^{-1} (3). Subtracting these fluxes then gives a lower boundary, in terms of fertilizer-P flux to soil, of 6.2 Tg P yr^{-1} and a zone of uncertainty of 6.2-11.2 Tg P yr^{-1}. This can be converted to a uniform rate of P addition to croplands of ca. 4.1 kg ha^{-1} yr^{-1}, assuming a total global cropland area of 1494 x 10^6 ha (99). Applying the zone of uncertainty gives a range of 4.1 kg ha^{-1} yr^{-1} to 7.5 kg ha^{-1} yr^{-1} for the P addition rate (Fig S5A).

For the P planetary boundary we focus on mined P applied to soils as a fertilizer. Significant amounts of P are also applied as manure (50,100). However, we differentiate them here because manure is P recycled internally in the agricultural system, while fertilizer P represents additional P added to agricultural systems from an inert source. It is important, however, in the context of this component of the P planetary boundary to recognize that more effective recycling of manure P can reduce P runoff and will also reduce the demand for fertilizer P.

Biogeochemical flows: nitrogen

Control variable

Anthropogenic input of reactive N to the Earth System occurs through (i) the anthropogenic industrial fixation of nitrogen from atmospheric N_2 via the Haber-Bosch process; (ii) intended biological N fixation; and (iii) unintended N fixation due to the emission of nitrogen oxides (NO_x) from transport and industry (5). N fixation via the Haber-Bosch process is by far the quantitatively most important mode of the intended anthropogenic N-fixation. As suggested by De Vries et al. (5), the combined input of N from intended human fixation processes ((i) and (ii) above) is proposed as the control variable for the planetary N-boundary. The unintended N fixation is not included in the control variable.

Proposed boundary value

De Vries et al. (5) estimated individual boundaries for nitrogen fixation based on critical limits for four major environmental concerns: atmospheric NH_3 concentrations, radiative forcing by N_2O, drinking water contamination by NO_3^-, and eutrophication of aquatic ecosystems. Depending on which of the environmental concerns was being addressed, the De Vries et al. (5) calculations suggest boundaries ranging from 20 to > 130 Tg N yr^{-1}.

Applying a climatic (N_2O) constraint results in the most stringent of these estimates (20 Tg N yr^{-1}), based on a climate change boundary set at a +1 W m^{-2} change in radiative forcing (1). All of the other potential N boundaries fall in the range 62-133 Tg N yr^{-1} (5).

Assuming that this stringent climatic-based potential N boundary is addressed in the climate change boundary, we then consider eutrophication of aquatic ecosystems as the environmental concern being addressed, as for P. Also, as for P, the appropriate control variable for the N boundary is the flow of N from soil to the freshwater system, as this is directly related to the risk of eutrophication. However, again for pragmatic reasons we adopt the application rate of intentionally fixed reactive N to the agricultural system. This control variable is easier to measure and track, and is more directly amenable to policy and management interventions. On this basis, the proposed boundary is 62-82 Tg N yr^{-1}, depending on the critical N concentration used (5). We take the lower value, 62 Tg N yr^{-1}, as the boundary itself and set the zone of uncertainty at 62-82 Tg N yr^{-1}. As for P, this range can be converted to a uniform rate of N addition to croplands of 41-55 kg ha^{-1} yr^{-1}, based on the total global cropland area (99; Fig. S5B).

In their analysis of potential planetary boundaries for N, De Vries et al. (5) also considered the human needs for food production. They projected a baseline human need for N fixation for a population of nine billion people of ~50-80 Tg N yr^{-1}, with the higher number assuming current N-use efficiency in agriculture and the lower a 25% increase in N-use efficiency (5). Their results are in the same order of magnitude as a recent global model analysis by Bodirsky et al. (2014) (101), who estimated the N amount required to satisfy a given future demand for agricultural products under different assumptions regarding consumption patterns and production technology. Using a combination of dietary changes (less consumption of animal products) and mitigation actions, including increased household waste recycling, reduced losses in animal waste management, and increased efficiencies in fertilization and livestock management, they showed that food requirements can be fulfilled at an N input of 95 Tg N yr^{-1}. The analysis of De Vries et al. (5) is even lower, but assumes even more rigorous mitigation approaches. Our proposed boundary and zone of uncertainty, calculated on environmental criteria, of 62-82 Tg N yr^{-1} compares well with these "N needs" estimates.

Biogeochemical flows: linkage between phosphorus and nitrogen boundaries

Our approach to exploring the links between the P and N boundaries is based on the coupling of these elements in plant growth. The average N:P ratio in growing plant tissue is approximately 11.8:1 (55). Currently the global N:P input ratio, based on N and P fertilizer application rates and agricultural N fixation, is approximately 8.6:1 (121:14 Tg y^{-1}), based on estimates for the year 2000 (53). This is lower than the ratio of approximately 11.8:1 in growing plant tissue. We consider that an application rate of N and P in fertilizers somewhat nearer the ratio that the crop takes up would be desirable. Using this approach would require the ratio of losses of N and P to the environment via leaching and emissions to the atmosphere to be equivalent to the N:P input ratio.

Currently the global N:P loss ratio is approximately 11.2:1 (138 vs 12 Tg y^{-1}), based on estimates for the year 2000 (53), thus being close to 11.8:1.

Using the lower P boundary as the basis, the N boundary would be 6.2 x 11.8 = 73 Tg N yr^{-1}, while using the upper end of the zone of uncertainty for P would lead to 11.2 x 11.8 = 132 Tg N yr^{-1}. Conversely, using the lower and upper values of the N zone of uncertainty (62 and 82 Tg N yr^{-1}, respectively) as the basis, the P boundary would be 5.3–6.9 Tg P yr^{-1}, being near the lower range of the P boundary. Comparing the two boundary values for each of P and N shows the high level of consistency between the two approaches:

P (independent): 6.2 Tg P yr^{-1}; P (from N and N:P ratio): 5.3 Tg P yr^{-1}
N (independent): 62 Tg N yr^{-1}; N (from P and N:P ratio): 73 Tg N yr^{-1}

The differences in these values are likely to be non-significant given the level of precision of the data available for the calculations.

We realize that use of an N:P ratio of 11.8 for the N to P inputs based on crop uptake could potentially lead to an overloading of aquatic systems with P relative to N, since the typical aquatic N:P mass ratio is near 14. The aquatic N:P ratio represents the net outcome of input and loss processes including denitrification and sedimentation. The ratio of N and P deposited on agricultural ecosystems is, however, different from the N:P ratio in runoff that flows into freshwaters, due to differences in the behavior of N and P in soil. N storage in agriculture soils is limited to biological process (net immobilization) and, in general, the N surplus (N input minus N removal by crops) is predominantly lost to air (NH_3, N_2O, NO_x and N_2 emissions) and water. On the other hand, P storage in agriculture soils is predominantly due to physicochemical processes (adsorption) and, in general, the P surplus is predominantly accumulated in soil, while only a small fraction is lost to water. Consequently, the current ratio of N/P loading to water is near 14, whereas the input ratio is near 8 (53). In summary, even though the N:P ratio of 11.8 is below 14, it does not necessarily lead to an overloading of aquatic systems with P relative to N due to differences in N and P retention in soils and processing in aquatic ecosystems.

