Title: Planetary boundaries for a blue planet

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Concepts underpinning the planetary boundaries framework are being incorporated into multilateral discussions on sustainability, influencing international environmental policy development. Research underlying the boundaries has primarily focused on terrestrial systems, despite the fundamental role of marine biomes for earth system function and societal wellbeing, seriously hindering the efficacy of the boundary approach. We explore boundaries from a marine perspective. For each boundary we show how improved integration of marine systems influences our understanding of the risk of crossing these limits. Better integration of marine systems is essential if planetary boundaries are to inform earth system governance.

Main Text:

The planet is subject to increasing anthropogenic impacts and is exhibiting global environmental change at an accelerating rate, eroding the natural capital that sustains human wellbeing and prosperity [1]. The challenge of understanding these large scale changes and their consequences for human wellbeing led to the development of a set of planetary boundaries by Rockstrom *et al*. [2] and Steffen *et al*. [3] to guide earth system governance. These boundaries identify key biophysical limits (Box 1; Table 1); it is proposed that by staying within these limits humanity may reduce the risk of crossing thresholds that could lead to devastating and potentially irreversible environmental change, ensuring the maintenance of critical ecosystem services [2,3].

The planetary boundaries framework has generated significant research interest, particularly within the earth systems governance literature e.g. [4]. Moreover, the ideas underpinning the framework have been incorporated into multilateral discussions and agreements regarding sustainability, such as the Sustainable Development Goals [5]. This level of engagement suggests that the planetary boundaries narrative has the potential to shape future environmental policy [6] and technological innovation [7].

Planetary boundaries integrate knowledge across the biophysical sciences and have been intimately linked to analyses of the Great Acceleration (see glossary Supplementary Note 1) [1]. To date, much of the research literature has focused on terrestrial social-ecological systems, with less emphasis placed on marine systems (Supplementary Note 2; Supplementary Fig. 1). In light of: (i) the global spatial dominance of marine ecosystems; (ii) the fundamental ecological differences between marine and terrestrial biomes [8]; (iii) the increasing human pressures on the world's oceans [9]; and (iv) the critical role marine systems play in supporting human wellbeing, particularly in developing nations [10], this imbalance seriously hinders the efficacy of the planetary boundaries framework in supporting earth system governance. In this paper, we provide guidance for redressing this imbalance. We explore research to support characterisation of planetary boundaries for a blue planet. We discuss the ways in which the various boundaries interact, and options for assessing these interactions to provide a more integrated and holistic understanding of global environmental change. Finally, we articulate a research agenda to support implementation of the framework to enhance environmental governance.

Characterising boundaries for a blue planet

To develop the boundaries for a blue planet we outline how the existing boundaries of Steffen et al.[3] could be amended through integration of concepts, processes and data that are applicable in marine systems (Fig. 1, Table 2). We highlight the potential implications of including marine systems in relation to our risk of crossing specific boundaries, and where important research gaps exist. Here we explore four boundaries in more depth, highlighting how broadening integration with marine research has significant implications for boundary characterisation: (i) land-system change to show how the scope of a boundary might be expanded to encompass marine systems; (ii) biogeochemical flows to explore how additional marine perspectives might support more robust tracking of regional issues in a global boundary; (iii) biosphere integrity to highlight a key knowledge gap; and (iv) human appropriated net primary production, a new terrestrial boundary proposed by Running [11], to provide an example of terrestrial-marine integration for a boundary that follows a different strategy to Rockstrom, et al.'s original boundary framework [12]. Our focus on these boundaries is illustrative but also pragmatic as we believe modifications to these boundaries could be achieved over relatively short time scales as the necessary datasets or underlying knowledge are already in place.

Land-system change

The land-system change boundary addresses links between habitat and climate [3]. Vegetation cover mediates climate through carbon storage, and by affecting the transfer of moisture and energy at the earth's surface [13]. Habitat change that shifts vegetation type alters carbon sequestration rates, albedo and evapotranspiration (see glossary Supplementary Note 1), and is likely to drive significant climatic changes, with deforestation, particularly of boreal and tropical forests, estimated to contribute most to these shifts (Table 2) [14]. However, this boundary and the underlying analyses do not account for the influence of marine biomes on climate, including that of ice, seagrass and mangroves (see [15] for the description of vegetation classification that underpins the land-system change boundary), nor do they account for how ocean-atmosphere coupling may counteract the effect of forest loss on climate [14,16].

Today, forests represent about 7% of the earth's surface [17], and potentially up to 13% historically [14], an area matched by continental shelves (6.3%) and a percentage far outweighed by the coverage of marine biomes (70.9%). Critically, just as forest biomes influence regional carbon and energy fluxes [14], mangroves and other marine systems are characterised by biogeophyscial processes that influence climate (Fig. 2; [18]). More importantly, this influence is of sufficient magnitude to warrant consideration in analyses of the impacts of habitat change on climate. For example, several coastal marine habitats have the highest carbon sequestration rates of any habitat on the plant (e.g. Salt marshes: 218 ±24 $gCm^{-2}yr^{-1}$ vs. Tropical forests: 4.0 ±0.5 $gCm^{-2}yr^{-1}$) [19,20]. Furthermore, it is estimated that deforestation is driving emissions of 1.2 Pg CO_2 yr^{-1} [21], whereas degradation of coastal wetlands (mangroves, seagrasses and marshes) alone is estimated to be driving emissions of 0.12-1.0 Pg CO_2 yr^{-1} [22], despite these wetlands covering <1% of the earth's surface. Similarly, the difference in albedo between boreal forest and grasslands (0.08 vs. 0.2) is smaller than the difference between sea ice and open ocean (0.1-0.81 vs. 0.07) [23,24]. In light of the large-scale habitat changes occurring in the coastal environment, modifying the land-system change boundary to incorporate marine systems is likely to significantly influence our understanding of the current risk of experiencing large-scale climatic effects from habitat modification.

