Article

Exploring pathways for world development within planetary boundaries

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The pressures humanity has been placing on the environment have put Earth's stability at risk. The planetary boundaries framework serves as a method to define a 'safe operating space for humanity'[1,2] and has so far been applied mostly to highlight the currently prevailing unsustainable environmental conditions. The ability to evaluate trends over time, however, can help us explore the consequences of alternative policy decisions and identify pathways for living within planetary boundaries[3]. Here we use the Integrated Model to Assess the Global Environment[4] to project control variables for eight out of nine planetary boundaries under alternative scenarios to 2050, both with and without strong environmental policy measures. The results show that, with current trends and policies, the situation is projected to worsen to 2050 for all planetary boundaries, except for ozone depletion. Targeted interventions, such as implementing the Paris climate agreement, a shift to a healthier diet, improved food, and water- and nutrient-use efficiency, can effectively reduce the degree of transgression of the planetary boundaries, steering humanity towards a more sustainable trajectory (that is, if they can be implemented based on social and institutional feasibility considerations). However, even in this scenario, several planetary boundaries, including climate change, biogeochemical flows and biodiversity, will remain transgressed in 2050, partly as result of inertia. This means that more-effective policy measures will be needed to ensure we are living well within the planetary boundaries.

In 2015, governments worldwide adopted the Sustainable Development Goals (SDGs), representing an ambitious agenda to promote human well-being, eradicate poverty and preserve the ecological integrity of the planet. The planetary boundaries framework is instrumental in evaluating the latter. The framework defines boundaries for a set of nine critical Earth system processes that demarcate the 'safe operating space' within which humanity has thus far been able to thrive, using the relative stability of Holocene climatic and ecological conditions as its baseline[1,2,5]. The boundaries typically represent levels beyond which environmental stress could lead to large-scale systemic and potentially irreversible environmental degradation. The most recent assessment shows that six of the nine planetary boundaries have already been transgressed[1,5].

The planetary boundary framework has garnered significant attention from the realms of science and policy[6–10]. The European Union, for instance, indicates, in its 8th Environmental Action Programme, that by latest 2050, Europeans should "live well, within the planetary boundaries"[11]. This raises the question if this is actually possible. The planetary boundary concept has also been the subject of scientific debate, for instance, concerning its dichotomous representation of environmental risk and the choice of specific limits[12–14] and, politically, the planetary boundaries have faced some controversy because of perceived trade-offs between environmental sustainability and the need for development to tackle poverty[15,16]. Over time, however, the planetary boundary concept has been further developed and operationalized. The Earth Commission, for instance, recently introduced socially just boundary values to complement the biophysically safe values[17], somewhat similar to earlier work on the so-called doughnut economy representation[18]. Several studies have aimed to improve planetary boundary indicators[5,19,20]. Overall, the planetary boundary framework has proven to be both an important analytical tool and a forceful communication tool emphasizing the multidimensional nature of environmental degradation.

So far, the use of the planetary boundary framework has predominantly served to highlight the unsustainability of the present state. Only a few studies have explored the future development of human activities in the operating space over time in ways that are either conceptual or partial in scope, such as for agriculture[21–24]. To increase the framework's relevance for policy-making, it needs to be applied to track future trends and demonstrate the consequences of different policy

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Table 1 | Planetary boundary framework as applied in this paper

Planetary boundary	Planetary boundary indicator					Pressure indicator	
Earth system process	Control variable[a]	Planetary boundary	Upper end of uncertainty zone	Reference	2015 value	Indicator	2015 value
Climate change	Forcing – GHGs ($W m^{-2}$)	1.9	2.6	0	2.36	GHG emissions	53.3 Gt CO_2-eq
Stratospheric O_3 depletion	O_3 concentration (DU) 60–90° S	276	261	330	280	CFC-12 (Freon) emissions	15–25 Gg yr^{-1}
Atmospheric aerosol loading	*Average $PM_{2.5}$ concentration ($\mu g m^{-3}$)*	10	25	5	21.9	BC emissions	11 Mt BC yr^{-1}
Ocean acidification	*pH*	8.01	7.94	8.2	8.05	CO_2 emissions	38.4 Gt CO_2
Biogeochemical flows							
N	*N balance (Tg N yr^{-1})*	62	82	0	131.5	Total fertilizer application	155.3 Tg N yr^{-1}
P	*P balance (Tg P yr^{-1})*	6.2	11.2	0	12		
Freshwater use	Water consumption (km^3)	4,000	6,000	0	3,440	Water consumption	3,440 km^3
Land system change	Area of forested land (Gha)	45	33	64	39	Agriculture area	48.3 Gha
Change in biosphere integrity	*MSA*	0.90	0.60	0.95	0.54	Global mean temperature increase, atmospheric N deposition, land use	

[a]The control variables in italics are different from the 2015 planetary boundary indicators[1] to allow for IAM analysis and to accommodate data availability limitations. The main text and Methods further explain the choices that were made. The pressure indicators were selected because they form the key driver of the environmental degradation of the control variable, based on the literature. In some cases, such as O_3 depletion and atmospheric aerosol loading, an illustrative pressure was selected.
BC, black carbon.

decisions related to sustainable development. In particular, a critical question concerns the need to reduce environmental pressures and return to within the planetary boundaries. This requires coupling the framework to data from model-based scenarios[3].

In this study, we make an important contribution by linking the planetary boundary framework to the scenario outcomes of the Integrated Assessment Model (IAM), IMAGE[4]. A key advantage of using IAMs for this purpose is their focus on interlinkages across different issues, across time (long-term trends in relation to near-term decisions) and space (different geographical scales)[12,25]. This has, for instance, been shown in the use of IAM-based scenario analyses in supporting climate-change policy[26]. For planetary boundaries analysis, a specific additional advantage is that the use of an IAM allows us to relate current Earth system conditions (most planetary boundary control variables, that is, the indicators used to measure the transgression of planetary boundaries) to socially relevant environmental pressure indicators. Because these can often be directly targeted in policies, this allows the planetary boundaries to be translated into actionable targets, such as GHG emissions or fertilizer use.

A dynamic view of planetary boundaries using IMAGE-based scenarios

We used the Integrated Model to Assess the Global Environment (IMAGE) scenario output to assess the development of environmental variables over time, based on the Shared Socioeconomic Pathways (SSPs) and additional policy assumptions. IMAGE addresses the impacts of future energy and agriculture systems on global environmental-change issues, such as climate change, biogeochemical cycles, air pollution, biodiversity loss and water scarcity[4]. These systems have been identified as key drivers of ecological degradation at the global scale[27]. The model has global coverage, but socioeconomic calculations were performed for 26 world regions, and environmental calculations were performed at a 5 × 5-min grid. IMAGE, together with other IAMs, has been deployed in the development of the SSPs[28,29].