The current pattern of P and N addition to agricultural areas is highly uneven, with a few areas of very high rates of usage (e.g., central North America, western Europe and northern China) and large areas of very low rates of usage (Fig. S5A,B). In this context, it is important to note that De Vries et al. (5) derived the planetary N boundaries of 62-82 Tg N yr^{-1} to avoid eutrophication of surface waters by reducing present N inputs in agricultural areas where N losses currently exceed critical limits for N in surface water. Inversely, they did not elevate the N inputs in areas where current concentrations were below critical limits (mostly in remote areas with less intense agriculture). In nitrogen-poor areas, agricultural production can be increased by allowing an increase in N input while still remaining well below the critical limits for eutrophication. Including such an increase would have raised the planetary boundary calculated by De Vries et al. (5). First indicative calculations indicate that this could be as high as the N boundary derived from the upper P boundary, i.e near 132 Tg N yr^{-1}. The proposed N boundaries here are thus likely an underestimate if an optimal allocation of N (and P) can be achieved across the planet.

The current globally aggregated rates of P and N application are 14 Tg P yr^{-1} (52) and 150 Tg N yr^{-1} (100), respectively. Thus, even if complete optimal allocation of P and N can be achieved across the planet, current loadings of P and N exceed environmental limits, and thus are transgressing our proposed planetary boundaries (see Fig. 3 in main text).

Land-system change

Control variables

Global: The area of forested land that is maintained on the ice-free land surface, expressed as a percentage of the potential area of forested land in the Holocene (that is, the area of forest assuming no human land-cover change).

Biome: The area of forested land that is maintained in each of the three major forest biomes – tropical, temperate, boreal – expressed as a percentage of the potential forest area in each of these three biomes.

Proposed boundary values

Global: 75% of potential forest cover should be maintained (or approximately 47.9 million km^2 of the ice-free land surface of Earth, based on areal estimates (56)). This boundary has been constructed as a weighted aggregate of the three individual biome boundaries as described below.

Biome: The estimated boundary for each of the biomes is based on (i) the relative potential of land cover change within each biome to influence the climate system remotely, especially at the global level (102); and (ii) the potential for a threshold within each of the forest biomes in which land-cover change beyond a certain area activates self-reinforcing feedbacks that lead to land-cover change across a much larger area.

Tropical Forest: 85% of potential forest cover should be maintained (approximately 19.3 million km^2), based on the following rationale. There are well-founded arguments that a threshold of land-cover change exists that, if crossed, would trigger the widespread conversion of the Amazon Basin tropical forest to a savanna or grassland (103-106). The self-reinforcing feedback mechanism involved in the threshold is the reduction of evapotranspiration resulting from the conversion of forest to cropland or grazing land, which beyond a certain point leads to a reduction in rainfall, which triggers further conversion of forested land to savanna or grassland.

A more difficult question is where this threshold might lie. For the present, a boundary at 15% conversion of the rainforest (85% forest remaining) has been suggested, which is approximately the present amount of deforestation. There is no strong evidence that the biome-level threshold has been crossed, although there is some evidence of regional regime shifts (107-109). There is also a suggestion that in the last decade the Amazon forests have become more vulnerable to drought and wildfire (110), which could be a harbinger of conversion to drier ecosystems.

Temperate Forest: 50% of potential forest cover should be maintained (approximately 9.5 million km^2). This is a provisional boundary only, based on sensitivity studies that evaluate the influence of the world's terrestrial biomes on the global climate (56,57). Both tropical forests (changing evapotranspiration) and boreal forests (changing albedo) have strong impacts on the climate system with global teleconnections from the regional changes, while temperate forests are assessed to have only moderate influence on the global climate.

Boreal Forest: 85% of potential forest cover should be maintained (approximately 19.1 million km^2). This is also a provisional boundary, as there is no equivalent research on the boreal forest biome (as for tropical forests) exploring where thresholds might lie in terms of the fraction of forest converted before self-reinforcing feedback mechanisms are activated, such as changes in fire regimes.

Figure S6 shows the area of forest cover remaining in the world's major forest biomes compared to the potential forest cover, color-coded to show the position of the control variable (area of forest land remaining) with respect to the boundary. The results shown in Figure S6 need to be interpreted with considerable caution. The database used to define the potential area of the forest biomes and that used to estimate the area of forest remaining do not use identical definitions of various forest types or what constitutes a forest compared to a woodland. In using the ESA GlobCover 2009 database (111) to estimate current forest cover, we used the 100-40% cover category of remaining forest to define where forest was present in a given area. This category would also include some degraded or partially cleared forests as "remaining forest", as well as some plantation forests such as palm oil. This category thus probably overestimates the actual amount of original forest cover remaining. This would lead to somewhat high percentages of remaining forest and thus to an optimistic estimate of the actual position of the control variable with respect to the boundary.

Aggregating the forest remaining compared to the potential forest for all of the biomes gives a global value of 62% forest remaining. The global boundary is 75% with a zone of uncertainty between 75% and 54%. Thus, the current value transgresses the boundary but lies within the zone of uncertainty. An independent estimate of the overall status of the land-system change boundary, which includes all forests, yields a value of 68% cover remaining (58), consistent with our estimate based on major, contiguous forest biomes only.

Freshwater Use

Control Variables

Global: At the planetary scale the control variable is defined as the maximum amount of consumptive blue water use (km^3/yr)

River basin scale: The control variable is the maximum allowed amount of blue water withdrawal from a river basin defined as average % of mean monthly flow (MMF).

The river basin control variable is based on the concept of "environmental water flow", EWF (112), which is defined as the minimum amount of blue water that must remain within a river basin (as an average % of mean monthly flow) to sustain ecosystem processes and resilience of inland and coastal landscapes. Thus, the withdrawal of water from a river basin and the EWF must add up to the mean monthly flow.

Determining EWF for a hydrological regime is complex, and specific to spatial eco-hydrological conditions (113). This complexity is reflected by the proposal of over 200 methods based on hydrological, hydraulic, habitation simulation and holistic approaches to estimate EWF (63). Nevertheless, a set of generic "rules" can be defined based on key characteristics of different river basins.

EWFs are based on the characterization of the quantity, timing, duration, frequency and quality of blue water flows required to sustain freshwater, estuarine and near-shore ecosystems and the human livelihoods and well-being that depend on them (60,114). EWF includes both baseflow and stormflow, i.e., low and high flow requirements to sustain ecosystem functions in river basins (115,116). EWF thus provides a reasonable aggregate proxy on which to base sustainable water use in a river basin.

Proposed boundary values

Global: A global consumptive water use of blue water not exceeding 4000 km^3 yr^{-1} (uncertainty range 4000-6000 km^3 yr^{-1})

River basin: A maximum amount of average monthly blue water withdrawals in river basins/segments of 25% of mean monthly flow for periods of low flow (25–55%), 40% for periods of intermediate flow (40–70%) and 55% for periods of high flow (55–85%).

Methodology for estimating river basin boundary

The boundary definition of allowed blue water withdrawals at river basin scale is calculated based on the EWF requirements:

River basin water withdrawal boundary (%) =

(MMF–(EWF+0.15*MMF))/MMF*100,

where MMF is mean monthly river flow, analyzed for each river segment. The rationale for the factor of 0.15*MMF added to EWF to determine the boundary is explained below.

MMF is relatively well quantified from hydrological observations, assessments, and models (117-119). The challenge is to define EWF. Different river types and river stretches have different minimum water requirements according to their seasonal hydrographs. For example, there are differences between rivers characterized by stable flow regimes (with year-round baseflow), monsoon rivers with >80% runoff flows concentrated in a 3-4 month rainy season, and ephemeral and unpredictable rainfed rivers with long periods of low or no flow. River basins may therefore be classified according to similarity in hydrological regime (61). Despite these difficulties several hydrological methods have been advanced to estimate EWFs (120-123, reviewed by (63)).[1] We acknowledge that other methods and metrics may be used to assess the effect of human water withdrawals and flow modifications on rivers and their ecosystems, such as those used in Nilsson et al. (124) and Vörösmarty et al (125).