Expanding the scope of the land-system change boundary to include marine biomes would require an alteration to the existing control variable (forest cover remaining), or addition of sub-boundaries demarcating the loss of marine habitats. Relative ice cover may be a useful sub-boundary across land and sea. Focusing more specifically on habitats unique to the oceans, due to the wide variety of marine biomes, a control variable such as three-dimensional structural complexity of the habitat [25,26], or area of seabed undisturbed by anthropogenic activities such as seabed mining, coastal hardening or fishing [27,28], may be appropriate. Biome-specific boundaries have been set for land-system change; similar biome-specific boundaries could be set for marine systems, for example 'acceptable' loss of 3-D structure on coral reefs may differ to that considered 'acceptable' for kelp forests. Such approaches are already getting attention as part of the European Union Habitats Directive and Marine Strategy Framework Directive [29], which has put significant effort into determining appropriate components for its aggregate 'sea-floor integrity' index (see glossary Supplementary Note 1) [30], and the Integrated Ecosystem Assessment process in the United States [31], which includes more than 30 potential habitat indicators. Integrating sub-boundaries on land and in the ocean to produce a coherent 'earth surface change' boundary is likely to prove challenging but represents an essential development in the planetary boundaries framework.

Biogeochemical flows

While some of the boundaries (e.g. climate) are linked to global-scale tipping points, other boundaries represent processes whereby regional-scale change accumulates to such a magnitude that there are global consequences (Table 2). The biogeochemical flows boundary, which is expressed as two sub-boundaries (nitrogen (N) and phosphorous (P)), represents such aggregative regional-scale effects [2]. The P boundary explicitly engages with cross-scale issues by incorporating a regional boundary that recognises heterogeneity in both nutrient inputs and the absorptive capacity of freshwater systems [32,33]. However, the integration of regional information is inconsistently applied across systems and in relation to nitrogen. Currently, the N and P boundaries purely focus on marine system change at the global scale (Tables 1 & 2) [3]. Background marine biogeochemical regimes are highly heterogeneous (horizontally and with depth), driving differences in biogeochemical cycling, primary productivity, and trophic pathways [34,35]. These differences cause spatial variability in the vulnerability of marine systems to anthropogenic nutrient flows [36], and suggest the need for a more nuanced treatment of this boundary to account for regional marine effects that are consistent with the existing regional treatment of the Phosphorous boundary in relation to freshwater systems. Importantly, a vast literature exists exploring the biogeochemistry of coastal and oceanic waters that could underpin such an extension to the boundary. For example, data are available on the export of nutrients from watersheds and submarine ground water [9,33,37]. Furthermore, both ecosystem modelling and empirical research are supporting regionally-derived water quality forecasts [36] and increased understanding of the variability in nutrient biogeochemistry within the world's oceans. The implications for altered primary productivity, food web structure, ecosystem function and resilience, and societal wellbeing have also been explored [38-40]. Given that eutrophication is one of the most frequently observed causes of ecosystem regime shifts globally (see glossary Supplementary Note 1; http://www.regimeshifts.org/), it appears that, of all the boundaries, scientists are best placed to provide quantified values for regional marine biogeochemical boundaries.

Accounting for regional marine biogeochemical flows goes beyond simply producing a more comprehensive boundary for human-derived N and P. Within the marine system Steffen et al. [3] recognised the importance of other elements when considering biogeochemical flows, but did not explore this avenue further. The marine biogeochemistry literature could inform the addition of other sub-boundaries such as iron (Fe) and silicon (Si). For example, Fe is regionally limiting within marine waters and Fe budgets are significantly impacted by anthropogenic disturbances [39,41]. Furthermore, regional enrichment patterns of N, P, Si and Fe within marine systems have broader-scale climatic and biodiversity implications [42,43]. Integration of these different components into the existing framework would help support an improved understanding of how the biogeochemical, climate and biosphere integrity boundaries interact to delimit a 'safe operating space' for humanity.

To date the focus of the biogeochemical boundary has been on bottom-up anthropogenic drivers such as the addition of fertilisers. However, top-down effects such as the influence of fisheries exploitation on biogeochemical cycles, are likely to have impacts that are of sufficient magnitude to affect the behaviour of this boundary [44]. While the indirect aspects of these effects are currently poorly understood, they are, along with the effects of fishing on ecosystem structure and function, a topic of burgeoning interest. Just as with hunting on land, fishing has the potential to influence geochemical cycling by disrupting ecosystem functioning via the removal of key species, the redistribution of relative biomass across trophic levels and the dilution of some nutrient mediating processes [45,46]. The magnitude of these effects and how they can be mitigated warrant further research and consideration within the existing boundary framework.

Biosphere-integrity: functional diversity

The biosphere integrity boundary was identified by Steffen et al. [3] as one of the two core planetary boundaries (along with climate change) as it is central to the state of the earth system – crossing either of these boundaries may shift the earth into a new state. This boundary focuses on the persistence and functioning of the biosphere. Persistence is underpinned by genetic diversity, whereas function is determined by the diversity of functional traits (Table 2) [3]. Characterising the functional diversity sub-boundary has proved to be particularly challenging because of the lack of a suitable control variable [47]. The biodiversity intactness index (BII), which estimates the proportion of biodiversity found in intact ecosystems that remains within a corresponding human-impacted ecosystem, was presented as a stopgap measure. Recently, BII has been estimated for terrestrial systems, using modelled intact area biodiversity as a baseline

[3,48]. Yet, there have been no studies estimating BII for marine systems. There is potential to broaden the coverage of BII studies to include the world's oceans using marine wilderness baselines (e.g. [49]). However, this may prove challenging for less well studied marine ecosystems, and species-level metrics such as BII are only indirectly linked to function. As a result, we suggest directing efforts towards developing a more appropriate control variable using a trait-based metric that is more closely tied to the functions provided by communities [47,50]. Size- and trait-based modelling of marine communities suggests one potentially robust avenue for exploring trends in the functional composition of communities from the Holocene into the Anthropocene [51]. Such an approach has three key advantages: (i) it allows estimation of undisturbed baseline states that are not reliant on wilderness areas which may be subject to anthropogenic disturbance, and as such, are not representative of 'Holocene-like' conditions [48,52]; (ii) the relative lack of focus on describing species within marine systems may prove problematic when attempting to estimate biodiversity change using empirical observations alone [53]; and (iii) recent integration of a range of traits into size-based modelling explicitly allows for estimation of changes in function, historically and in response to future anthropogenic impacts [54].