The SSPs explore the possible impacts of not having specific new policies to implement global sustainability goals. We focus on SSP2, given its role as a 'middle-of-the-road' development trajectory, assuming no major shift in current societal trends (that is, business as usual (BAU)). To explore the uncertainty associated with different socioeconomic developments, we compared results with SSP3 (a more pessimistic case, which assumes that regional competition slows down economic and technological development and leads to higher population growth) and SSP1 (a modest shift towards higher resource-use efficiency, rapid technology development and low population growth)[29,30]. To evaluate whether it is possible to change current development patterns to stay within the planetary boundaries, we first focused on the impact of implementing the 1.5 °C target of the Paris Agreement (that is, climate policy). Given synergies with other planetary boundary processes, the key question here is to what degree climate policy alone can bring the Earth system back within the planetary boundaries. Subsequently, we investigated a set of additional sustainability policies relating to biodiversity, land and water use, and biogeochemical flows (that is, sustainability). The key energy and land-use developments in these scenarios are shown in Supplementary Information Section 2. In our results, we focus on 2030 and 2050 (given the lower amount of uncertainty), but also show the 2100 results to highlight the impact of inertia.

The planetary boundary framework[1] identifies two critical values for each control variable, the planetary boundary itself (a safe boundary above which the risks of system-wide environmental degradation increase, albeit still with considerable uncertainty) and the upper end of the uncertainty zone (the start of the high-risk zone, where impacts are known to be severe). The planetary boundary control variables are mostly variables that describe the current state of the environment (relating to possible irreversible environmental degradation). However, IAMs typically represent the full causal chain of environmental degradation from human activity (for example, energy use) to pressure (for example, GHG emissions) to environmental change (for example, forcing or climate change), including indicators of environmental pressures that can directly be influenced by policies, such as emissions and fertilizer application[3].

In the analysis, we used the 2015 planetary boundary formulation as a basis[1], this currently being the most widely used and which presents geospatially resolved mappings together with analysis of systemic links of several processes in the framework (for example, nitrogen (N) and phosphorus (P) flows, biome-level ecosystem changes, atmospheric aerosols and environmental water flows) (Table 1). For most indicators, the 2023 planetary boundary formulation is similar to that of 2015. In applying the planetary boundary framework, in combination with IMAGE, some decisions had to be made about operationalizing the

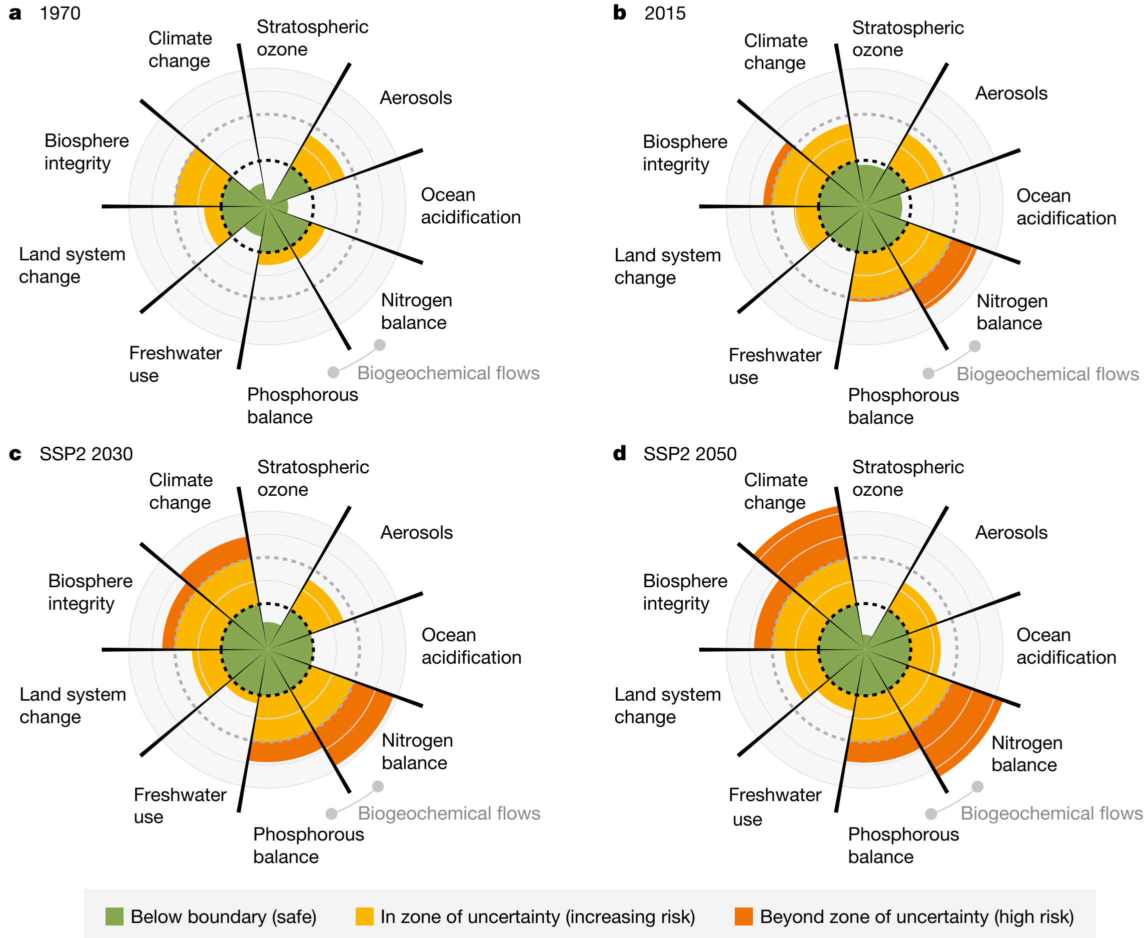

Fig. 1 | Development of the control variables for planetary boundaries over time, historic period and assuming BAU for 2030 and 2050 (SSP2, BAU). **a**–**d**, Control variables for planetary boundaries for 1970 (**a**), 2015 (**b**), SSP2 2030 (**c**) and SSP2 2050 (**d**). The green zone is the safe operating space, the pale orange represents the zone of uncertainty (increasing risk), and the dark orange is the high-risk zone. The planetary boundary itself lies at the intersection of the green and pale orange zones. The control variables have been normalized to the reference value, planetary boundary and the upper end of the uncertainty zone, as explained in the Methods. The control variables and values used are indicated in Table 1. The planetary boundary figures are a useful conceptual visualization tool, but still subject to limitations, as discussed in the literature[50].

planetary boundary control variables (Methods). For climate change, we used radiative forcing, given the wider coverage of GHGs and the availability of suitable data (aligning the values with the carbon dioxide (CO_2) concentration boundary[5]). For atmospheric aerosol loading, we did not use aerosol optical depth, but instead focused on the average concentration of particles smaller than 2.5 µm, using a value that led to fulfilment of the minimum health guidelines, globally based on the World Health Organization (WHO), as our reference point[31]. This change was motivated by data availability, but also by the increasing policy attention to pollution and its relationship with aerosol loading (the same change was made by the Earth Commission for the just boundary). For ocean acidification, we used pH, a measure of seawater acidity, instead of aragonite saturation (given the data available in the literature), based on a relatively simple correlation with cumulative CO_2 emissions (Methods). For biogeochemical flows, we used the N and P balance indicators (for soils)[32]. Because stratospheric ozone (O_3) is not an IMAGE output, exogenous calculations, based on the same scenario assumptions, were used instead[33]. Finally, the mean species abundance (MSA) was used to evaluate biosphere integrity[34]. The MSA is conceptually similar to the biodiversity intactness index (BII)[1] or the intact natural ecosystem indicator[17], but includes a wider set of pressures (N deposition, climate change and land use). The reference values were derived from planetary boundary papers (Methods). For all boundaries, we changed the scaling of the outcomes below the planetary boundary, given the more dynamic use here (Methods and Extended Data Fig. 1).

