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'Planetary boundaries' — exploring the challenges for global environmental governance

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A range of studies from Earth system scientists argue that human activities drive multiple, interacting effects that cascade through the Earth system. Recent contributions state and quantify nine, interacting 'planetary boundaries' with possible threshold effects. This article provides an overview of the global governance challenges that follow from this notion of multiple, interacting and possibly non-linear 'planetary boundaries'. Here we discuss four interrelated global environmental governance challenges, as well as some possible ways to address them. The four identified challenges are related to, first, the interplay between Earth system science and global policies, and the implications of differences in risk perceptions in defining these boundaries; second, the capacity of international institutions to deal with individual 'planetary boundaries', as well as interactions between them; third, the role of international organizations in dealing with 'planetary boundaries' interactions; and fourth, the role of global governance in framing social–ecological innovations.

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Introduction

The possible implications of abrupt climate change have induced considerable scientific and political attention. Recently, scientists engaged with global sustainability have put the climate issue in a broader Earth system context by exploring additional so-called 'planetary boundaries' [1••,2]. These are nine, possibly non-linear Earth system processes that manifest themselves at the planetary level and include climate impacts, ozone depletion, atmospheric aerosol loading, ocean acidification, global freshwater use, chemical pollution, land system change, biodiversity and biogeochemistry. 'Planetary boundaries' are however not fixed. They represent estimates of how close to an uncertainty zone around a potential threshold that the global human community can act, without seriously challenging the continuation of the current state of the planet within which human settlements and cultures have flourished.

Drawing a 'safe operating space for humanity' [1••,2] is bound to be a highly controversial project. Nevertheless, the framework does capture a more general insight from the Earth system science community: that global environmental change unfolds between complex and multiple bio-geophysical systems with possible non-linear dynamics.

Until now the implications of 'planetary boundaries' for policy-making and institutional analysis are unexplored. Whilst some responses from international policy-makers have been positive, others have questioned the usefulness of the approach from a governance perspective [3,4]. Given these highly conflicting perspectives, it is remarkable that the scholarly study of the implications of multiple, interacting and possibly non-linear global environmental changes have been a rather peripheral research object.

Here, we explore the notion of 'planetary boundaries' from the perspective of Earth system governance (ESG) [5••]. This is the first attempt to provide a synthesis overview of the global governance challenges that follow from the recognition that human activities drives multiple, interacting effects that cascade through the Earth system [6–8]. We explore the issue by asking:

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What are the implications of multiple, interacting and quantified 'planetary boundaries' for Earth system governance (ESG)?

Our analysis is by no means an exhaustive list or analysis of ESG challenges. Rather, we focus on what we believe are novel ESG challenges posed by the 'planetary boundaries' framework. In the following, we elaborate the issue further by discussing four interrelated ESG challenges that follow from the notion of interacting and quantified PB, as well as some possible ways to address them analytically.

'Planetary boundaries', science and policy

The first challenge we explore is the one that arises as Earth system science meets the field of global policies. It should be noted that the analysis presented in Refs. [1••,2] synthesizes decades of research from a number of academic fields concerned with the Earth system. The quantified boundaries could therefore be viewed as an operationalization of the biogeophysical component of 'sustainable development' [9], or as a target for emerging notions of ESG [10]. This way of thinking resonates well with key international agencies such as United Nations Environment Programme (UNEP) [11], but the implications of 'planetary boundaries' for ESG, have a range of unexplored and controversial dimensions.

First, the concept of 'boundaries', can be viewed as strongly normative. Whilst 'boundaries' can hold a positive connotation as a motivation for collective action [12], they also imply contested scientifically defined frames to human activity. One example is the likely North–South dimension in defining what constitutes a 'safe' operating space. Rockström and colleagues explicitly chose a conservative boundary in the identified 'zone of uncertainty' [[1••], p. 473, [2], Fig. 2]. Whilst this might seem reasonable based on the precautionary principle, it is also likely to induce considerable debate between nations with different needs for development. The governance challenges posed by the interplay between differences in economic interests and risk perceptions, are well known. International attempts to address deforestation [13], protect coral reef ecosystems [14•], govern fisheries [15] and transboundary river basins [16] have all had limited success due to differences in interests and risk perceptions between international, national and local interests. 'Planetary boundaries' however, pose additional challenges due to their uncertainties, and dynamic features.