Modelling changes in the functioning of ecosystems is an important step, but there is also the need to choose specific indicators for the control variable to monitor changes empirically. This is a complex undertaking, but simulation testing, such as in fisheries indicator research, could be used to understand which are the most informative indicators, to gain insights into current status, trends and thresholds in function [55,56]. For example, ecosystem models have been used in simulations to test the efficacy of a range of indicators in the context of the effects of fishing and ecosystem state. The models are used to represent the ecosystem and its perturbation (e.g. fishing pressure and climate change scenarios) and to generate 'data'. Indicators estimated from these data are then compared against the trajectories in the ecosystem model to see how well they capture the true levels of change [55].

Regardless of the control variable used, accounting for marine systems in the functional diversity sub-boundary is likely to have significant consequences for our understanding of the current state of play. Newbold et al. [48] estimated that nearly 60% of terrestrial systems have crossed the proposed functional diversity boundary to some degree, based on BII. Accounting for marine biomes, which dominate the earth's surface, may give a very different picture.

Human-appropriated net primary production

Since the publication of the initial framework, human-appropriated net primary production (HANPP) has been proposed as a new strategy that could potentially replace a number of the original boundaries because it is relatively straightforward to measure and integrates many of the other interacting boundaries; primary production is influenced by habitat type, climatic conditions, availability of carbon dioxide, nutrients and freshwater, and in turn supports biosphere integrity [11]. The studies proposing HANPP as a boundary have focused purely on terrestrial systems [11,57], despite marine and terrestrial primary production being approximately equal in magnitude [58], research suggesting that similar proportions of productivity flow to fisheries on continental shelves as is appropriated by humans on land [59,60], and the oceans being comparable to land as a carbon sink [61]. However, it should be noted that the productivity estimates focus on slightly different characterisations of primary productivity, for example marine estimates focus on surface waters and do not account for spatial variability in the vertical patterns in primary productivity. Furthermore, terrestrial estimates represent biomass accumulation, whereas those in the ocean represent new production. If HANPP is to be used as a replacement, integrative planetary boundary, addition of marine productivity is key and is achievable with existing knowledge (Supplementary Note 3), although further work will be needed to harmonise terrestrial and marine estimates to ensure they represent equivalent metrics. Nonetheless, preliminary mapping of terrestrial and marine HANPP highlights the highly heterogeneous distribution of society's appropriation of primary productivity; the regions of least concern, such as the open ocean, and the regions where limits are being approached both on land and in the sea, e.g. South East Asia (Fig. 3; Supplementary Note 3). Where fisheries catches are approaching productivity limits, the problem is likely to be exacerbated by climate change [62]. Moreover, some of the geo-engineering solutions proposed as technological options for addressing climate change involve the direct modification of marine ecosystems and production, e.g. via ocean fertilisation [63], highlighting that planetary boundaries in the oceans may face large and increasingly pressing challenges.

Understanding boundary interactions

The planetary boundaries encompass some which represent structural changes that impact important processes (e.g. land-system change which impacts climate), whereas others represent the processes themselves (e.g. climate) [64]. This dual nature of the boundaries was initially a pragmatic approach, but it also highlights the close coupling of earth systems. The consequence is that the different boundaries cannot be viewed in isolation. Boundary interactions drive considerable uncertainty regarding the direction, scale and rate of change likely to be observed in earth systems, and the potential reversibility of any undesirable changes [65,66]. Thus, the modifications we have suggested to the framework need to be explored against the backdrop of these interactions. Highlighting this need may seem redundant, but, while the issue of boundary interaction has been discussed (38% of papers reviewed in Supplementary Note 2), it has rarely been dealt with explicitly (but see [66]). As a result, we suggest that modifying the boundaries to more comprehensively account for marine ecosystems should not simply mean setting new, static boundary values. Rather, the planetary boundaries framework as a whole might be better served by boundary 'windows' that cover a range of possible values. Such an approach allows for uncertainty around the behaviour of individual boundaries and their interactions with each other, as these influence where boundaries should be best placed to avoid undesirable changes to the Earth System [66]. Furthermore, it builds on Rockstrom *et al.'s* delineation of a zone of uncertainty around each boundary [2]. Anderies *et al*. [66] explore how boundary windows might work in relation to interactions between the climate change and land-system change boundaries. This slightly more reflexive version of the planetary boundaries framework does not preclude effective management; rather, it is more in line with a precautionary approach due to the high uncertainty surrounding the behaviour of earth system processes [67]. Moreover, it is directly in-line with adaptive management processes best suited to acting under uncertainty [66], where actions and targets are updated as new information becomes available [68]

Exploring boundary interactions and uncertainty will be largely reliant on systems modelling that accurately captures biophysical-human feedbacks [69]. There is a growing suite of ecosystem models arising from both aquatic and terrestrial disciplines, which provide robust ways of investigating the importance of different biophysical processes, and their non-linear interactions and feedbacks across scales [70,71]. Model ensembles (see glossary Supplementary Note 1) allow for comparisons among model outputs [72], providing a powerful approach to explore risk in relation to boundary dynamics, how human responses can modify those dynamics, and our likelihood of crossing interacting boundaries. Management strategy evaluation, a tool initially developed for fisheries management [73] is now being used much more widely to explore virtual worlds under a range of different scenarios [74]. The modelling challenges going forward are many (e.g. handling uncertainty, improved capacity to represent cross-scale processes, provision of pragmatic approaches that can be applied with fewer resources), but amongst the greatest is the inclusion of human influences, and how they have added to the interconnected nature and interdependency of the boundaries.