Baseline development

The calculations of planetary boundary control variables, based on IMAGE, provide a similar pattern for 2015 to earlier assessments, but with some differences that merit discussion (Fig. 1). The 2015 planetary boundary assessment[1] showed four planetary boundaries being transgressed—climate change, biogeochemical flows, land system change and biosphere integrity—with biosphere integrity and biogeochemical flows even exceeding the zone of uncertainty. The recent 2023 study adds transgression of the planetary boundaries for new entities and freshwater change (based on different calculations)[5]. The IMAGE calculations show results similar to those in the 2015 study, but based on the change in methods, the planetary boundary for aerosols is also transgressed now (see ref. 31), implying the transgression of five planetary boundaries. The same observation was made by the Earth Commission, with the value for aerosols based on protecting human health being far more stringent than the safe value based on Earth system considerations[17].

The use of IMAGE allowed us to track the development of planetary pressures over time, which showed rapid environmental degradation[35] (Fig. 1). First, the 2015 situation represents a clear deterioration

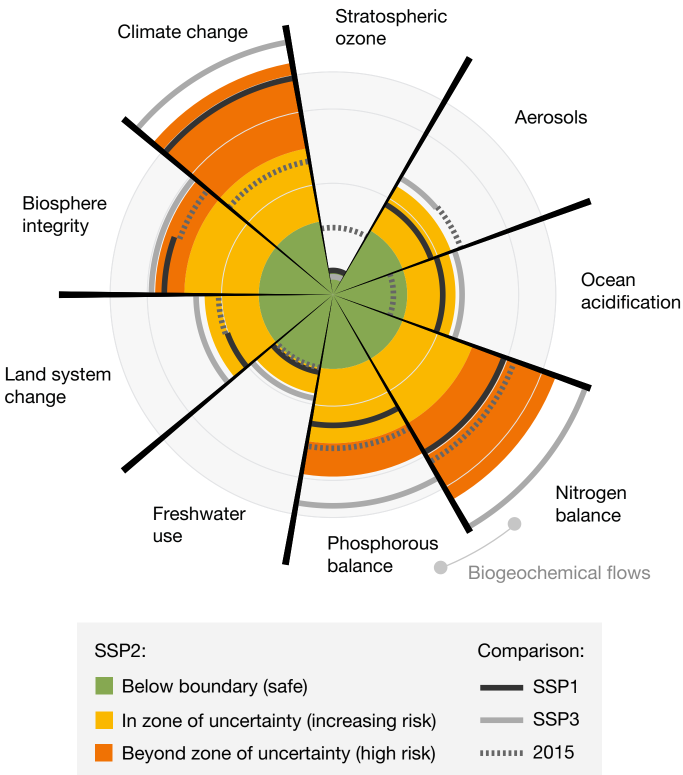

Fig. 2 | Future development of control variables of the planetary boundaries without additional policies for 2015, and for 2050 with SSP1 and SSP3. The SSPs represent different development trajectories for the world. For an explanation of the different zones and the limitations of the current representation, see Fig. 1.

compared to 1970 for most planetary boundaries (with the exception of air pollution in some regions), particularly climate change, biogeochemical flows and biodiversity. The SSP2 scenario shows further degradation for nearly all indicators towards 2030 and 2050. This means that, without specific response measures, the planetary boundaries were transgressed for five processes in 2030 and 2050 and, for climate and biogeochemical flows, the values are in the high-risk zone. Also, the values for freshwater and ocean acidification would be very near to a transgression. By contrast, trends in stratospheric O_3 concentration are projected to improve slightly. For air pollution, the values are more or less constant as a net effect of the expected improvement in air pollution control regulation and increases in energy consumption. Looking at the longer trend (to 2100), the SSP2 scenario suggests further degradation, with the exception of stratospheric O_3 concentration and, now more clearly, air pollution.

To illustrate the uncertainty related to alternative socioeconomic development, Fig. 2 shows the results for SSP1 and SSP3. The developments in SSP3 lead to a worse result for most indicators, driven primarily by a much higher population growth. By contrast, the SSP1 scenario projects a more favourable outlook for these planetary boundaries, where its lower population growth is accompanied by modest dietary shifts and changes in agricultural production patterns. However, the SSP1 outcomes still show a situation in which most planetary boundaries are transgressed.

Living within planetary boundaries

Given the projected worsening trend in the BAU case, an important question is, what would it take to live within planetary boundaries, as aspired to in the European Union's 8th Environment Action Programme? From an Earth system perspective, historical changes have already altered the fundamental biogeochemical and biophysical functioning of the planet in irreversible ways[36], so the policy aspiration must be taken to mean living in such a way that strongly mitigates current pressures on the planetary boundary control variables and reverses the impacts of human-driven pressures to whatever extent possible. Here we explore a set of measures discussed in the literature to determine the effort needed to bring society back within the planetary boundaries. Although these measures are considered technically feasible, according to various studies, there are different views on the societal feasibility of such major transformations[37]. It is important to further study the feasibility of measures such as large-scale shifts in diets or significantly improving the efficiency of water use (see, for instance, refs. 37–39). This is also related to justice as societal support for mitigating GHG emissions has been shown to strongly depend on how the mitigation effort is distributed[40].

In current policy discussions, most attention is given to climate change. Given the existing synergies between climate change and other sustainability challenges, one could wonder how far implementing the Paris Agreement would go in meeting the goal of living within the planetary boundaries. The impact of policies implementing the 1.5 °C target (SSP2-1.9) is shown in Fig. 3. This scenario is among the most ambitious scenarios in the literature[41]. The strong reduction in fossil fuel use in this scenario does not mean that the PB level for climate change is reached: the climate control variable is still beyond the planetary boundary value, but forcing is still decreasing in 2050 as a result of net negative CO_2 emissions. Key inertias that prevent reaching the planetary boundary value by 2050 include Earth system processes (for example, the net CO_2 flux back from the ocean to the atmosphere after reaching a peak concentration), limits to the negative emissions potential (for example, available land for reforestation and bio-energy, as well as sequestration potential), and the speed of societal changes[37,42]. The climate mitigation scenario does result in clear synergies for N flow disturbance and air pollution, and partly for land system change. These result from systemic changes in the energy system (switching away from fossil-fuel combustion), the reduction in nitrous oxide (N_2O) emissions and reforestation as part of climate policy. However, progress is insufficient to avoid that in this scenario, with transgression of the planetary boundaries being worse in 2050 than in 2015. In some cases, trade-offs also play a role. The most important is that climate policy induces bio-energy production, leading to some upward pressure on land system change, although the net impact of climate policy is slightly positive (via additional afforestation).