Pastor et al. (63) have developed the new Variable Monthly Flow (VMF) method, which we have used in calculating the basin scale planetary boundary for water. The VMF method takes into consideration the need to sustain natural variable flow regimes while it can also be aggregated and validated at basin and global scale. It classifies flow regimes into high-, intermediate- and low-flow months by taking into account intra-annual variability. It then allocates EWF as a percentage of mean monthly flow (MMF), following the natural variability of river flow. Specifically, it allocates 30% of MMF as EWF during high flow seasons (when MMF is > 80% of MAF, where MAF is mean annual flow), 45% of MMF during intermediate-flow seasons (when MMF is 40–80% of MAF), and 60% of MMF during low-flow seasons (when MMF < 40% of MAF). In extremely dry conditions (MMF < 1 $m^3 s^{-1}$) there is no EWF allocation.

Table S2 shows EWF calculated by the VMF methodology and the average maximum withdrawals (1 – EWF) that emerge from these estimates. A range of uncertainty is added to reflect the variability in EWF estimates from different EWF methodologies (as compared to the VMF method; 63). The planetary boundary level is placed at the lower end of the uncertainty range for each flow regime (low/intermediate/high), necessitating the term 0.15*MMF to be added to EWF to determine the boundary value as MMF – (EWF+0.15*MMF).

The estimate of monthly and annual EWF requirements is based on simulations of "pristine" river discharge conditions in the absence of current anthropogenic land use, irrigation and reservoir storage. Note, however, that irrigation, land use, reservoir storage

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[1] For instance, the Tessmann method allocates a percentage of mean monthly flow varying from 40% of MMF during high flow seasons to 100% of MMF during low flow seasons. The Tennant method allocates 20% of mean annual flow (MAF) during low flow seasons and 40% of MAF during high flow seasons. The Smakhtin method allocates Q90 as a base flow and an additional percentage of MAF during high flow seasons.

and reservoir operation were considered in the analysis of withdrawals in order to derive their aggregate (including possible downstream) impacts on the naturalized flow conditions. We carried out a new analysis for this paper using the dynamic global vegetation and water balance model LPJmL ((126), with an updated version of the land use patterns in (127)). The model was used to simulate river flow globally at a spatial resolution of 0.5° by 0.5° on a daily time step over the period 1981-2000 (after (63) as in (6)). The model runs were forced by the GPCC full reanalysis dataset version 5 for precipitation (128) with a synthetic number of wet days per month (129), and the CRU TS3.10 climatology for cloudiness and temperature (130). These flow volumes were translated into monthly EWFs and averaged over the 20-yr period. River basins are delineated according to the STN-30p drainage network (http://www.wsag.unh.edu/Stn-30/stn-30.html).

The range of average maximum withdrawals for different flow regimes based on EWF (from 40% at high flow to 70% at low flow) is a reflection of different eco-hydrologic characteristics of rivers. The scientific uncertainty, which is estimated at ±15% for each flow regime (Table S2), originates from an assessment of the variability in EWF estimates when applying different EWF methods (see 6,63). It is this uncertainty range (Table S2), and not the average maximum allowed withdrawal based directly on EWF itself, that determines the boundaries and zones of uncertainty in Table 1 (main text).

The LPJmL simulations applying the VMF methodology result in a global average EWF of 33% of MAF; for the –15% and +15% cases EWFs are 18% and 48% of MAF, respectively. This compares well with other EWF methodologies, where a comparison of five different methods in LPJmL resulted in a global average EWF of 25–46% of MAF, with variable flow regimes such as the Nile having lower EWFs (ranging from 12 to 48% of MAF, depending on the EWF estimation method) than stable tropical regimes such as the Amazon (ranging from 30 to 67% of MAF) (details in 63).

In order to assess the current status of (non)-transgression of EWF (i.e., the degree to which average monthly water withdrawals already exceed the allowed volumes), daily water withdrawals for irrigated agriculture (summed up to mean monthly values) were calculated using LPJmL for each 0.5° grid cell and month over the period 1981-2000 (following (126) and (131)). Domestic, manufacturing, thermoelectric and livestock water use were accounted for using data available annually for 1981–2000 from (132) and disaggregated to 20-yr monthly averages.

Figure S7 shows the results of this assessment. For each cell an annual monthly average EWF is calculated based on the three boundary definitions in Table S2, which together with the withdrawal estimates gives an annual average value of actual (non)-exceedance of allowed withdrawal as compared to EWF. Note that this figure presents the average situation for months with transgression only (see complementary analysis below). The differentiation between a safe operating space (in green), entering a danger zone (in yellow) and entering a high risk zone (in red), are defined by including the ±15 % uncertainty range for different EWF methods, as shown in Table S2 (that is, MMF – (EWF+0.15*MMF) defines the boundary for water withdrawals and MMF – (EWF-

0.15*MMF) defines the other end of the uncertainty zone).

The patterns shown in Figure S7 support an earlier analysis by Smakhtin et al. (122), who used a method based on annual flow values determined at river outlets. We stress that our results reflect the regionally and temporally variable patterns of environmental flows compared to the patterns of withdrawals, which enables us to identify fractions of a river and its basin with transgressions. Thus, our analysis demonstrates a “danger zone” or “high risk zone” only for some, yet rather extensive, parts of the Murray-Darling and Colorado basins rather than for the entire basins. We note that model uncertainties may affect results in some regions, such as in the Nile basin where macroscale hydrological models generally tend to overestimate flows (which may lead to an underestimation of transgressions). Overall though, our results correspond well with other estimates of withdrawal limits based on EWF. A recent assessment of a wide spectrum of different river basins indicate an average EWF of 37% of mean annual flow (63). An earlier study (122) indicated an EWF range of 30-50% of mean annual flow, with maximum allowed withdrawals of 50-80%.

The number of months when the various thresholds are crossed is of importance in understanding the implications of water withdrawals for ecosystems. Figure S8 displays the data according to how many months each year the water thresholds are exceeded. The upper panel corresponds to the analysis shown in Fig. S7 in the sense that it shows the duration of exceedance of the freshwater withdrawal boundary (MMF – (EWF+0.15*MMF)). The lower panel shows the combination of these features, i.e. duration (number of months) of transgression and severity of transgression, into one index. This map indicates extensive areas where transgression of the freshwater boundary occurs during more than half of the year.

A first analysis applying the river basin-scale boundary approach described above to the global level (6) shows that the proposed boundary of a maximum withdrawal of blue water (25–55% of mean monthly flow) corresponds on average to a global-level withdrawal of 2800 km^3 yr^{-1}, with an uncertainty range of 1100 – 4500 km^3 yr^{-1}. This compares fairly well with the proposed global freshwater boundary of 4000 km^3 yr^{-1} (4000–6000 km^3 yr^{-1}) but also suggests that it may be lower if estimation methods yielding high EWF values are used.