Marine boundaries and governance

The global environmental governance challenges presented by the planetary boundaries concepts are well documented [4], but have been seldom explored specifically for marine systems (Supplementary Fig. 1). Critically, including marine biomes within the framework exacerbates these challenges, as governance necessarily must account for both sovereign and common-pool resources. Furthermore, monitoring and enforcement within the high seas presents a unique set of governance challenges not experienced in terrestrial biomes [75]. Thus, accounting for broad-scale marine habitat change in an 'earth surface change' boundary and enforcing policies to counteract these changes across remote ocean areas, are likely to be both difficult and contested. As such, we posit that the inclusion of marine biomes within the planetary boundary concept may present larger and more immediate challenges to earth systems governance than currently realised.

Responding successfully to the full suite of unique marine-specific challenges outlined in this paper will require complementary efforts across multiple jurisdictions. This will be best achieved through collaborative, global, multi-actor governance networks that promote collective action, foster learning and nurture trust among diverse stakeholders [5]. Such participatory governance approaches will also allow decision-makers to capitalise on scale-specific knowledge (e.g. local or cultural knowledge), so as to match governance responses to the scale of a problem [76]. In combination, these attributes enhance societies' ability to respond adaptively to disturbances across multiple spatial scales [77]. The successful implementation of such networked approaches to governance will, however, require new and innovative institutional arrangements that actively foster participation and collaboration among stakeholders, and manage power imbalances among different actors [78]. Research is needed to explore the optimal institutional design for supporting the assessment and integration of planetary boundaries into global environmental governance initiatives.

The changing nature of the planetary boundaries, coupled with high degrees of uncertainty and boundary interactions, also necessitates innovative and forward-looking approaches to governance that allow decision-makers to be proactive in anticipation of global environmental change. In this regard, the emerging concept of 'anticipatory governance' may prove important [79]. Initially developed in the field of technology, anticipatory governance is defined as 'a broad-based capacity extended through society that can act on a variety of inputs to actively steer society towards desired outcomes [80]. This is achieved via stakeholder-inclusive foresight activities, such as scenario development, which allow participants to envision plausible futures, contingencies and consequences and develop the necessary knowledge base for addressing the social, ethical, and policy challenges associated with global environmental challenges [81,82]. Furthermore, by virtue of its proactive approach to environmental governance, anticipatory governance also allows for the early identification of the core capacities, technologies and enabling conditions that must be developed to underpin the transformative changes required [83].

Conclusions

Planetary boundaries research has primarily focused on terrestrial systems, in part because there is a perception that so much remains unknown about the oceans. However, given the fundamental dependence of the global biosphere on oceanic components and processes, this imbalance threatens the integrity of the planetary boundaries approach and the usefulness of conclusions drawn from it. Thus, if we are to advance the framework from a useful heuristic to a set of guidelines for earth system governance, we need to better account for marine systems. For some boundaries, such as HANPP, increased integration may simply mean addition of marine data. In other cases, expanding the scope of the boundary may be necessary, e.g. moving from a land-system to an earth surface change boundary. Marine research may also help support characterisation of boundaries where there is current uncertainty how to proceed, e.g. biosphere integrity. Moreover, a better understanding of how the boundaries interact is fundamental to operationalising planetary boundaries, and marine research has important contributions to make in this regard. Most of the data and techniques necessary to initiate this increased integration of marine systems are available but there is considerable scope for further work (Table 2). For example, here we focus on modification of the existing planetary boundaries. These boundaries are not the only options. Exploration of additional boundaries that describe biophysical processes inherent to marine systems and that are central to earth system function such as changes in vertical mixing and ocean circulation patterns, presents a fertile arena for new research. Rather than putting the oceans to the side, the important knowledge gaps associated with those biomes signal the need for extensive additional research if planetary boundaries are to inform effective earth system governance that supports societal well-being on a blue planet.

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Competing interests

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Data Availability Terrestrial data used in global HANPP map were downloaded from https://www.uni-klu.ac.at/socec/inhalt/1191.htm. Marine data used in global HANPP map are freely available from http://dx.doi.org/10.4226/77/58293083b0515

Supplementary Information

Supplementary Note 1: Glossary

Supplementary Note 2: Literature review methods

Supplementary Note 3: Materials and methods for calculating and mapping human appropriated net primary production, including data availability statement

Supplementary Table 1: Trophic efficiency schedule detailing percentage energy transfer among trophic levels

Supplementary Figure 1: Publications referencing planetary boundaries

References

Table 1 (inset in Box 1): Five steps in the characterisation of planetary boundaries defined by Steffen *et al.* [3]. Knowledge of the processes and system dynamics that support the resilience of the earth system informs the selection (step 1) and categorisation of boundary processes (step 2). Understanding of the relationships between human impacts and system structure and function supports the adoption of suitable response variables (step 3) and control variables (step 4). Finally, availability of data allows estimation of the current value of control variables (step 5). Data for examples derived from [3]. Further information on the example boundaries is available in Table 2.

Step	Description	Example 1	Example 2
1. Process	Select biogeophysical processes central to earth system function and regulation.	Climate	Nitrogen (sub-boundary of biogeochemical flows)
2. Categorise	Identification of process as: • Threshold behaviour vs. gradual change • Regional process that aggregates up to global level vs. global scale process	• Threshold behaviour • Global scale	• Gradual change • Global scale
3. Response	Identify suitable response variable that highlights qualitatively different regional or global states.	Loss of polar ice & glacial freshwater stocks. Changes to regional climate and flows to carbon sinks	Eutrophication of aquatic systems
4. Control	Identify suitable control variable that drives changes in response variable, is consistent across ecosystems and may be evaluated using available data	1. Atmospheric carbon dioxide concentration 2. Radiative forcing at top of atmosphere	Human-driven nitrogen fixation
5. Current state	Estimate current value of control variable(s)	1. 398.5 ppm CO_2 2. 2.3 W m^{-2}	62 Tg N yr^{-1}

[a] see glossary Supplementary Note 1

Table 2: Boundaries for a blue planet. Exploration of current boundary characterisations as defined by Steffen *et al.* [3] and how they might be modified to better integrate marine systems. Boundaries are split into three main types with respect to terrestrial-freshwater-marine linkages: boundaries that integrate across systems, those that are unique to a particular system but may have analogues in other systems, and boundaries that have no analogue.