A key question, therefore, is what ambitious, but technically feasible, policies can further reduce transgression of the planetary boundaries. In the sustainability scenario, shown in Fig. 3, we consider a set of measures recently explored in a multi-model study to address the nexus-related SDGs (Table 2). The measures include a shift towards the EAT–*Lancet* planetary health diet, a halving of food loss, a significant improvement in water-use efficiency (based on the best-available technology) and an improvement in N-use efficiency (NUE) to maximum levels (the impacts of this set of measures in the absence of climate mitigation are shown in Supplementary Information Section 3). It is important to note that, for the efficiency measures, no further improvement is assumed after 2050. Although this list is not exhaustive, the measures can be assumed to be (at least) as similarly ambitious as the climate target.

The sustainability scenario clearly shows that it is possible to significantly reduce the increase in environmental degradation towards 2050 (Fig. 3). For nearly all planetary boundary elements, this would reduce the pressure back to the 2015 value or better (as in the case for aerosols, the disturbance of biogeochemical flows (although still in a high-risk state) and land system change). However, the planetary boundary value would, for most indicators, still be transgressed. This is partly due to inertia. Again, for climate change, the radiative forcing in the climate policy and sustainability scenarios is reducing in

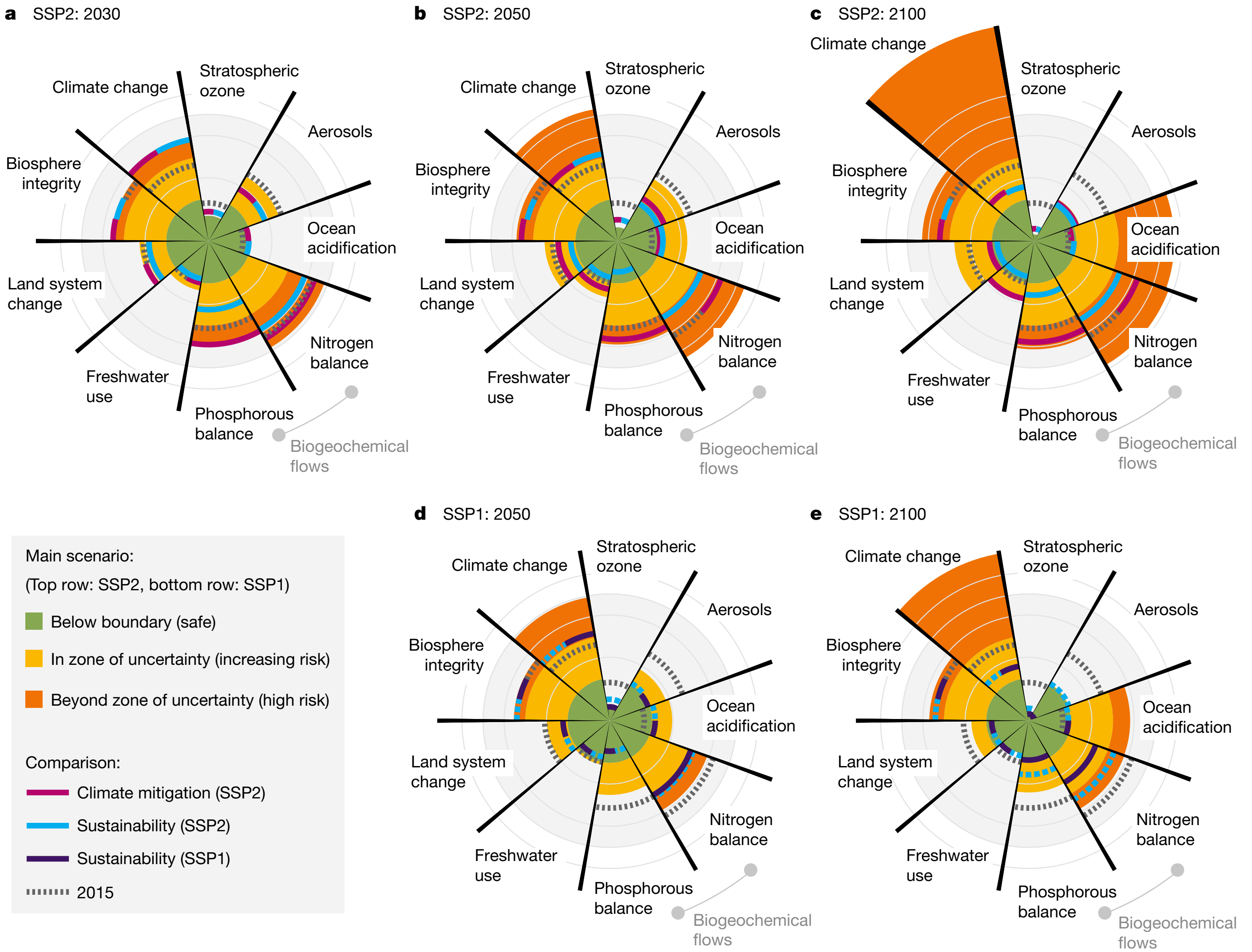

Fig. 3 | Development of the control variables of planetary boundaries for the BAU scenario (SSP2) and response scenarios in 2030, 2050 and 2100. **a**–**c**, BAU (SSP2, end of coloured wedge) and response scenarios (coloured lines), in 2030 (**a**), 2050 (**b**) and 2100 (**c**), showing the impacts of the climate-mitigation-only scenario (magenta lines) and the sustainability scenario (blue lines), including all measures indicated in Table 2. **d**,**e**, SSP1 (end of coloured wedge) and impact of response scenarios starting from SSP1 (coloured lines), in 2050 (**d**) and 2100 (**e**), showing the sustainability scenario (purple), compared with the SSP2-based version (blue dotted lines). For an explanation of the different zones and the limitations of the current representation, see Fig. 1.