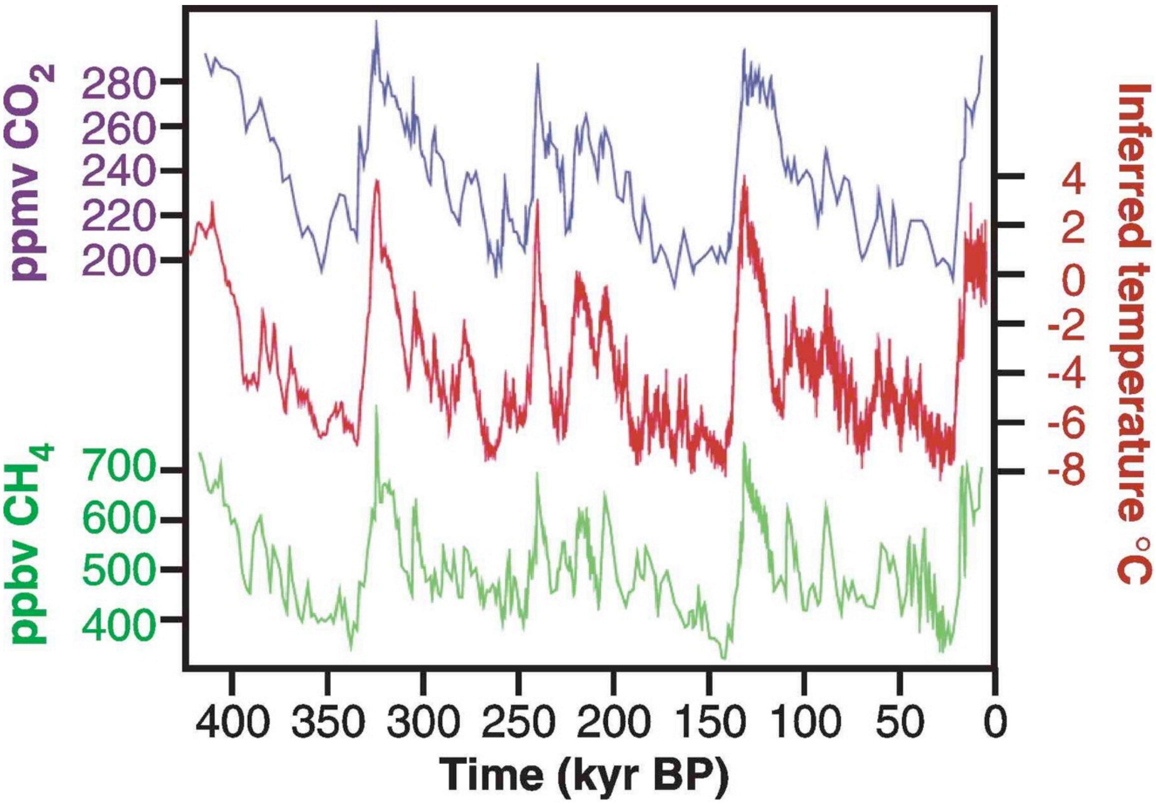


Fig. S1. The 420,000-year Vostok (Antarctica) ice core record, showing the regular pattern of atmospheric CO_2 and CH_4 concentration and inferred temperature through four glacial-interglacial cycles (16, adapted from 133). Anatomically modern humans evolved around 200,000 – 250,000 years ago (134).

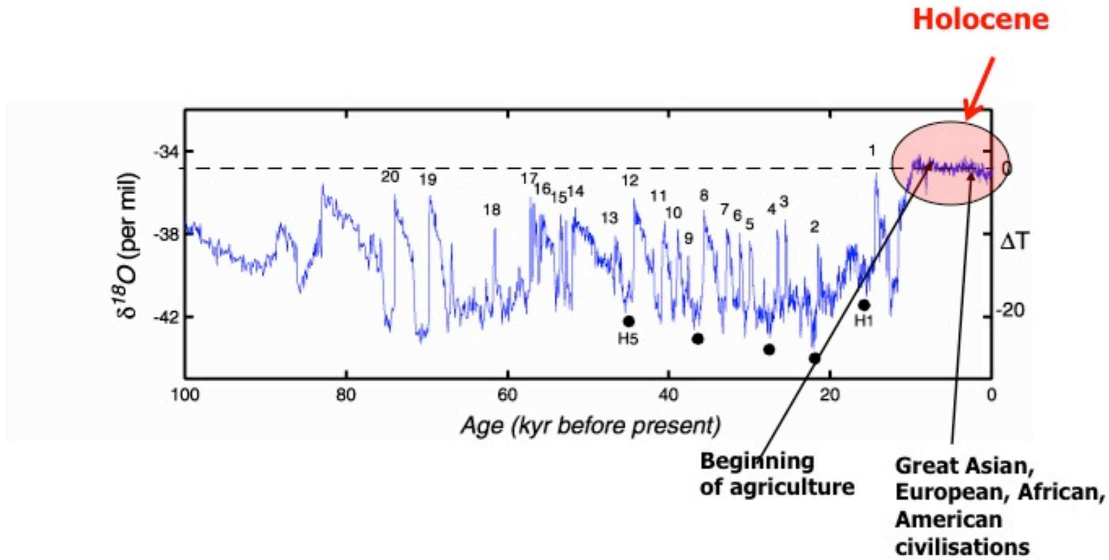


Fig. S2. Record of $\delta^{18}O$ per mil (scale on left) from the Greenland Ice Sheet Project (GRIP) ice core, a proxy for atmospheric temperature over Greenland (approximate temperature range on ^{o}C relative to Holocene average is given on the right, showing the relatively stable Holocene climate during the past ca. 10,000 years and Dansgaard-Oeschger events (numbered) during the preceding colder glacial climate (135). Note the relative stability of temperature for the last 11,700 years (the Holocene) compared to the earlier ice age period.

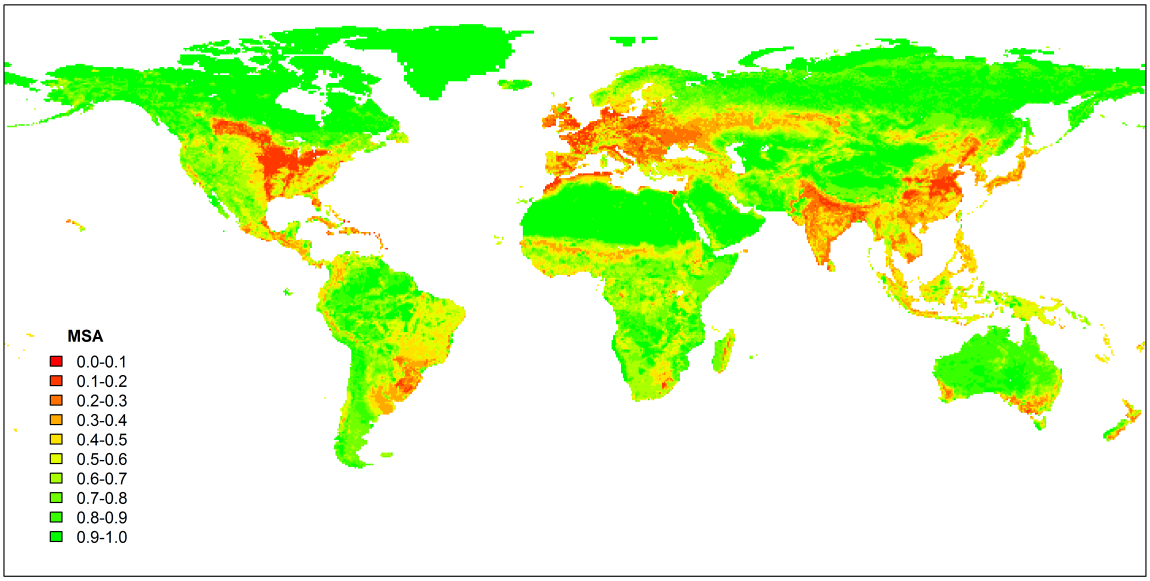


Fig. S3. The global distribution of combined relative mean species abundance of original species (MSA) as an approximation of the aggregated human pressure on the terrestrial biosphere (136).