	Current boundary characterisation	Suggested integration	Data to support integration	Implications of increased marine integration on boundary characterisation
Boundaries that integrate across terrestrial, freshwater and marine systems	**Biogeochemical flows** ***Response variable*** Human influence on biogeochemical flows driving eutrophication and large-scale anoxic events. ***Control variable – Nitrogen*** Human driven N fixation ***Control variable – Phosphorous*** Global-flow from freshwater to marine systems; Regional-flow from applied fertiliser to erodible soils.	Broaden scope to account for (i) regional effects of changing biogeochemical flows from land to oceans: declining resilience of coastal ecosystems e.g. coral reefs [84], hypoxia and changes to marine food webs [38,40,85]; (ii) broader range of nutrients, e.g. Fe [41]; (iii) top-down anthropogenic influences through exploitation and sediment resuspension [44,86].	Global export of nutrients from rivers to coastal waters and influence on primary productivity [9,33,87]. Modelling of altered ecosystem structure and function with changing nutrient regimes [36].	Boundary will be more sensitive to regional changes in biogeochemical cycling and marine food webs. Due to the close links between biogeochemical cycling in oceans, climate and biodiversity, this increase in boundary sensitivity may help limit concurrent changes in climate and biosphere integrity.
	Novel entities ***Response variable*** Undefined beyond the potential to impact earth system structure and function, and effect not easy to reverse. ***Control variable*** Undefined	Boundary remains undefined due to the lack of a tractable approach that encompasses the >100,000 anthropogenic chemicals [88]. But there are a number of novel entities that are widespread in the marine realm e.g. plastics, that will be central to efforts focused on characterising this boundary.	Plastics: Global flows of plastic into the oceans [89]. Distribution of plastic debris at global and regional scales e.g. [90]. Organic and inorganic pollutants: Global flows of organic and inorganic pollutants to coastal waters. Distribution of pollutants in world's oceans [9].	Assists with defining a planetary boundary that is representative of the broad-scale impact of novel entities on earth system structure and function.
	Climate change ***Response variable*** Loss of polar ice & glacial freshwater stocks. Changes to regional climate and flows to carbon sinks ***Control variable*** Concentration of atmospheric CO_2; radiative forcing at top of atmosphere	Boundary already integrates knowledge of marine systems [91]. However, there is a need to account for regional climate changes as these may exceed global mean changes and impact areas that are vulnerable or particularly important for human wellbeing [92], e.g. reefs likely to demonstrate regime shifts within the currently defined boundary [93].	Modelling of the response of specific, vulnerable regions under different climate scenarios, e.g. biomes such as coral reefs [93,94] and the Arctic [92].	Provides a more comprehensive picture of the state of the climate system and the potential for large-scale and deleterious change within the current boundary. Moving the boundary to account for these changes may help counteract anticipated costs linked to sea level rise and declines in crop productivity in the tropics, which may occur within the current boundary value [93].
	Stratospheric ozone depletion ***Response variable*** Severe UV radiation effects on human health and ecosystems. ***Control variable*** Concentration of O_3.	Boundary already integrates knowledge of marine systems [95]. But there is a need to more clearly understand the interactions between ozone depletion, climate and biogeochemical cycling in the	Modelling of boundary interactions [96].	As with other boundaries, better understanding of interactions among biophysical processes may drive development of a moving window for the stratospheric ozone depletion boundary.

		oceans [96].		
	Atmospheric aerosol loading ***Response variable*** Interference with global monsoon systems; severe effects on human health. ***Control variable*** Global-Aerosol optical depth (AOD); Regional-seasonal mean of AOD.	Boundary already focuses on ocean-atmosphere interactions, but is currently only defined for the South Asian Monsoon region.	Further research is needed to characterise this boundary for regions other than the South Asian Monsoon region.	Further research is needed to understand the implications of these additions.
	Biosphere integrity ***Response variable*** Loss of ecosystem function and services. ***Control variable – genetic diversity*** Extinction rate. ***Control variable – functional diversity*** Biodiversity intactness index (BII).	Initially, there is a need to account for marine systems in estimates of currently defined control variables [48,97], or similar metrics [98]. However, efforts are also needed to modify control variables to better reflect underlying processes of interest, e.g. ecosystem function may not be closely tied to species diversity as used in the BII [47].	Baseline values for community composition are available for marine systems either based on wilderness areas or ecosystem modelling [49], allowing for the calculation of the BII. Size-based modelling, and indices arising from integrated ecosystem assessment are available to explore trends in functional diversity [51].	In the short term, integration using BII is likely to have a significant effect on our understanding of the current state of biosphere integrity. More importantly, changes to the control variable for functional diversity are likely to provide more robust ways of exploring human impacts and predict potentially extreme changes to earth system functioning.
Boundaries with analogues in different systems	**Land-system change** ***Response variable*** Contribution of terrestrial biomes to biogeophysical processes that regulate climate. ***Control variable*** Forest cover remaining at global and regional scales. Three forest biomes identified: tropical, temperate and boreal.	Need to expand scope of boundary to account for marine habitat changes, producing an 'Earth surface change' boundary. A range of biome specific control variables could be introduced in addition to forest cover, e.g. area of seabed undisturbed by anthropogenic activities, such as coastal hardening or fishing gears [27,99,100], or an index of sea-floor integrity [30].	Knowledge of contribution of marine biomes to large-scale climate regulation and carbon budgets [18,101]. Quantification of habitat change driving loss of structure, increasing turbidity and changing biogeochemical flows with implications for climate, e.g. on filter feeding communities [102]. Distribution of anthropogenic disturbance of marine habitats [103].	Boundary will be more reflective of habitat change impacts on processes that regulate climate. This change may alter our view of the current and future risk of habitat change influencing climate.
Boundaries with no analogues	**Ocean acidification** ***Response variable*** Eradication of marine species that secrete calcium carbonate, e.g. as shells or skeletons; changes to carbon storage in marine systems. ***Control variable*** Aragonite saturation state.	Focus of this boundary is marine systems, but current characterisation narrowly targets aragonite saturation state and thus consequences for secretion of calcium carbonate [104]. This selection is justified by its focus on the 'weakest link' [2]. But characterisation of this boundary would benefit from the expanding literature on other effects of ocean acidification on marine systems: physiological, e.g.	There is an deepening, synthetic understanding of the organismal, population and ecosystem effects of ocean acidification [106], which would support a broadening of the scope of this boundary.	A core outcome would be a better understanding of how the ocean acidification interacts with other boundaries, including climate change via carbon sinks, and biosphere integrity through changes to food webs arising from physiological, behavioural and photosynthetic effects.