One reason is that estimated quantified boundaries are likely to change over time, a fact that seriously complicates attempts to reach political agreements through scientific consensus [17]. The changing nature of 'planetary boundaries' is not only due to possible scientific advances which can result in revised estimates of individual boundaries, but also as the result of bio-geophysical interactions amongst the boundaries [1••,2,7].

This interconnectedness highlights insufficiently elaborated issues related to the information processing capacities of ESG. Governance failure is imminent when the information needed to monitor 'planetary boundary' processes and their interactions, is dispersed amongst a wide set of agencies and scientific communities [18•,19••]. The interaction amongst the PB climate change, ocean acidification and marine biodiversity provides an example of this. Ranges of international as well as non-governmental organizations address different aspects of the marine-climate-ocean acidification complex, ranging from the UN Food and Agriculture Organization (FAO), to the International Council for the Exploration of the Sea (ICES), the World Bank and UNEP and its science centres. Differences in organizational goals, approach, culture and structure are however known to account for the reluctance of agencies to share information with each other, and with external non-state actors [20].

Such fragmentation poses severe ESG challenges if interactions between 'planetary boundary' processes result in rapid and unexpected environmental change. Previous analyses show that institutional capacities tend to be severely outstripped when amplifying feedbacks in social–ecological systems [21]: either do not match previous experiences; embed scientifically and socially contested cause and effect relations; lead to secondary effects that cascade rapidly in time and space; and when information integration and analysis are challenged by organizational silos and geographical and temporal gaps in ecological monitoring [43].

A final issue is related to the speed of iteration of Earth system scientific assessments and reporting. This has been an emerging controversial issue for the Intergovernmental Panel on Climate Change (IPCC) [23] as an increasing number of actors call for more rapid assessments to keep up with the developments of climate science. This debate has additional implications for global coordination and institution building around 'planetary boundaries'. As the global sustainability community makes advancements in the understanding of 'planetary boundaries' and their interactions, how often to iterate syntheses and outreach activities, remains a crucial ESG challenge.

Moving ahead

Despite serious governance challenges related to information processing and monitoring in institutionally fragmented settings, it should be noted that a number of arenas for cross-system scientific synthesis indeed have emerged in the last decades. The Millennium Ecosystem Assessment [19••] provided an important, and collaborative

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scientific process that holds great potential due to its cross-disciplinary approach and combination of global outlook and regional depth. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) currently being developed could potentially play a fundamental role in the science-policy landscape for biodiversity and ecosystem services [24] not only by setting international knowledge standards but also by constructing spaces for deliberation between science and societal actors [25].

However, IPBES' impact on global and national policy cannot be taken for granted, as indicated by decades of insights about the use and uptake of scientific knowledge in policy-making and governance [26,27]. As observed by [26,28], increased salience of an issue is not enough to trigger international action, but needs to be combined with institutional mechanisms that enhance the credibility and legitimacy of the information produced.

Next steps in research in ESG should hence explore the institutional architecture [5••] needed to support repeated and integrated assessments of 'planetary boundaries', with a special emphasis on possible interactions where institutional fragmentation is severe; as well as explore institutional mechanisms that enhance the salience, credibility and legitimacy [28] of 'planetary boundaries' science.

Government, governance and 'planetary boundaries'

A second challenge is the degree to which current institutional arrangements have the capacity to deal with individual 'planetary boundaries', and their interactions. In elaborating on this issue we focus first on institutional reform to address individual boundaries, and second on how to address interactions between them.

Individual 'planetary boundaries'

Despite the scientific usefulness of defining a 'safe operating space for humanity', any discussion about possible institutional solutions at the international level, has to acknowledge that these always are the result of negotiation between sovereign states [17,29]. At least two main options seem to exist to address this: either to create *new* institutions at the international level, *or* to adjust existing ones to adequately address individual 'planetary boundaries' and their interactions.

Each of these options has different benefits and drawbacks, a discussion with clear parallels to ongoing debates about the regulation of engineering experiments interventions in the climate system, known as geo-engineering [65]. Whilst a 'new' institutional framework based on the notion of 'planetary boundaries' could bring some coherence into a highly fragmented institutional landscape, the development of such a framework is likely to be very slow, or end up being watered out due to the biogeophysical and political complexities of the issue.