2050, but it takes time to undo the emissions overshoot up to that period (and for the temperature to respond). Transgressing tipping points could possibly even worsen this. For biodiversity, increasing climate-change impacts play a critical role in limiting the possibility of reversing the biodiversity trend (see also ref. 43). The role of this inertia is illustrated in the 2100 panel (Fig. 3c), which shows clear further improvement for climate change and, to some extent, for biodiversity (owing to the reduced climate-change impact). Trends in aerosol loading and freshwater use are easier to reverse because there is less biophysical inertia involved (for example, aerosols have a very short atmospheric lifetime), the most important inertia being related to societal transformation. For nutrients, the 2100 results show a temporal reversal of the earlier improvement with no further efficiency improvement assumed, whereas yields were assumed to increase further (leading to a reduction in agricultural land and biodiversity improvement). However, the results highlight that even more ambitious policies will be needed if the aim is to fully return to the planetary boundary's safe operating space in this century. Inertia and irreversible losses provide a compelling reason for societies to act sooner rather than later.

Another question is whether starting from the SSP1 scenario (with lower population and consumption levels) leads to a better result. Figure 3 shows that this is indeed the case, but the differences in 2050 are small because the policies implemented lessen the differences between SSP1 and SSP2 (for example, the diet shift and the climate policy aiming for 1.5 °C). In the longer run, differences in population size and agricultural practices play a larger role, as illustrated in the 2100 results for biogeochemical cycles. If the policies of the sustainability scenario are implemented without the climate policy (Supplementary Information Section 1), a notable improvement still occurs in nearly all indicators. However, the results for climate change and acidification are now restricted to the land-use-related impacts of the dietary shift (for example, forest growth due to reduced agricultural land use). For all other planetary boundaries, the positive policy impact is diminished because of the lack of synergies with climate policy. The biophysically defined planetary boundary values themselves cannot, in most cases, be directly controlled. It is therefore important to identify a set of pressure indicators that can be related to policy. We derived a set of pressure variables that can be directly influenced by policy-making. Table 3 indicates the values for the three scenarios. Depending on the

Table 2 | Overview of measures included in the sustainability scenario

Category (policy)	Measure as implemented in the model
Climate mitigation	Implementation of the 1.5 °C target of the Paris Agreement, implemented via price on GHG emissions, following SSP2-1.9 (ref. 41)
Food-consumption change	Shift towards a healthy diet, as defined by EAT–*Lancet* (80% implementation in 2050 and 100% in 2100)[45]
Reduction of food waste	Reduction in food loss by consumption group (overall leading to halving food waste in 2050)[46]
Water withdrawal for energy, industry and households	Implementation of efficiency in water use in industry, the residential sector and electricity generation (leading to an overall reduction of around 20% in 2050)[47]
Water withdrawal for irrigation	Reduction in water use for irrigation to ensure environmentally and ecologically sustainable levels (leading to a reduction of around 30% in 2050)[48]
Use of N fertilizers	Increase in NUE to maximum levels by 70–80% in 2050 (compared to 50% as the baseline)[49]

Table 3 | Values for pressure indicators as leverage to reduce transgression of the control variables of the planetary boundaries

Pressure indicator	Unit	2015	2050		
			BAU[a]	CP	SU
GHG emissions	$GtCO_2$-eq yr^{-1}	1.0	1.4	0.1	0.1
CFC-12 (Freon) emissions	Gg yr^{-1}	1.0	0.0	0.0	0.0
Aerosol emissions	Gg BC yr^{-1}	1.0	0.7	0.5	0.4
CO_2 emissions	$GtCO_2$ yr^{-1}	1.0	1.4	−0.1	−0.00
Fertilizer use (N)	Tg N yr^{-1}	1.0	1.4	1.1	0.8
Fertilizer use (P)	Tg P yr^{-1}	1.0	1.4	1.3	0.8
Freshwater use	km^3 yr^{-1}	1.0	1.2	1.1	0.8
Total agricultural area	Gha	1.0	1.1	1.0	0.9

[a]BAU for SSP2.

Pressure indicators are all normalized to their 2015 values. CP, climate policy; SU, sustainability scenario.

policy ambition, these values can be used as targets in policy-making. For most variables, considerable reductions in the pressure indicators are needed to reverse the planetary boundary trends (such as for GHG and CO_2 emissions).

Living well in a dynamic safe operating space

Our study has shown that coupling IAM scenarios to the planetary boundary framework can provide insights into potential future developments, under different policy choices, of the stability of critical Earth system processes. This allows us not only to study baseline scenarios, but to explore what is needed to remain (and live well) within a safe operating space. Such dynamic use of the planetary boundary framework can inform policy-makers and society on the transformations required to ensure a stable and resilient planet. Meeting the various goals set in multilateral environmental agreements (such as the Paris climate policy targets, the Kunming–Montreal Convention on Biodiversity 15 target and the United Nations' SDGs by 2030) requires an integrated policy approach. The stability of the functioning of the planet is a prerequisite for positive policy outcomes on climate and biodiversity, and development outcomes for the United Nations' SDGs. This necessitates a wider whole-Earth system approach to policy-making, going beyond climate change and biodiversity, while accounting for synergies and trade-offs among the planetary boundaries. For the calculations, we adjusted some planetary boundary indicators to make them more suitable for model-based analysis, but we strongly encourage further work on the development of a standard set of planetary boundary indicators that can be used for both static and dynamic purposes. In that context, it is important to distinguish indicators reflecting environmental risk (the planetary boundary indicators) from indicators reflecting environmental pressure that can be used in setting goals (Table 3). On this basis, some planetary boundary indicators could even be reconsidered (for example, indicators more directly reflecting water scarcity or ecosystem degradation as a result of the disruption to biogeochemical cycles).

Further work is needed. First, the results shown here are based on a single model. In Supplementary Information Section 4, we discuss, in detail, the key uncertainties involved in this assessment, among others, by comparing IMAGE results to the range of model outcomes reported in the literature. From this discussion, it can be concluded that, for individual planetary boundaries, the results are consistent with the current literature, but there are substantial uncertainties, including the exact outcomes for land use and biodiversity (Supplementary Information). It would be useful to follow up this initial study on the use of planetary boundaries in a scenario context with a multi-model exercise allowing for robust insights (for example, ref. 44), also incorporating Earth system model results to complement the IAM outcomes. All in all, the results show that current trends, if unchecked, will lead to the degradation of important Earth system processes, especially with respect to climate change, biosphere integrity and biogeochemical flows (N and P). Six of the eight planetary boundaries analysed are projected to be transgressed, mostly beyond the upper value of the risk zone. Only O_3 depletion and atmospheric aerosol loading are projected to improve towards 2050 in the baseline, mainly as a result of current policies. It should be noted that, in this analysis, the scenarios do not focus on ensuring minimum conditions for decent lives (for example, in terms of access to energy and water), which could lead to even stronger environmental pressures, depending on the method of implementation.