		protein synthesis and behavioural, e.g. predator avoidance [105]; photosynthesis and nitrogen fixation [106].		
	<u>Freshwater use</u> ***Response variable*** Regional climate; changes to moisture balance, productivity, biodiversity and climate. ***Control variable*** Global-blue water consumption; Basin-blue water removal.	Expand assessment of the current status of this boundary to account for the demands of seafood production on freshwater supplies. Currently the assessment is based on agriculture, industry and domestic water usage [3], with no accounting for aquaculture.	Few studies have quantified freshwater use in seafood production. Where research has been performed, methodologies are often inconsistent among studies, reducing transparency [107]. Nonetheless, existing research suggests freshwater usage can be considerable and highly variable across aquaculture systems [107]. In light of the growth of the aquaculture sector [108], additional work is needed to understand the contribution of seafood production to freshwater use [107].	Boundary will be more reflective of shifts in the balance of food production among terrestrial and marine sectors. Fish production has tripled in the last 50 years, predominantly driven by increases in aquaculture production, and exceeding increases in livestock production [108]. If this trajectory continues, accounting for the magnitude of freshwater use in seafood production will become increasingly important to understand the increased risks of crossing the freshwater use boundary.

Figure Legends

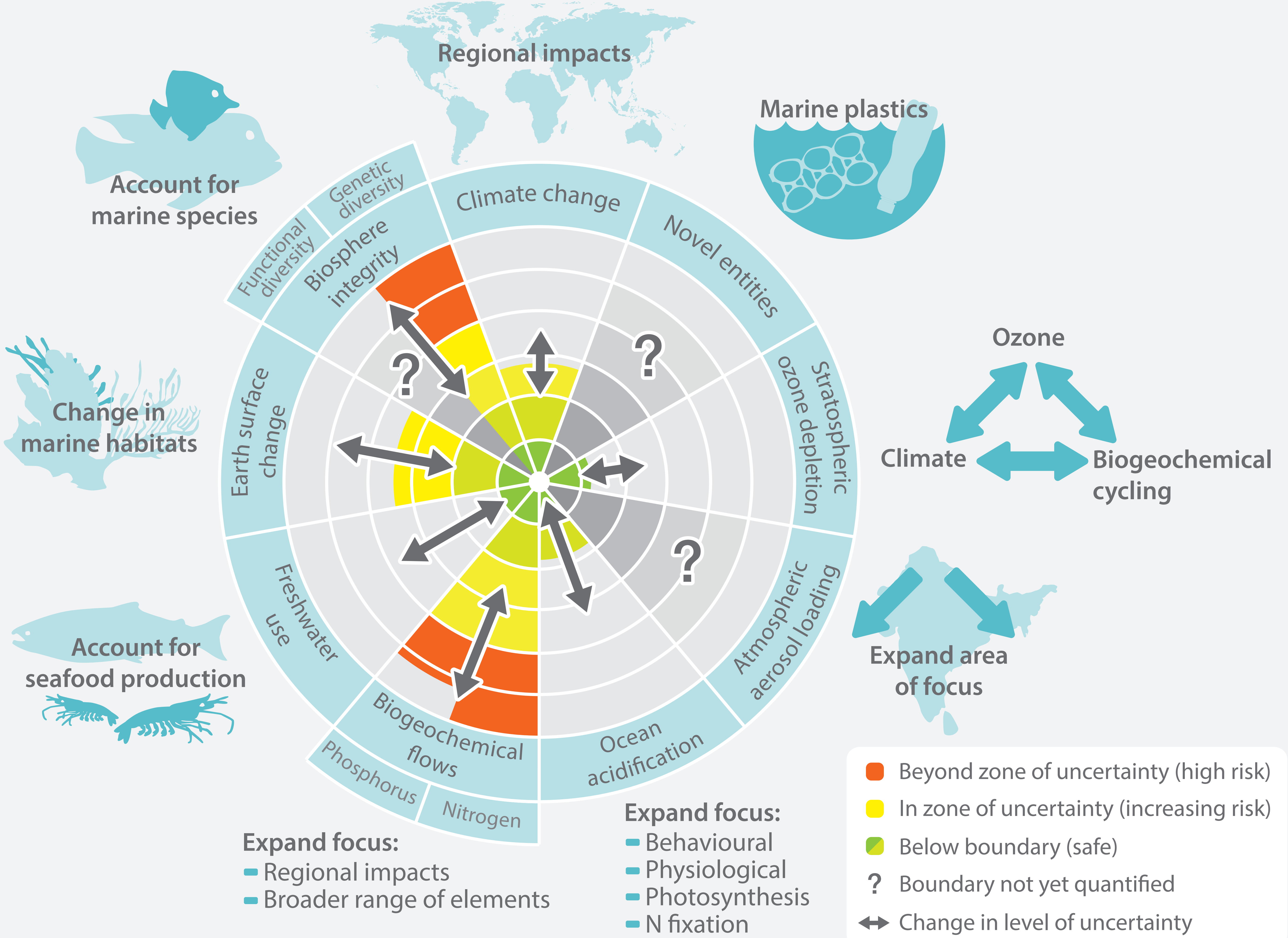
Figure 1: Shift in understanding of the uncertainty and risks associated with crossing the planetary boundaries arising from more comprehensive integration of marine systems into the framework. Images surrounding boundaries indicate examples of changes to planetary boundaries to support improved integration of marine systems. Full details of suggested changes provided in Table 2. Earth surface change boundary represents an expansion of the original land-system change boundary suggested by Steffen et al [3]. N – nitrogen, P – Phosphorous. Figure modified from Steffen et al [3].