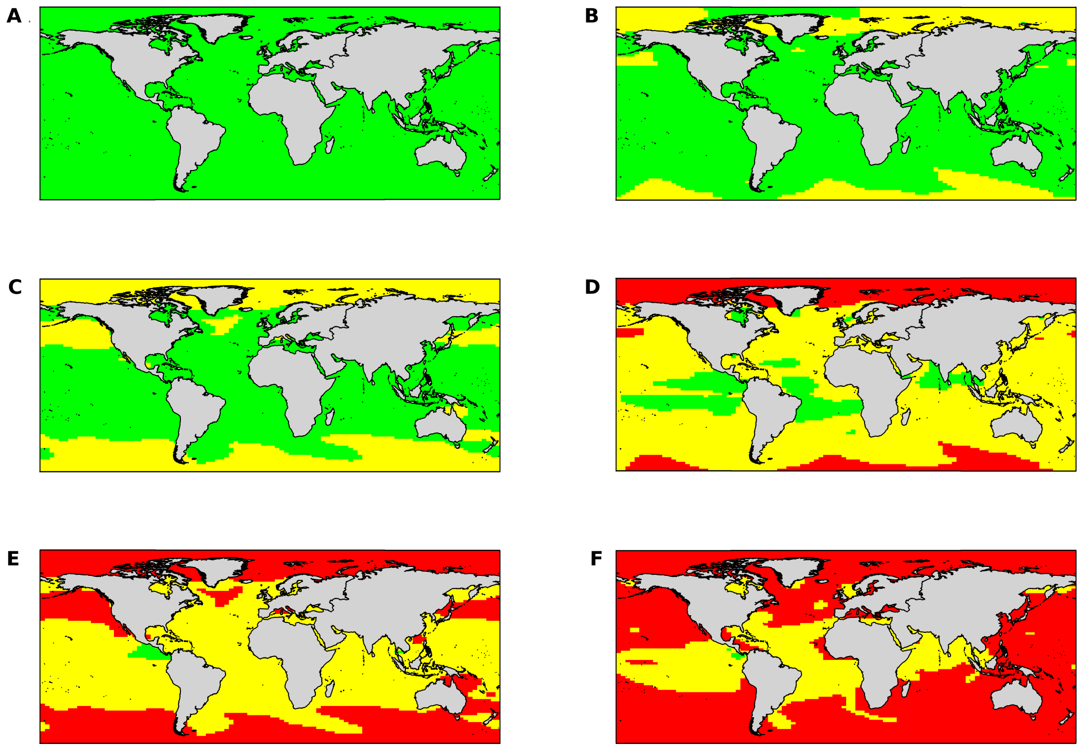


Fig. S4. The ocean acidification boundary: values of the control variable, aragonite saturation state (Ω_{arag}), under (a) 280 (pre-industrial state); (b) 380; (c) 400 (approximately current state); (d) 450; (e) 500; and (f) 550 ppm atmospheric CO_2 concentrations. Green represents regions where Ω_{arag} is below the boundary; yellow where it has transgressed the boundary but is still within the zone of uncertainty; and red where it is beyond the zone of uncertainty. Based on data from (137).

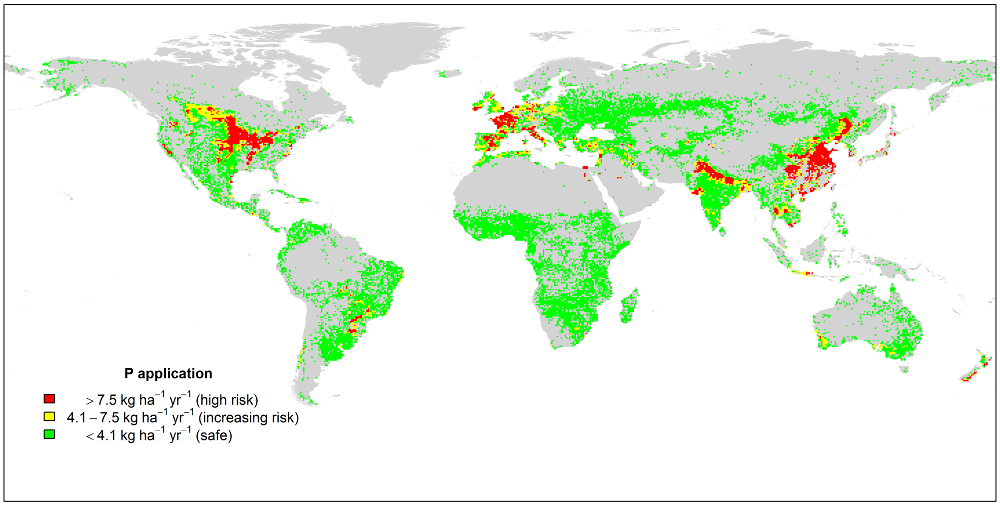


Fig. S5A. Geographical distribution of the control variable for phosphorus for the biogeochemical flows boundary, highlighting large agricultural zones where the P boundary is transgressed. The control variable is expressed as the uniform application rate of P in kg ha^{-1} yr^{-1} (see 33). Green represents regions where the application rate is below the boundary; yellow where it has transgressed the boundary but is still within the zone of uncertainty; and red where it is beyond the zone of uncertainty. Only cropland areas are color-coded; non-cropland areas are grey. Application rates of P from (138); cropland area data from (99). The down-scaled boundaries shown here are derived from the global boundary assuming a uniform rate of addition of P; local and regional pollution limits may deviate significantly from these boundaries.

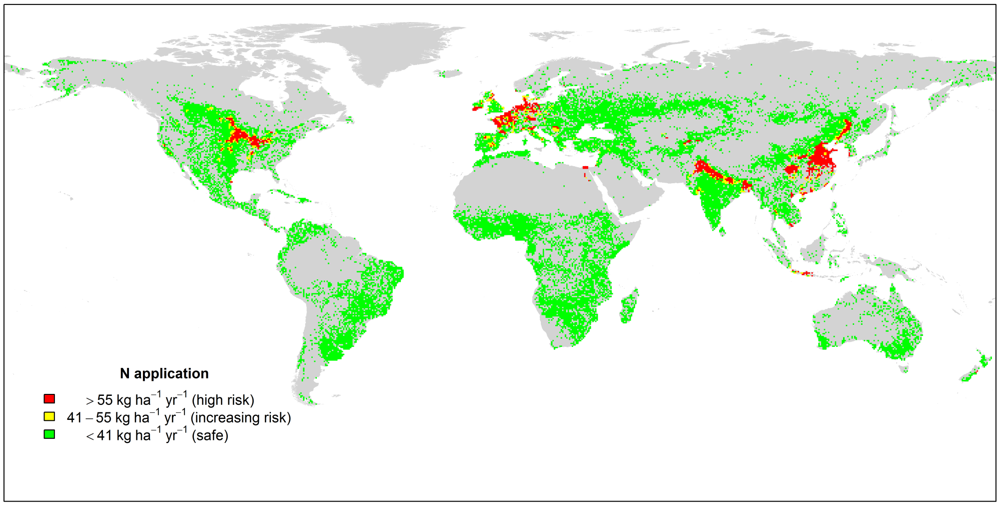


Fig. S5B. Geographical distribution of the control variable for nitrogen for the biogeochemical flows boundary, highlighting large agricultural zones where the N boundary is transgressed. The control variable is expressed as the uniform application rates of N in kg ha^{-1} yr^{-1} (see 33). Green represents regions where the application rate is below the boundary; yellow where it has transgressed the boundary but is still within the zone of uncertainty; and red where it is beyond the zone of uncertainty. Only cropland areas are colour-coded; non-cropland areas are grey. Application rates of N are from (138); cropland area data are from (99). The down-scaled boundaries shown here are derived from the global boundary assuming a uniform rate of addition of N; local and regional pollution limits may deviate significantly from these boundaries.