Importantly, the analysis also shows that ambitious action can make an important difference, bringing humanity considerably closer to the safe operating space and reducing planetary boundary overshoot. Here we explored ambitious climate policy, a shift to the Eat–*Lancet* planetary health diet, halving food waste, improving water-use efficiency based on the best-available technology and increasing nutrient-use efficiency to the maximum level focusing mostly on 2050. Although such measures are considered technically feasible in the literature, it is an open question whether they can also be implemented based on social or institutional feasibility considerations. It is important to further address this in subsequent research. Such work can also concentrate on the distribution of effort in each transformation to address the justice dimension. Another critical topic includes the type of policies and strategies to implement these transformations, and that can prevent trade-offs and enhance positive strategies. It is important to note that the set of actions analysed here, despite their transformative character, does not bring the world fully back within planetary boundaries before 2050. This is partly because more time is needed to reverse the large cumulative and high current rates of pressures on critical Earth system processes, as also shown by the 2100 results (for example, sustaining net negative GHG emissions, such as those considered here, will lead to a further reduction in radiative forcing). Also, other ambitious policies could help to return us to below planetary boundary levels before 2050. In this study, we have not expanded our action toolbox to include, for instance, a reduction in material consumption levels, considering changes in economic growth and ambitious air pollution control policies. Such measures would make it technically possible to get closer to the safe space, and could be analysed further in subsequent research. Overall, it is clear that humanity has reached a critical juncture. Business-as-usual trends will lead the world in an increasingly dangerous direction. Ambitious policies can reverse this trend. This, however, requires ambitious, urgent and universal action.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-025-08928-w.

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Methods

The results presented in this paper were implemented using the IMAGE framework. Below, we briefly describe the IMAGE model and the way the planetary boundary control variables are calculated.

Description of the IMAGE model framework

IMAGE is an integrated assessment modelling framework that simulates the global and regional environmental consequences of changes in human activities. Detailed model documentation is available online (www.pbl.nl/IMAGE). The model has been designed to analyse large-scale and long-term interactions between human development and the natural environment and identify response strategies to global environmental change based on assessing options for mitigation and adaptation. The IMAGE framework is structured around the causal chain of key global sustainability issues and comprises two main systems: (1) the human or socioeconomic system that describes the long-term development of human activities relevant for sustainable development; and (2) the Earth system that describes changes in natural systems, such as the carbon and hydrological cycle and climate. The two systems are linked through emissions, land use, climate feedbacks and potential human policy responses. Most of the socioeconomic parameters are simulated for 26 regions, and most environmental parameters are calculated at a geographical grid of 30 × 30 or 5 × 5 min.

Important inputs to the model are descriptions of the future development of the direct and indirect drivers of global environmental change, with exogenous assumptions on population, economic development, lifestyle, policies and technology change forming a key input into the energy system model (Targets Image Energy Regional model, TIMER) and the food and agriculture system model (Modular Agricultural General Equilibrium Tool, MAGNET). TIMER is a system-dynamics energy system simulation model describing key trends in energy use and supply, with changes in model variables calculated based on information from the previous time step. MAGNET is a computable general equilibrium model with high detail for the agricultural sector. It uses information from IMAGE on land availability, suitability and changes in crop yields due to climate change and agricultural expansion into heterogeneous land areas. Together with the drivers described above, the regional consumption of, production of and trade in agricultural commodities are computed. The results from MAGNET on production and endogenous yield changes are used in IMAGE to calculate spatially explicit land-use change and the environmental impacts on the carbon, nutrient and water cycles, biodiversity and climate. Here a rule-based system allocates crop production to the grid based on yields and distance from other agriculture areas. The IMAGE global nutrient model (IMAGE-GNM) is a process-based simulation model that calculates the fate of N (ref. 51) and P from land to sea[52,53]. It is coupled with the hydrological PCRaster Global Water Balance model, which provides all water fluxes. The IMAGE-GNM describes the flow and retention/removal of the N and P delivery from agricultural and natural soils to surface waters, and the in-stream loss processes in all surface waters (lakes, reservoirs and rivers).

In IMAGE, the main interaction with the Earth system is through changes in energy, food and biofuel production that induce land-use changes and emissions of CO_2 and other GHGs. A key component of the Earth system is the Lund–Potsdam–Jena managed land (LPJmL) model, which is hard-coupled to IMAGE. The LPJmL model covers the terrestrial C cycle and vegetation dynamics[54]. On this basis of the regional production levels and the output of LPJmL, a set of allocation rules in IMAGE determine the actual land cover. Climatic change is calculated as the global mean temperature change using a slightly adapted version of the Model for the Assessment of GHG-Induced Climate Change version 6.0 (MAGICC6) climate model[55]. The changes in temperature and precipitation in each grid cell are derived from the global mean temperature using a pattern-scaling approach. The model accounts for several feedback mechanisms between climate change and dynamics in the energy, land and vegetation systems.

IMAGE is often used in conjunction with the Global Biodiversity model for policy support (GLOBIO), designed to evaluate the impacts of five human pressures on terrestrial biodiversity intactness, including climate change, land use, atmospheric N deposition, infrastructure and hunting[56]. Biodiversity intactness is quantified based on the MSA indicator, which represents the mean abundance of original species in an impacted situation compared to their abundance in an undisturbed reference situation, hence being indicative of biosphere integrity. For the present study, we focused on the integrity of terrestrial plant communities. We implemented the relationships between the terrestrial plant MSA and the three human pressures affecting it (climate change, land use and atmospheric N deposition) in the IMAGE modelling framework, allowing us to quantify MSA as a function of these three pressures directly in IMAGE (see also Supplementary Information Section 4 for the exact relationships used).

Description of calculation of planetary boundary control variables in IMAGE

Below, we describe how we used IMAGE to quantify the planetary boundary control variables. This includes model parameters and reference values. The data for the main IMAGE output for all scenarios, as well as the data calculated for the planetary boundaries, can be found via Zenodo at https://doi.org/10.5281/zenodo.10203631.

Climate change. The IMAGE model dynamically calculates GHG emissions from the energy, industry and land-use sectors based on a detailed process-level representation of these systems. The model also calculates full CO_2 fluxes on land based on the LPJml and the Bern ocean C model included in IMAGE[54]. Greenhouse gas emissions are input to the simple climate model MAGICC6, which calculates the radiative forcing and global temperature change[55]. The 2015 planetary boundary framework proposes a boundary of 350 ppm CO_2, with 350–450 ppm CO_2 as the zone of increasing risk. These values broadly correspond with scenarios that aim for 1.5 and 2.6 W m^{-2}. Therefore, these values have been used here (instead of the 1.0 and 1.5 W m^{-2} values provided in the 2015 planetary boundary paper[1]). The forcing value for 2015 from IMAGE is slightly different than that used in the planetary boundary 2015 paper, partly as a result of the different definition. The difference is, however, within the uncertainty range. The method is also described in refs. 55,57.

Stratospheric O_3 depletion. The exogenous scenario output from Coupled Model Intercomparison Project Phase 6 (CMIP6) is based on similar scenarios. The 2015 planetary boundary framework proposes as a boundary a less than 5% reduction from the pre-industrial level of 290 Dobson units (DU) (5–10%), assessed by latitude. Because stratospheric O_3 depletion is mostly a problem over Antarctica, we used the 90–60° S band, as assessed based on CMIP6 data[33].