A number of international institutions that match specific boundaries already are indeed in existence. Examples include the Montreal Protocol on Substances that Deplete the Ozone Layer, and the United Nations Framework Convention on Climate Change and the Convention on Biological Diversity (CBD). Some, such as the Montreal Protocol [30•], have been effective whilst others, like the CBD, have suffered from weak implementation capacity [31]. Other boundaries such as global water cycles [32], global nutrient cycles, ocean acidification and land-use change including deforestation and conversion to agriculture [14•], are considerably less well captured by existing international institutions, and would require considerable international political momentum to induce global reform. In addition, even though all PB are not governed through a coherent institutional architecture, they are still affected by a range of non-environmental international clusters, such as those related to world trade [30•,33,34].

This is not a trivial observation. The impacts of the rapid expansion of biofuels on a range of 'planetary boundaries' are illustrative in this sense. Whilst the major drivers play out at the global level, for example, through decline in global stocks of grain, increasing energy costs, increased global food demand, speculation in financial markets [35], the ability of the international system to mitigate the social–ecological impacts in a coordinated way, seems severely constrained. More precisely, the biophysical impacts of the rapid expansion of biofuels on 'planetary boundaries' such as land-use change (no regime existing); hydrological cycles (no regime existing); biodiversity (weak regime); and increased global uses of phosphorous and nitrogen (no regime existing) are difficult to tackle due to the complex institutional setting, and absence of international environmental institutions as well as overarching principles to guide their conduct [35].

Interactions between 'planetary boundary' processes

Provided ESG could be arranged in such a way as to match each planetary boundary, the question remains how the *interactions* between these would be regulated. Again, the question is whether to attempt to create overarching institutions, or focusing on creating inter-linkages and synergies amongst existing institutions.

Drawing on the analysis presented by Young [36], the problem complexes implied by the notion of interactions between 'planetary boundary' processes, incorporate many of the characteristics that make the emergence of robust inter-institutional coordination very difficult. That is, these interactions are at present not well-understood scientifically; they are difficult to match or 'fit' institutionally due to their multilevel (local–global) interactions;

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and interventions are likely to interact with a range of environmental and non-environmental institutions. This poses a critical collective action dilemma: sovereign states are the key locus of action in the international system, yet the complex dynamics of the Earth system seriously dilutes the incentives for collective action (cf. [37]).

Moving ahead

A further elaboration of overarching principles in international law could potentially be an approach to tackle these difficult challenges. Overarching principles are crucial as they allow for the governing of interactions between different institutions, and the regulation of norm-conflicts between these institutions. Examples here include the principle of common but differentiated responsibilities, integrated funding mechanisms, and joint mechanisms of custom control [30•]. Many of the different issue areas of world trade law are for example regulated under the overarching principles enshrined in the Agreement on Establishing the World Trade Organisation [17].

Similar overarching agreements could hence theoretically also be conceived for the governance of interactions between 'planetary boundary' processes. In terms of international law, the concept of 'planetary boundaries' even invites further exploration of the concepts of peremptory norms of international law (*ius cogens*), that is, norms that no state may derogate from [8]. The practical consequences would obviously be debatable, however it opens up for important general discussions amongst ESG scholars about the role of international law in supporting not only legal certainty and openness, but also flexibility and multilevel linkages across boundaries [38].

The issue of institutional interactions has been elaborated in detail [30•,33,34,39•,40]. One interesting development in the field is the argument that these interactions could be managed strategically by international organizations (IOs), to promote environmental policy integration at the international level [39•]. Some suggested strategies include the endorsement of inter-institutional learning through joint management amongst international bureaucracies; expert assessments aiming to promote inter-institutional learning and diffusion; and giving environmental objectives 'principled priority' in cases where environmental and non-environmental institutions are in conflict [39•,40]. Overarching principles and agreements, as well as the strategic management of institutional interactions hence all provide interesting future pathways for more detailed analyses of ESG and 'planetary boundaries'.

International organizations and interactions between 'planetary boundary' processes

A third and related ESG challenge focuses on the role of IOs such as the UNEP and the United Nations Development Programme (UNDP). IOs play a key role in global environmental governance as coordinators, knowledge brokers, bridging organizations, and by setting international agendas [41]. Although IOs have been studied extensively [30•,41,42], the emphasis has largely been on their ability to deal with incremental environmental change, rather than non-linear processes and 'planetary boundaries' interactions. The difference between trying to govern individual incremental environmental changes, versus rapid interacting change, is fundamental.