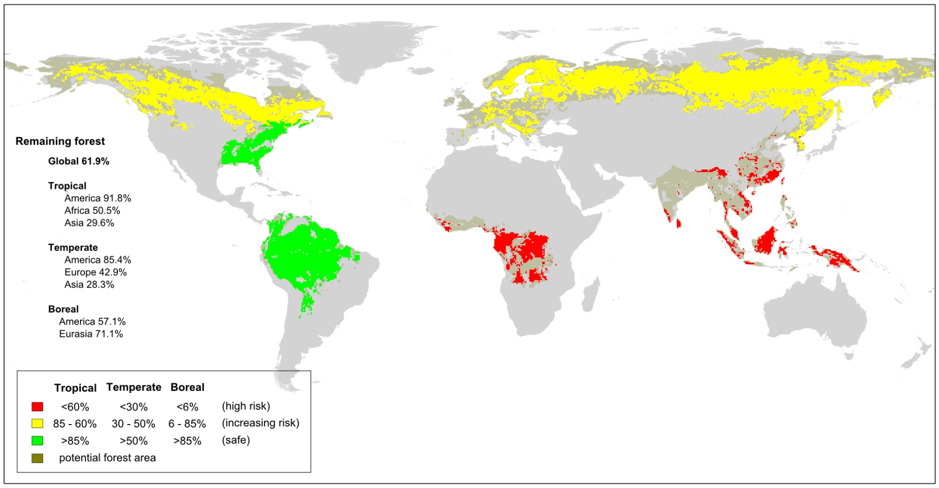


Fig. S6. Area of forest cover remaining in the world's major forest biomes compared to the potential forest cover, color-coded to show the position of the control variable (area of forest land remaining) with respect to the boundary. Areas not covered by major forest biomes are shown in grey. The lighter-colored background areas represent the area of potential forest biomes as estimated by (139). Only large, contiguous areas of forest have been used here to define the major biomes. Much smaller, isolated areas of forest (e.g., temperate forests in the northwest of the USA or along the east coast of Australia) have not been included in the analysis. The area of forest remaining in each of the biomes is represented by the deeper colors overlain on the light background. These areas have been calculated from the ESA GlobCover 2009 project database (111).

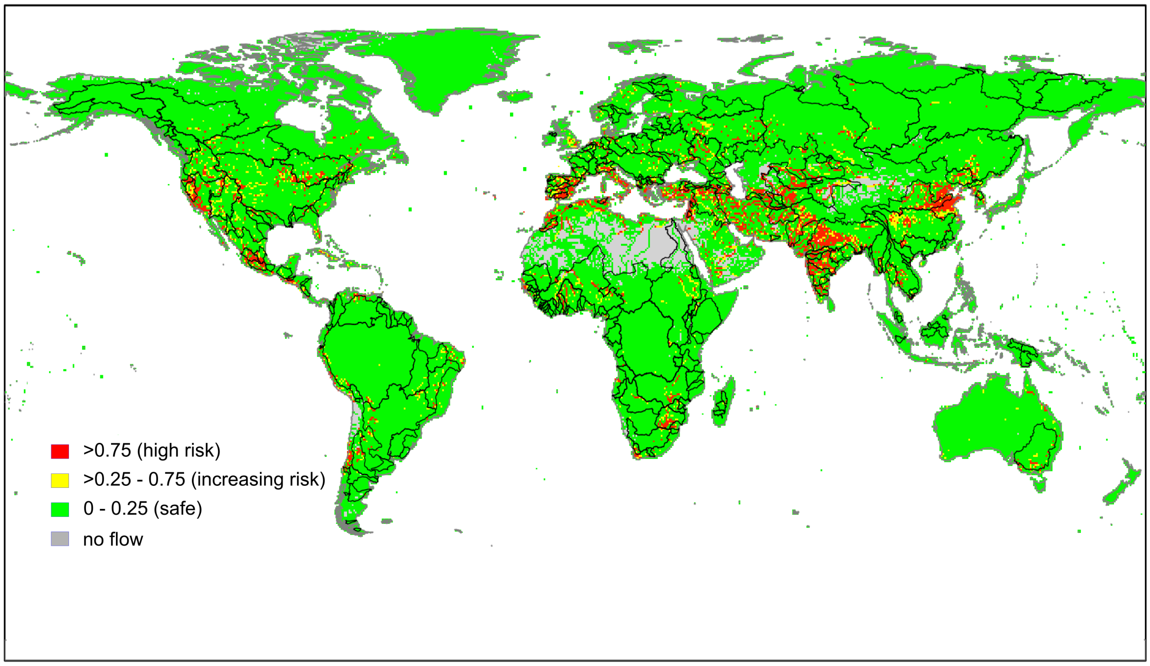
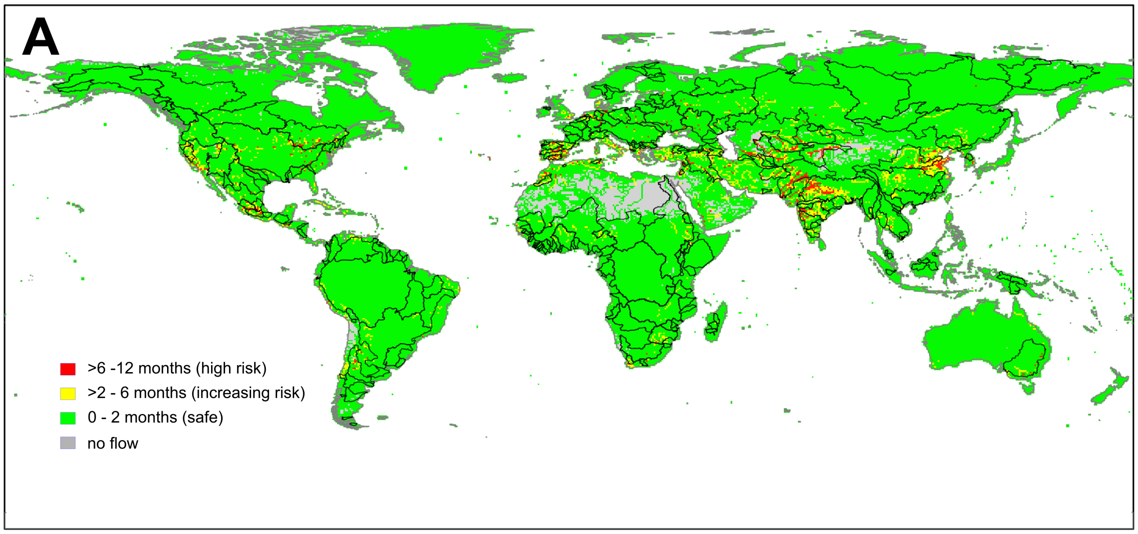


Fig. S7. Transgression of the allowed monthly water withdrawals defined by EWF, plotted as the degree of exceedance (fraction of maximum allowed level) during months that show such an exceedance. For example, green (within safe space) means that average exceedance in the respective months is still below the uncertainty range. The results are shown for all river stretches on a global 0.5° spatial grid, computed for this study with the LPJmL model based on 1981–2000 monthly averages of MMF, EWF (VMF method from (63) ± an uncertainty range to account for other methods) as well as agricultural, industrial and domestic water withdrawals (see 33). Major river basins are delineated.