Atmospheric aerosol loading. The IMAGE model calculates emissions scenarios for air pollutants based on activities in the energy, industry and land-use sectors in combination with emissions factors[57]. The outcomes are in line with the SSP projections of other models. The air pollutant emissions are used as input into the Fast Scenario Screening Tool (FASST) model to calculate particulate matter less than 2.5 µm ($PM_{2.5}$) concentrations. The values used are the population-weighted average annual concentration of $PM_{2.5}$. We used the WHO interim values of 10 and 25 mg m^{-3} as the planetary boundary and the high end of the risk zone, respectively[58]. The planetary boundary value is equal to the most ambitious interim value proposed by the WHO[58] and between the value of 15 mg used by the Earth Commission[17] and the WHO guideline of 5 mg (ref. 58). For the upper end of the uncertainty zone, we used the second interim value proposed in the WHO guidelines and, as a reference, we used the pre-industrial level indicated by CMIP6 calculations[59].

Ocean acidification. Ocean acidification was estimated using a relationship between cumulative CO_2 emissions and ocean pH using a correlation of SSP data and the pH numbers reported from CMIP6 (see below in Additional information on methods)[60]. The 2015 planetary boundary control variable values were translated into pH equivalents using the information available on the correlation between these variables.

Biogeochemical flows (imbalance of N and P cycles). The IMAGE-GNM model represents the global nutrient cycle of N and P in detail. Key inputs from the IMAGE model are spatial-explicit patterns of cropland and grazing land, livestock numbers and N deposition. The model calculates the balance between inputs and outputs of N and P based on, among other items, water flows and retention and removal processes[32]. For N, the surplus input on cropland and pastures is used. For P, the total surplus is used. We used the planetary boundary and upper-end values from the 2015 planetary boundary framework, given that the values for the imbalance on agricultural soils are similar to the flow variables defined by the planetary boundary paper for 2015 (ref. 1), and the indicators are also conceptually linked.

Freshwater use. Freshwater withdrawals comprise water used for irrigated agriculture and extraction for municipal, industrial and energy use. Irrigation water availability and use is calculated in LPJmL fully coupled to IMAGE, which dynamically represents the hydrological cycle as well as the growth of crops, grass and natural vegetation using the concept of plant functional types[54]. The demand for non-agricultural water use is calculated in IMAGE using a detailed end-use-oriented model[47]. Water demand is met in the order (1) municipal, (2) industrial and energy and (3) irrigation. If insufficient water is available for irrigation, the crop model uses rain-fed yields instead. We used the global indicator proposed in the 2015 planetary boundary assessment—that is, the consumptive use of blue water (from rivers, lakes, reservoirs and renewable groundwater stores) as the global-level control variable, with 4,000 $km^3\ yr^{-1}$ as the boundary value and 6,000 $km^2\ yr^{-1}$ as the upper-end value.

Land system change. The demand for food, feed, timber and bioenergy is dynamically calculated in IMAGE[61]. In combination with changes in management and global trade, spatially explicit land-use change is determined as driving, for example, the conversion of natural ecosystems or the abandonment of agricultural land. For the planetary boundary, we used the total forest area from IMAGE in combination with the control values of the 2015 planetary boundary framework.

Biosphere integrity. For biosphere integrity, we used the MSA for terrestrial plants, based on the GLOBIO (version 4) model[62]. This indicator takes into account the impact of changes in land use and management, climate change and N deposition on terrestrial plant community intactness. The MSA is conceptually similar to the BII used in the 2015 planetary boundary assessment, with it focusing on the 'naturalness' of ecological communities compared to a reference state without significant human disturbance. In the 2015 planetary boundary assessment, BII values were only presented for southern Africa. For the MSA, we used a value of 90% for the planetary boundary, as also proposed in the 2015 planetary boundary paper for the BII, representing a highly natural and stable state. For the upper end of the uncertainty zone, we used a value based on the Earth Commission's suggested range of 50–60% for intact natural systems based on nature's contribution to people[17], but we scaled this number to account for the difference in 2015 between the MSA indicator and the intactness indicator used by the Earth Commission (45–50% versus 54%).

In the 2015 Earth Commission assessment, the values for the Earth Commission and the upper end of the uncertainty zone were used to scale all the values (Extended Data Fig. 1). Because the results here vary over a wider range, we introduced a change on the low end (that only influences values below those of the Earth Commission). We used the pre-industrial value as an additional benchmark, set at zero (in the middle of the circle).

Scenario implementation

The main implementation of the IMAGE scenarios is discussed in the Supplementary Information (IMAGE 3.4 implementation of the scenarios used in: is world development within planetary boundaries possible?), while a more in-depth description of a very similar baseline scenario has been previously published (https://www.pbl.nl/sites/default/files/downloads/pbl-2021-the-2021-ssp-scenarios-of-the-image-3-2-model_4740.pdf). Data on the IMAGE scenarios are available at Zenodo (https://doi.org/10.5281/zenodo.10203631). In addition, Extended Data Table 1 provides a brief overview of the scenarios and Extended Data Table 2 provides an introduction to the main assumptions. A detailed description and a reference to the data files can be found in Supplementary Information Sections 1 and 2 (including the relevant references).

Additional information on methods

For the control variables for ocean acidification and N and P imbalance, some additional information is needed.

Ocean acidification. Plotting cumulative CO_2 emissions (from the SSP scenario database) versus ocean pH, as calculated using the CMIP6 model[60], provides a good correlation, as shown in Extended Data Fig. 2. Clearly, additional processes might play a role in ocean acidification (for example, the relationship with other biogeochemical cycles), but these are not captured in the current Earth system model results. This relationship is used to calculate the values for ocean acidification, expressed in pH, for the IMAGE scenarios. On the basis of earlier projections of future pH and the surface saturation state with respect to aragonite in the Southern Ocean under various Special Report on Emissions Scenarios, the proposed planetary boundaries for aragonite saturation could be translated in pH values[63]. It would be useful to better capture this Earth system process in future planetary boundary assessments.

N and P balance. The nitrogen use efficiency (NUE) in 2050 depends on the NUE in 2015 and the change between 1980 and 2015, which is corrected for the future N yield change relative to the historical yield change. The NUE values do not exceed those for SSP1. For regions where the NUE had a negative trend (East Africa, China and Korea), the future NUE was assumed to decline by less than 5% for the period 2015–2050. For China, a constant NUE of 0.38 is assumed after 2015, because current policy in China is actively reducing the N fertilizer load.

Data availability

Data on the scenarios and the data presented in the paper are available at Zenodo (https://doi.org/10.5281/zenodo.10203631)[64] (with a full description in the Supplementary Information).

Code availability

The model code for the planetary boundary figures is available at Github (https://github.com/imagepbl/planetary_boundaries).

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Competing interests There are no competing interests.