For example, whilst some implications of climate change and ocean acidification on marine ecosystems can be projected with some certainty, others are likely to unfold as non-linear social–ecological surprises at multiple levels — such as regional collapses of coral reef ecosystems, and rapid irreversible loss of fish stocks with severe food security implications. This poses a difficult coordination challenge for IOs. On the one hand, dealing with incremental changes in 'planetary boundaries' (say, coordinating policies to deal with the food security impacts of ocean acidification) require coordinated action evolving around repeated interactions, predictability and execution by nations, regional organizations and IOs (see above). At the same time, dealing with ecological surprise and cascading effects of environmental change, requires multilevel and *ad hoc* responses, where a high degree of flexibility and experimentation is allowed [43]. Intriguingly enough, these two capacities seem to be difficult to maintain within the same institutional architecture [20,44].

Another challenge relates to the *mandates* of IOs. The mandate of IOs has, and will continue to, change over time as their respective member states identify emerging global needs [30•]. Against the backdrop of 'planetary boundaries' and their interactions, identifying negative and harmful interactions between international institutions, and proposing, negotiating and implementing counter-measures could therefore be an emerging future mandate of IOs.

Although the UNEP might seem like the obvious actor to be entrusted with such tasks, existing shortcomings in the influence of this programme makes its transformation into a stronger specialized agency of the United Nations — a World Environment Organisation [45] — promising. However, a highly centralized organization runs the risk of creating negative side effects and increase complexity to international environmental decision-making processes [46].

Focusing less on the idea of one centralized organization, there is also an important aspect of the role of IOs as coordinating a range of international, cross-sectoral and multi-organizational initiatives, such as those elaborated in the literature on polycentric systems in climate policy [47], and international partnerships and networks [48]. These initiatives could be viewed as self-organized

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complements to formal international agreements, by providing the sort of 'bridging' functions previously identified for the governance of large-scale ecological systems [49,50].

Currently, this remains a potential, however. We know little empirically about how and if these partnerships and interconnected networks enhance the 'fit' [51••] between global environmental governance and social–ecological dynamics at planetary scales. Whilst actor networks of this sort can be seen as a strength by supporting flexible polycentric decision making, with high degrees of diversity in approaches [29,47,52••], it can also cause malign diffusion of responsibility, induce accountability problems, and lead multi-actor networks to externalize the costs of their actions onto others [53]. This is a particular problem in cases where international mandates are vague, international monitoring is weak or non-existing, and scientific uncertainties about cause and effect are considerable.

Moving ahead

The role of IOs as coordinators and key actors in globally spanning polycentric initiatives hence remains a key research issue for scholars of ESG. Whilst the field has made substantial progress in identifying the strengths and weaknesses of IOs in ESG [31,45,46], much remains to be done in the context of 'planetary boundaries'. The key in this context is to explore, firstly, how existing transnational polycentric initiatives address the diverse set of 'planetary boundaries' identified by Rockström *et al.* [1••]; secondly, unpack their ability to address complex Earth system interactions through, for example, new sets of cross-system monitoring systems (elaborated in section 'Planetary boundaries, science and policy'); and thirdly, elaborate whether IOs could play a role in initiating and coordinating these two.

Innovations and governance of 'planetary boundaries'

A fourth challenge is related to the role of global environmental governance in supporting, coordinating and regulating 'innovations' — that is, the introduction of novel technologies, management practices, organizational structures or institutional solutions that profoundly changes the system in which they arise (cf. [54]). The need for integrated technological, institutional, social and ecological innovations to deal with the problems of global environmental change is well known in the literature [55]. Providing food security for a future human population of nine billion, without transgressing several of the identified 'planetary boundaries' is only one critical example of the need for water, agricultural and institutional innovations [56].

Supporting and regulating innovation through global policies are however far from a simple task. Despite an increasing interest in innovation by international actors — such as the World Bank's 2009 World Development Marketplace, and the 2007 ECOSOC Innovation Fair — current academic understandings of innovation dynamics tends to have bias towards technical systems [57,58], rather than on innovations that address social–ecological feedbacks, and support the stewardship of ecosystem services (for example [21,58–61]).

Innovations of this latter kind are not necessarily only local phenomena, but can have large-scale effects through diffusion or up-scaling, like the suggested re-greening of the Sahel [61], or controversial schemes for iron fertilization of oceans for carbon-dioxide removal. The diffusion dynamics and externalities of innovations highlight the need for not only supporting innovation, but also establishing overarching governance principles that help resolve potential conflicts, and facilitate scientific and societal debate in institutionally fragmented settings [30•]. These issues have however attracted little systematic attention from the ESG community. For example, the intricate linkages between innovation dynamics and global governance play a marginal role in the ESG Science plan [5••].