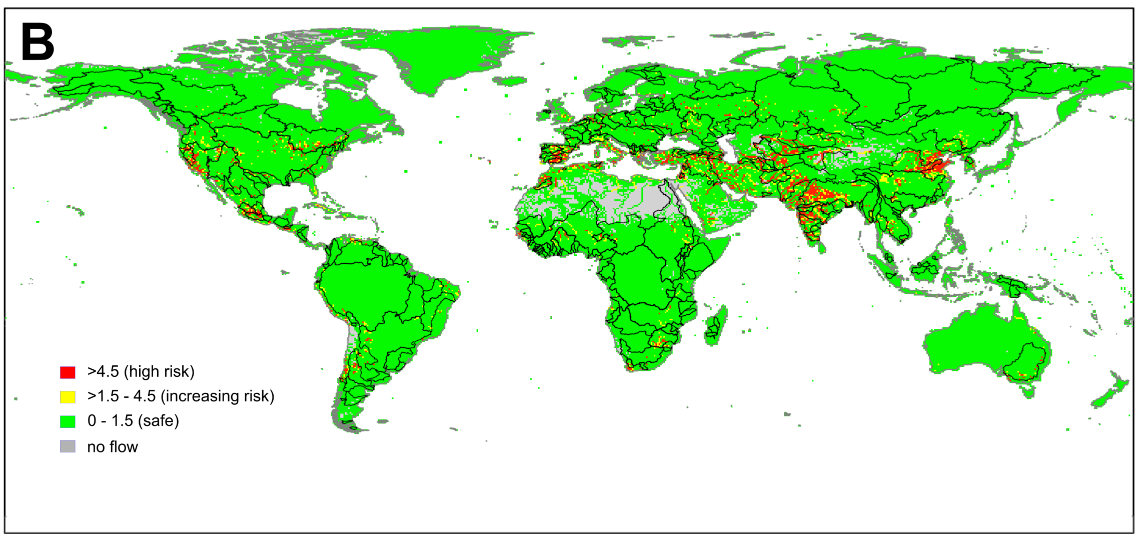


Fig. S8. Upper panel: Number of months per year with a transgression (by any degree) of allowed water withdrawals, corresponding to Figure S7. Lower panel: Risk index, defined as the product of duration and severity of transgression. EWF is estimated according to the VMF method by the method of Pastor et al. (63), here based on a different model setup and a new risk metric (see 33 for details).

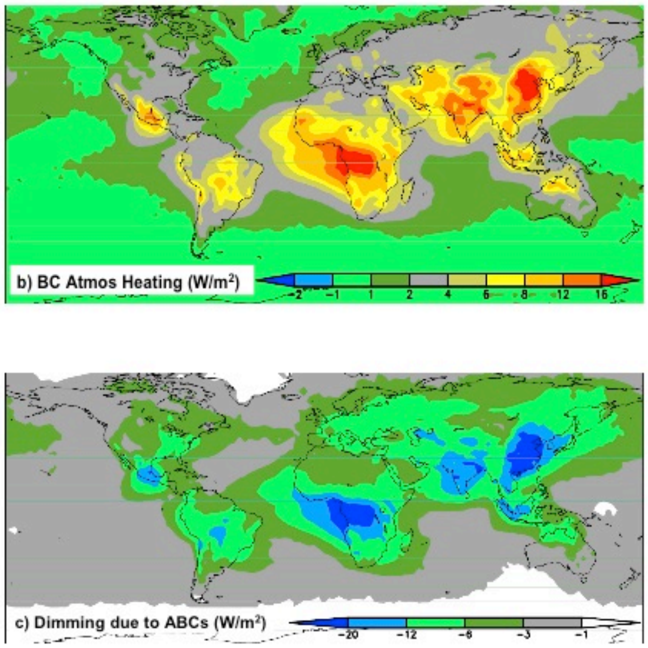


Fig. S9. Heating of the air by black and brown carbon (top panel) and dimming of the surface by all aerosols, including co-emitted aerosols (bottom panel). The impacts of human emissions of aerosols include weakening the monsoons and melting Himalayan/Tibetan glaciers. From (140).

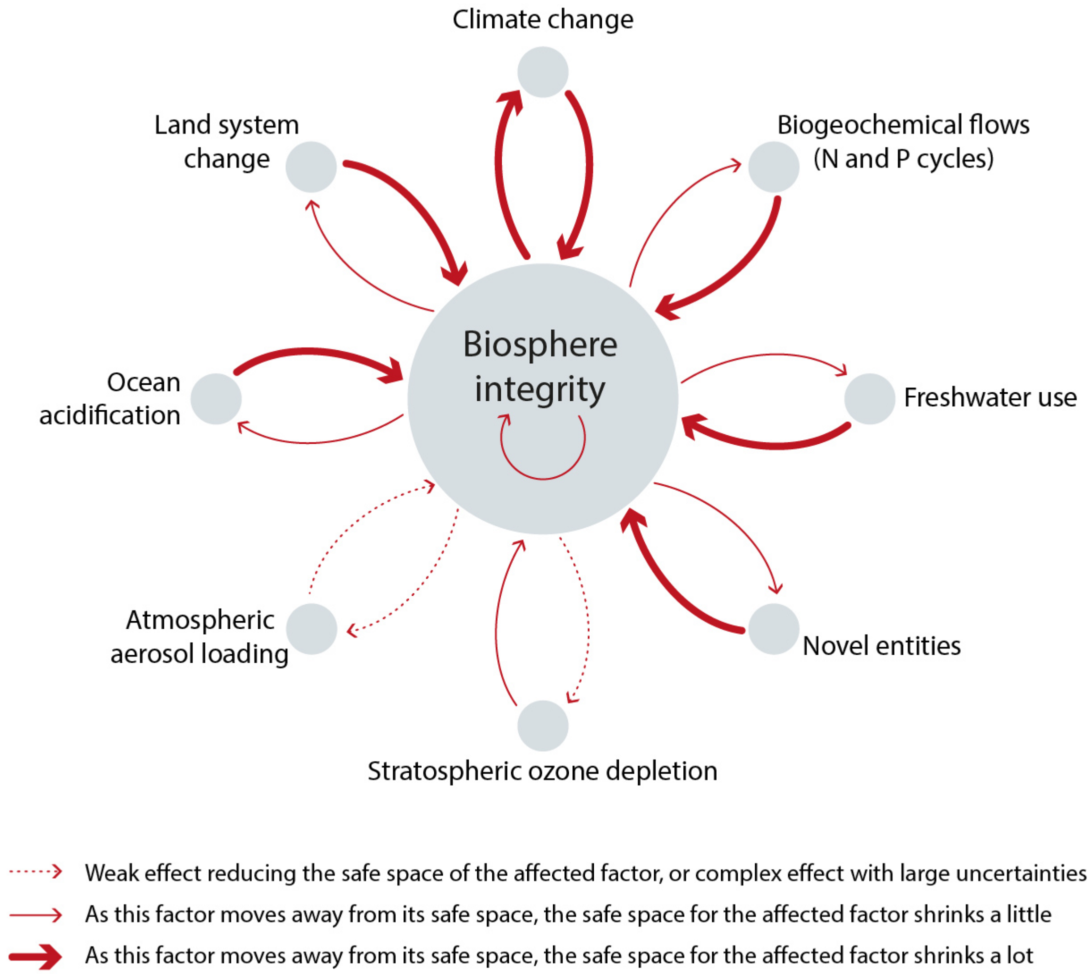


Fig. S10. The interaction between the biosphere integrity planetary boundary and other planetary boundaries. As a given factor (i.e. boundary type, such as biosphere integrity or climate change) moves further away from its own safe space, the arrows indicate changes in the factor (another boundary type). In all cases positive feedbacks exist, so a change in the factor away from the safe space will also move the affected factor away from the safe space. Thicker arrows denote stronger and more closely related effects. Thinner arrows indicate weaker and less closely related effects while dashed arrows indicate a weak and/or complex effect with large uncertainties. Adapted from (7).