Additional information
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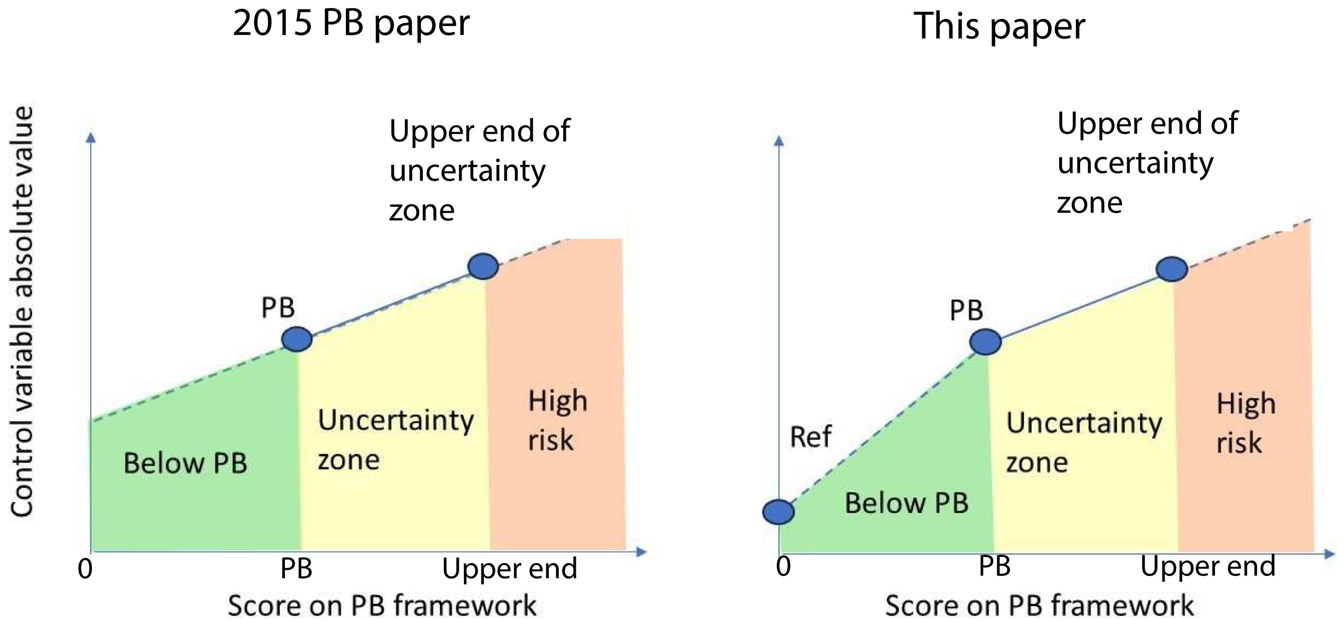
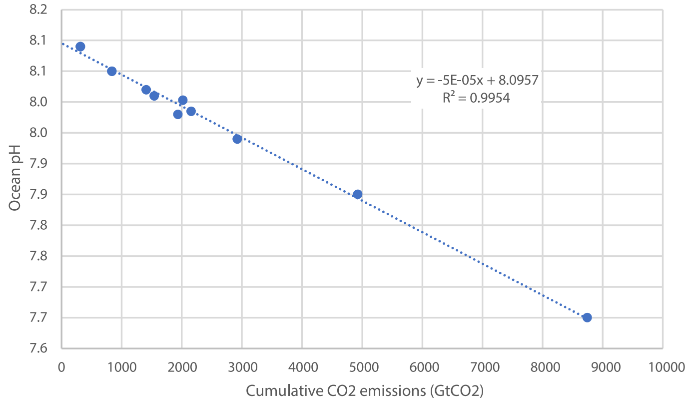


Extended Data Fig. 1 | The applied scaling in the 2015 PB paper and here. In the 2015 PB paper, the PB and upper-end of the uncertainty zone values were used to linearly scale all values of the control variable also outside the range of these values. Here, we used the reference value (often based on the undisturbed state) as third variable in order to better represent the dynamic values for the control variable in this paper. A small exception was made for the biogeochemical flows. Given the wide range of the data, here the data was scaled with the upper end of the uncertainty zone once the values are above the upper end (below the upper end exactly the same equation is used).



Extended Data Fig. 2 | Relationship between cumulative CO_2 emissions and ocean pH in CMIP6 results (used in this paper). The figure uses the ocean acidity results from CMIP6 calculations[60] in combination with the cumulative CO_2 of the corresponding scenarios.

Extended Data Table 1 | Scenario used, key characteristics and their labels

Scenario	Short label	Key characteristic
Business-as-usual (BAU)	SSP2	Reference scenario
Climate policy (CP)	SSP2-1.9	Climate policy scenario consistent with 1.5°C target
Sustainability (SU)	SSP2-1.9-Sus	Climate policy scenario consistent with 1.5°C target and additional sustainability measures
SSP1	SSP1	Alternative scenario without additional policies but with modest sustainable development orientation
SSP3	SSP3	Alternative scenario describing a regionalized world

The scenarios as referred to in the main text, the figures as well as the data files.

Extended Data Table 2 | Main assumptions for each scenario

	BaU	CP	SU	SSP1	SSP3
Population growth	Medium	Medium	Medium	Low	High
Economic growth	Medium	Medium	Medium	High	Slow
Technology	Medium development	Medium development	Medium development	Rapid technology development	Slow technology development
Trade	Medium	Medium	Medium	Full international trade	Trade barriers
Energy demand	Medium	Influenced directly by climate policy		Relatively low	Low due to slow development
Energy efficiency	Medium			High	Low
Energy supply	Medium assumptions			Focused on renewables	Focused on domestic resources
Food demand	Medium	Medium	80% introduction of EAT-LANCET diet	Higher share of plant-based protein	Medium
Agricultural efficiency	Medium	Medium	Medium	High	Low
Food waste	No change	No change	-50% compared to current	-33% compared to current	+33% compared to current
Land-use regulation	All current protected areas maintained	Current protected areas + protection of high-carbon ecosystems for climate mitigation	Protected areas are expanded to 30% of terrestrial land area + protection of high-carbon ecosystems for climate mitigation	Protected areas are expanded to 30% of terrestrial land area	Only strictly protected areas are maintained
Nitrogen use efficiency (NUE)	Medium development of NUE	The NUE is assumed to increase with 50% of the difference between the NUE in 2015 and the "maximum" NUE of Zhang (2015).	The NUE is assumed to increase with 80% of the difference between the NUE in 2015 and the "maximum" NUE of Zhang (2015).	The NUE is assumed to increase with 50% of the difference between the NUE in 2015 and the "maximum" NUE of Zhang (2015).	NUE remains constant at todays levels
Water use regulation	None	None	Restriction of surface water extraction to protect aquatic biodiversity	None	None
Water use efficiency in energy, industry and households	Medium	Medium	High	High	Low

Qualitative description of the main assumptions for each scenario that are translated into the quantitative model input. Many key input and output are included in the supplementary information.