Innovation is a complex and socially contested process driven by the interplay between micro (such as the individual inventor) and macro (such as policies and economic context) dynamics. This implies that any governance approach designed to support or regulate innovation, needs to consider its multilevel nature [62]. Whilst this might seem like an almost impossible task, some interesting national governance experiments have nonetheless emerged the last few years. These will prove useful in trying to link ESG to innovation as they relate to 'planetary boundaries'.

Moving ahead

A suite of strategies are worthy of further analysis in the context of 'planetary boundaries'. One example is the creation of 'space for innovation' and 'transition arenas' — that is attempts to bring together networks of diverse actors that develop a shared understanding of how they collectively can influence dysfunctional and path-dependent systems, such as water and waste management and energy supply [54]. These sorts of spaces for informal interactions have not only proven to be important for social learning, but also allow for innovation [63].

Lastly, decision-makers must be able to continuously monitor, evaluate and diffuse emerging insights from experimentation. These strategies are currently being explored through national policies in the Netherlands [54], Austria, and Australia [64].

Whether and how these 'spaces' or 'arenas' can be created and framed at the international level in the context of 'planetary boundaries', is an interesting question worth further exploration by the ESG community. Particular

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Table 1

'Planetary boundaries' and possible intervention points.

Possible intervention	Potential	Limitations
Intergovernmental platform/s for iterated global and regional environmental assessments	Could help overcome institutional fragmentation and monitoring gaps. Could provide important space for deliberation between science and societal interests.	Impact on international and national policies cannot be taken for granted, especially in cases where causality is complex and interventions are perceived to conflict with national interests.
Overarching principles	Have the ability to govern the interaction between different international institutions, regulate norm-conflicts, and increase efficiency and effectiveness by providing for general standards of behaviour.	Unclear applicability for 'planetary boundaries'; likely to be contested with unclear practical implications.
Interaction management	International inter-organizational learning, knowledge diffusion and joint management could lead to international policy integration able to deal with interactions between 'planetary boundary' processes.	Unclear how to integrate issues related to 'non-regimes', as well as rapidly unfolding surprises where international institutions are missing, or where institutional settings are complex and contested.
Expanding the mandates of international organizations	Negative institutional interactions can be identified, and countermeasures negotiated and implemented. Regular assessments can support international attempts to stay within 'planetary boundaries'.	Difficult to assign one single international organization to oversee suite of activities, and possibilities of negative institutional side effects due to institutional fragmentation at the global level.
Global multi-actor networks	Can function as self-organized complements to formal international mechanisms, and provide bridging function at the international level especially for interactions between 'planetary boundary' processes.	Collective action problems remain, and could lead to the diffusion of responsibility. Possible externalities difficult to deal with at the international level.
Global policies to support innovation	Could help support, frame and upscale innovations that address 'planetary boundaries', by supporting the generation and stewardship of ecosystem services.	Possible externalities and conflicts emerging as the result of unintended effects of innovation need to be dealt with at the international level.

emphasis should be placed on analysing; the sort of conflicts that emerge at global scale when trying to actively support or regulate innovation (for example [17,65]); the diffusion dynamics of innovations that address not only technical systems, but also social–ecological interactions and their institutional setting; and whether it is at all possible to upscale insights from national innovation governance experiments to the regional and international level.

Conclusions

What are the implications of multiple, interacting and quantified 'planetary boundaries' for ESG? Calls for international institutional and UN reform are common [8,30•,57,66], yet should build on a thorough understanding not only of the features of the international system, but also the complex dynamics of the Earth system. As we have explored, the notion of 'planetary boundaries' embeds a range of challenges for global environmental governance. These include the need to elaborate the institutional architecture of repeated, legitimate and inclusive PB assessments; the role of IOs and their ability to oversee regional and globally spanning polycentric initiatives; and the need to take the support and regulation of social–ecological innovation seriously. Table 1 summarizes the main insights from this synthesis overview. In essence, each cell indicates a possible way ahead for both research and attempts to reform ESG.

Hence the notion of 'planetary boundaries' brings a number of important ESG issues to the front. 'Planetary boundaries' could possibly provide a new target for emerging attempts to support an international environmental governance structure that is more integrated, and synergistic [30•], and help steer self-organized multi-organizational networks and social–ecological innovations. However, a range of issues related to the interplay between Earth system science and policy; a suite of monitoring and information processing challenges; as well as possible differences in risk perceptions in defining what is a 'safe' boundary condition, remain critical and poorly explored subjects.

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