Table S1: Transgression of one or more of the six of the PBs at the sub-global level would have consequences for the functioning of the Earth System at the global level (adapted from 50).

Planetary boundary	**Regional impacts with global implications if the boundary is transgressed**
Biosphere Integrity	The loss or degradation of entire biomes (e.g., coral reefs), or of the biodiversity components associated with large-scale ecological processes (e.g. predation, nutrient cycling) would have substantial impacts on regional and distant social/ecological systems (141,142). Changes in these biospheric processes could be large enough to compromise the Earth's ability to sustain human societies as we know them, especially through impacts on ecosystem goods and services, such as food production and climate regulation.
Novel entities	Chemical pollutants can damage health and disrupt ecosystem functioning over large areas which can result in global scale impacts (80,143-145), or affect abiotic processes such as the greenhouse effect (18) or stratospheric ozone chemistry (146)
Biogeochemical flows (P and N cycles)	Widespread eutrophication of freshwater bodies affects the freshwater boundary through reduced availability of water that is fit for human use, which drives further modification of the global hydrological cycle (3,5,147). Coastal eutrophication creates dead zones and harmful algae blooms that disrupt food webs and fisheries (148).
Land-system change	Deforestation of the Amazon basin has teleconnections to global climate (56,103-105,149); regional land-system change affects rainfall patterns at the continental scale (150).
Freshwater Use	Human diversion of (i) water vapor (green water) flows disrupts climate regulation (103,151) and (ii) liquid (blue) water flows induces collapse of aquatic ecosystems (152).
Atmospheric aerosols	Aerosol loading alters the hydrological cycle, radiative balance, albedo, and biosphere processes. Aerosol loading over the Indian sub-continent can trigger an abrupt shift of the Indian monsoon to a drier state, influence Asian monsoon circulation, and could also accelerate the melting of the Himalayan glaciers (67,153-157).

Table S2. Environmental water flow (EWF) requirements (% of mean monthly runoff) for different flow regimes (low flow, intermediate and high flow), and the associated maximum allowed withdrawals. The river basin-scale water boundary is placed at the lower end of the uncertainty range (marked in the table in grey cells). The average values are based on the VMF method (63), while the uncertainty range approximates the uncertainty among different EWF calculation methods. That is, for the low flow regime, for example, the uncertainty range for an EWF of 60% (45-75%) gives a range of maximum allowed withdrawals of 25-55%, an average maximum allowed withdrawal of 40%, and a boundary set at 25% (lower end of uncertainty range).

Flow Regime	**EWF**	**Maximum Allowed Withdrawal**		
		Average	Uncertainty Range	
			Low	High
Low Flow	60%	40%	25%	55%
Intermediate	45%	55%	40%	70%
High Flow	30%	70%	55%	85%

Table S3: Examples of significant interactions between both of the core boundaries – climate change and biosphere integrity – and all of the other boundaries.

Earth System process	**Interaction with Climate Change boundary**	**Interaction with Biosphere Integrity boundary**
Climate change	N/A	Many changes in ecosystem functioning at many scales from changes in temperature, rainfall patterns, extreme events and other changes in the physical climate system. Large-scale changes in the distribution and composition of biomes. Projected large increases in extinction rates of many taxa from rapid climate change. In the other direction, biospheric sinks of carbon are important in reducing radiative forcing due to human activities
Biosphere integrity (earlier “biodiversity loss”)	Erosion of resilience in both terrestrial and marine ecosystems results in higher risk of climate-induced tipping points in ecosystems, and hence reducing their capacity to act as carbon sinks (e.g. loss of methane from melting permafrost)	N/A
Novel entities (earlier “chemical pollution”)	CFCs and some of their replacements like HFCs are strong GHGs	Many adverse effects on organisms – e.g., toxicity, population declines, increased rate of biodiversity loss (POPs, EDCs, organometallics, radiation etc.) Flow-on effects of species alterations and loss to ecosystem functioning.
Stratospheric ozone depletion	Affects atmospheric circulation in the southern hemisphere, with consequences for storm tracks and rainfall patterns; possible implications for uptake of	Increases UV-B at Earth’s surface, especially in southern high latitudes in austral spring; impacts on the functioning and composition of marine ecosystems

	CO_2 in the southern ocean; cools the surface and the stratosphere	
Ocean acidification	Weakening of marine carbon sink; increases airborne fraction of CO_2, amplifying feedback to warming	Threat to coral reefs and other calcifying organisms; likely flow-on effects up marine food chains
Biogeochemical flows: interference with P and N cycles	Atmospheric N species affect radiative forcing: N_2O is a strong, long-lived GHG; NH_3/NH_4^+ and NO_x contribute to aerosol formation, and alter hydrological cycling	Impacts on ecosystem functioning through the increase and redistribution of many important nutrients, especially N and P. Implications for biodiversity distribution on land and ocean (habitat change). The biosphere also absorbs and transforms many P and N compounds, decreasing the perturbation in flows. Eutrophication reduces positive effects of biodiversity on ecosystem stability (158)
Land-system change	Deforestation, forest degradation and agricultural practices can all emit CO_2 (and CH_4 and N_2O) to the atmosphere, amplifying warming. Conversely, forest preservation, reforestation and better agricultural practices can reduce emissions and absorb C from the atmosphere into vegetation and soils. Historically 15-20% of GHG emissions come from land system change.	Conversion of natural to human-dominated ecosystems changes functioning and, in general, leads to less resilient ecosystems. Habitat fragmentation and conversion of habitats for human use is historically the largest driver of biodiversity loss in terrestrial ecosystems. There can also be indirect effects through changes in disturbance regimes, alteration of water vapour flows at continental scales, introduction of invasive species, etc.
Freshwater use	Reduction of growth in natural ecosystems, reducing carbon sink in standing vegetation and soils. Increase in CH_4 emissions from pondages and irrigation;	Changes in functioning and species loss in river, wetland and lake ecosystems through diversion of water for human use. This lead to losses in regulating and other

	decrease in carbon transport from land to ocean via rivers.	ecosystem services, such as buffering during extreme events.
Atmospheric aerosol loading	Affects radiative forcing in complex ways (mainly cooling, but black and brown carbon cause warming). Alters tropical atmospheric circulation. Also affects precipitation amounts (e.g., cooling aerosols reduce global precipitation) and patterns, and hence land C sink strengths. Black and brown carbon deposited on snow and ice cause melting of glaciers and sea ice	All aerosols, natural and anthropogenic, cause surface dimming and thus slow the hydrological cycle. Acidic aerosols (sulfate, nitrate) can damage freshwater ecosystems and soil biota. Heavy smoke from excessive biomass burning and other combustion can be harmful and toxic to plants and animals; Dust loadings alter the distribution of nutrients and light availability, affecting primary production. The biosphere can also remove many aerosols from the atmosphere

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