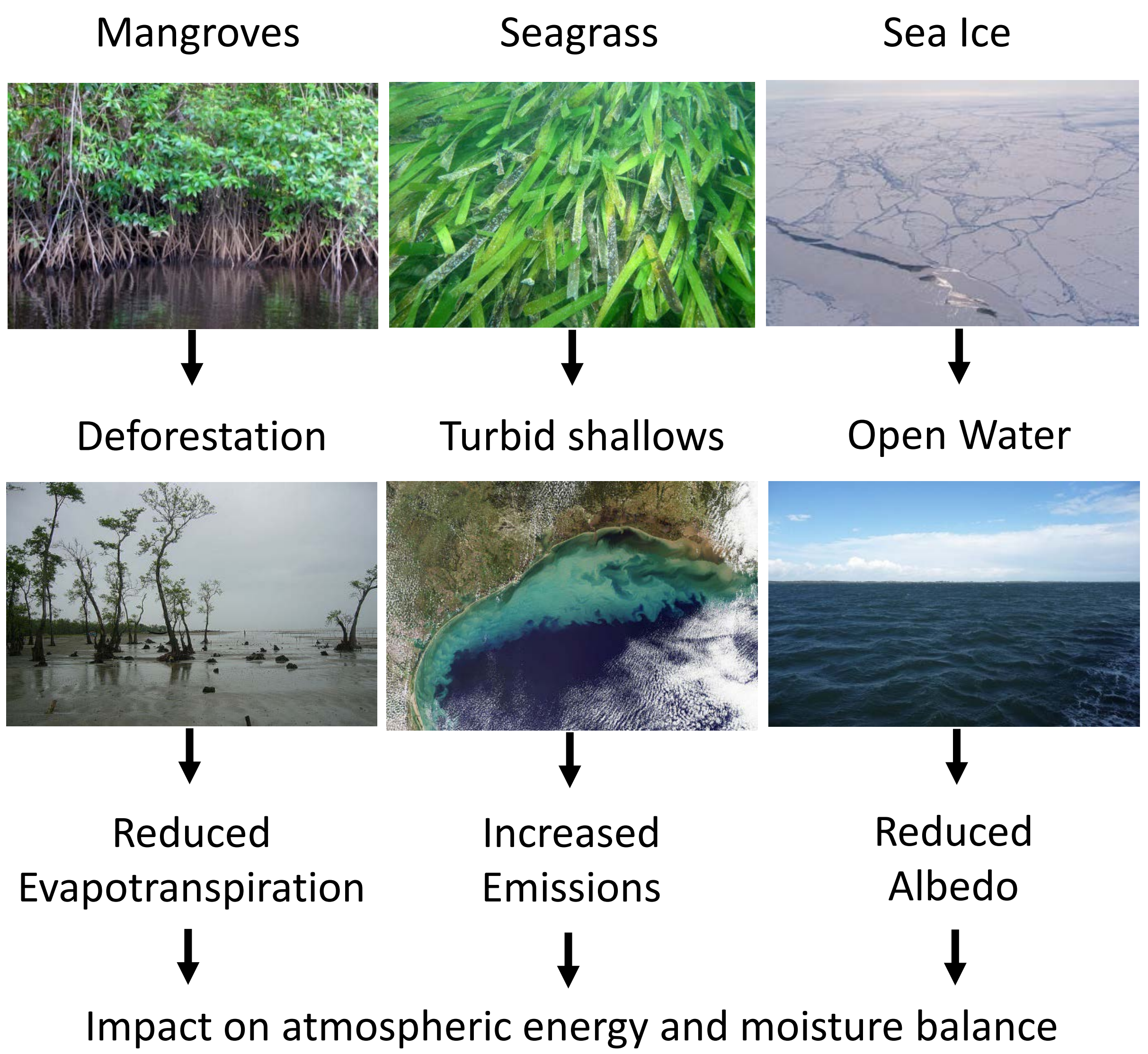
Figure 2: Examples of habitat degradation occurring in marine ecosystems that have the potential to impact on global climate through changes to carbon storage, and transfer of energy and moisture to the atmosphere. Note, illustrations of the effect of habitat change on carbon, energy and moisture balance for each ecosystem are not comprehensive, for example, mangrove loss will result in increased emissions as well as reduced evapotranspiration. Photo credits: Mangroves - CIFOR (CC BY-NC 2.0); Seagrass – J St. John (CC BY 2.0); Sea ice & Turbid water – NASA; Mangrove clearing – eutrophication&hypoxia (CC BY 2.0).

Figure 3: Global distribution of human appropriated primary production (HANPP) presented as percentage of net primary production (NPP) utilised. Data represent average values from 1998-2002. Terrestrial data sourced from [60]. Details of methods provided in Supplementary Note 3.

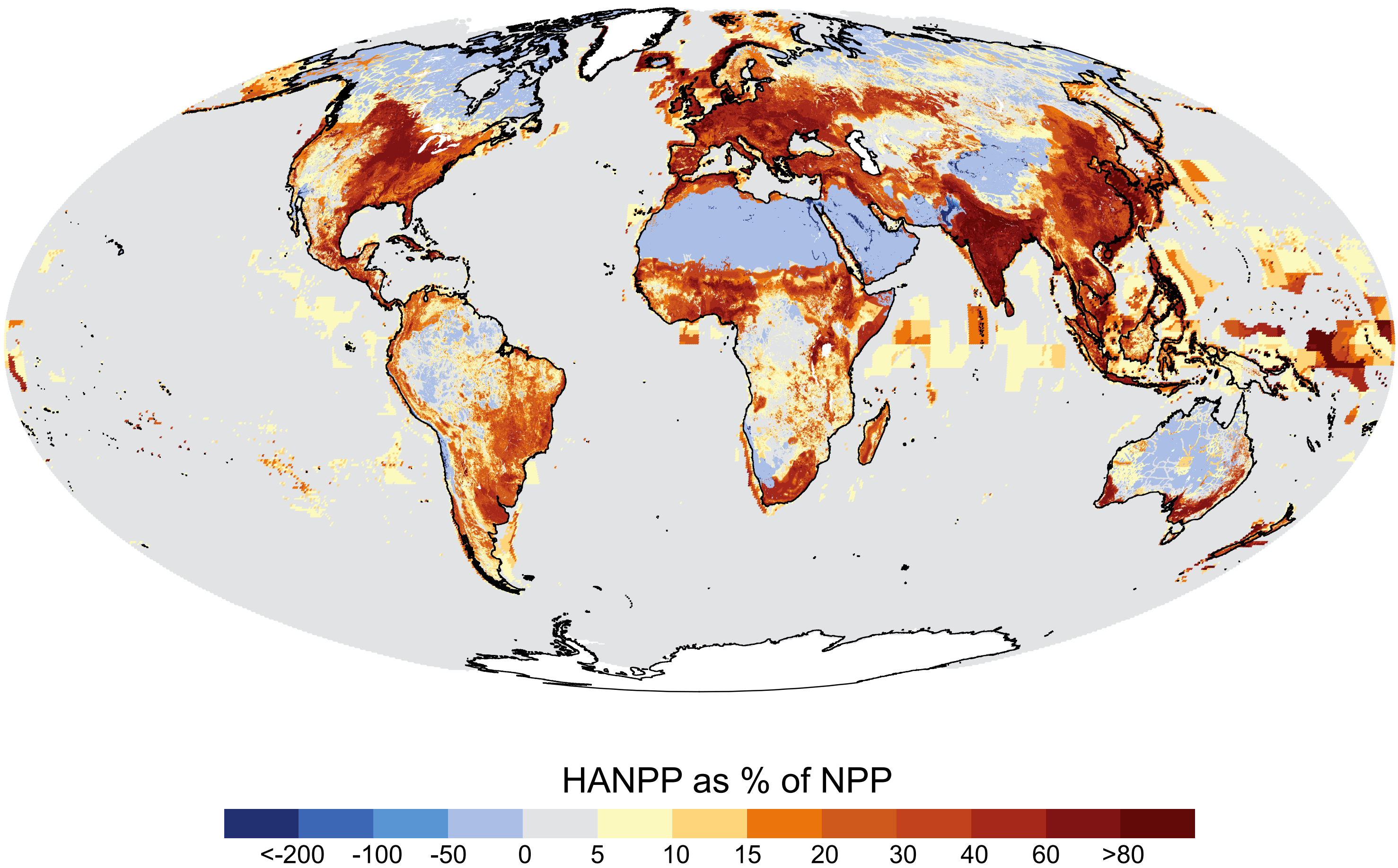
Box 1 (with Table 1 inset): Planetary Boundaries Framework

The framework delineates limits for nine biophysical processes that regulate conditions on earth. States consistent with the Holocene are presented as desirable, because these are the only conditions we know will support human society [2]. The framework differentiates between processes that may show global-scale transitions (e.g. climate change) and processes where regional-scale change accumulates up to have global level consequences (e.g. biosphere integrity) [3]. A further distinction is made among processes that may exhibit thresholds between distinct regimes (e.g. climate), and processes that are likely to show gradual change in response to human pressures (e.g. freshwater use). For each process, a response and control variable (see glossary Supplementary Note 1) are defined (Table 1). Two boundaries - climate change and biosphere integrity - have been identified as 'core' boundaries. It is proposed that the crossing of either of these boundaries would drive the earth system in to a radically different state [3]. Boundaries are set to avoid *thresholds* in response variables with tipping points, or to avoid *unacceptable* levels for response variables exhibiting gradual changes [2]. Thus, the setting of boundary values relies on judgements of acceptable risk, as well as knowledge of the relationship between human impacts and environmental change [2]. It is thought that the climate, land-system, and biogeochemical boundaries, and the genetic diversity component of biosphere integrity, have already been transgressed [3]. Boundary values have not yet been determined for novel entities or stratospheric aerosol loading, and current values of the functional diversity component of biosphere integrity have only been estimated for terrestrial systems.


Regional impacts
Marine plastics
Account for marine species
Change in marine habitats
Account for seafood production
Genetic diversity
Functional diversity
Biosphere integrity
Climate change
Novel entities
Stratospheric ozone depletion
Atmospheric aerosol loading
Ocean acidification
Biogeochemical flows
Phosphorus
Nitrogen
Freshwater use
Earth surface change
?
?
?
Ozone
Climate
Biogeochemical cycling
Expand area of focus
Expand focus:
Regional impacts
Broader range of elements
Expand focus:
Behavioural
Physiological
Photosynthesis
N fixation
Beyond zone of uncertainty (high risk)
In zone of uncertainty (increasing risk)
Below boundary (safe)
? Boundary not yet quantified
Change in level of uncertainty



Mangroves
Seagrass
Sea Ice
Deforestation
Turbid shallows
Open Water
Reduced Evapotranspiration
Increased Emissions
Reduced Albedo
Impact on atmospheric energy and moisture balance


HANPP as % of NPP
<-200 -100 -50 0 5 10 15 20 30 40 60 >80