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ANNUAL REVIEWS

Annual Review of Environment and Resources

The Boundaries of the Planetary Boundary Framework: A Critical Appraisal of Approaches to Define a "Safe Operating Space" for Humanity

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Annu. Rev. Environ. Resour. 2020. 45:497–521

First published as a Review in Advance on May 6, 2020

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-012320-080337

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Keywords

planetary boundaries, earth system targets, planetary stewardship, earth system governance

Abstract

In 2009, a group of 29 scholars argued that we can identify a set of "planetary boundaries" that humanity must not cross at the cost of its own peril. This planetary boundaries framework has been influential in generating academic debate and in shaping research projects and policy recommendations worldwide. Yet, it has also come under heavy scrutiny and been criticized. What is today's overall significance and impact of the notion of planetary boundaries for earth system science and earth system governance? We review here the development of the concept and address several lines of criticism, from earth system science, development studies, and science and technology studies. We also examine some applications of the framework, discuss broader governance implications, and reflect on actual policy relevance. In concluding, we explore the most recent incarnation of the planetary boundaries framework in its avatar as earth system targets supported by an Earth Commission.

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INTRODUCTION

In 2009, a group of 29 scholars published an article in *Nature*, advancing an approach to define a "safe operating space for humanity" (1). The group argued that we can identify a set of nine "planetary boundaries" that humanity must not cross at the cost of its own peril. Since this 2009 publication, the concept of planetary boundaries has been highly influential in generating academic debate and in shaping research projects and policy recommendations worldwide. At the same time, the concept has come under heavy scrutiny as well, and many critics have taken the floor contesting the broader framework as well as its implementation and interpretation. Partially because of this critique, the original proposition of nine planetary boundaries has undergone various reformulations and updates by their proponents and an emerging network of scholars specializing in planetary boundary research.

Planetary boundaries: specific values for parameters chosen at a safe distance from dangerous levels or tipping points in key earth system processes; if crossed, the possibility to maintain the Holocene-like state for humanity in the Anthropocene diminishes significantly

Earth system science: a relatively new field of scientific research aiming at understanding the structure and functioning of the Earth as a complex adaptive system

What is today's overall significance and impact of the notion of planetary boundaries for earth system science and earth system governance? We provide here a review of recent conceptual, analytical, prescriptive, and critical work around the proposition of scientifically determined planetary limits to the operating space of human societies. We focus on literature that refers to "planetary boundaries" but cover also similar terminology that describes the same idea, such as "planetary guard rails" and "tolerable windows" and the concept's most recent reincarnation as "earth system targets."

To structure this review, we conducted a citation analysis drawing on the Web of Science. We took three key publications by the original planetary boundary theorists as starting points, namely the 2009 paper in *Nature* (1), the more extensive parallel 2009 paper in *Ecology and Society* (2), and the 2015 update paper in *Science* (3), which have collectively received more than 7,000 citations in the past decade. This approach allowed us to find key bodies of literature that the planetary boundaries concept has influenced, as well as key authors who have shaped the debate. Given the sheer number of published contributions, however, our review is exemplary rather than exhaustive, focusing on the leading publications that shaped the debate or papers that we see as illustrative of a discursive strand. Our review crosses academic disciplines and covers contributions from environmental science, law, ethics, economy, geography, management, as well as political science.

We organize the review as follows. After a conceptual and historical introduction into this debate, we review the development of the concept of planetary boundaries over the past decade. We then address several lines of criticism, from earth system science, development studies, and science and technology studies (broadly defined), and examine several applications of the framework, notably in attempts at downscaling to local or regional boundaries and in national or global sustainability assessments. Next, we discuss governance implications of the planetary boundaries framework, as they are debated in the literature, along with broader impacts on dominant paradigms of economic growth, sovereignty, and the anthropocentrism/ecocentrism debate. We also briefly reflect on the impact of the framework in actual politics. At the end of this review, we explore in some detail the most recent incarnation of the planetary boundaries framework, now in its avatar as earth system targets supported by an Earth Commission.

Earth system governance: a new paradigm of governance in the Anthropocene for steering societies toward preventing, mitigating, and adapting to earth system transformations from a planetary perspective

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EMERGENCE AND DEVELOPMENT

Original Proposition

The original 2009 paper in *Nature* suggested nine boundary conditions in the earth system that could, if crossed, result in a major disruption in (parts of) the system and a transition to a different state, which is likely to be hostile to human prosperity. The proposed planetary boundaries included climate change, biodiversity loss, the nitrogen cycle, the phosphorus cycle, stratospheric ozone depletion, ocean acidification, global freshwater use, land use change, atmospheric aerosol loading, and chemical pollution. For each of these planetary boundaries, one or more control variables were identified (e.g., atmospheric carbon dioxide concentration), which in turn were assigned with numerical boundary values at a "safe" distance from dangerous levels, or where applicable, "tipping points" in earth system processes (1).

The group of authors consisted of 29 experts, including Nobel laureate Paul Crutzen, and was led by Swedish scholar Johan Rockström, who convened the workshop. Almost all authors had a background in the natural sciences. By design, their assessment effort was science-driven, meant as "an expert assessment and synthesis of the scientific knowledge" (3, p. 9). Input from civil society or governments, for example, was not systematically sought after, even though all planetary boundaries might suggest political action with profound consequences for national and global governance. The proponents of the planetary boundaries framework themselves acknowledged in 2009 that determining a "safe" distance involves "normative judgments of how societies choose to deal with risk and uncertainty" (2, p. 3); yet, this normativity had no consequences for the assessment process itself. Instead, the approach chosen in 2009 was to define from a purely scientific, expert-driven perspective a safe operating space for humanity, as the title of the article suggests (1).

Eventually, the framework should allow for quantification of threshold parameters, as a guide also for political responses. For some planetary boundaries, the group in 2009 suggested that the current state of knowledge was too uncertain to allow for quantification. Yet, for other earth system processes, the group felt confident enough to suggest a specific boundary value. In this endeavor, they erred on the side of caution and a strict interpretation of the precautionary principle: Where they saw remaining uncertainties, the group suggested the lower values for the boundary that they identified. They concluded that three planetary boundaries had been crossed already. On climate change, for instance, the boundary value proposed was 350 ppm, which had been passed long ago in the second half of the twentieth century. Regarding biodiversity, the current extinction rate is more than 100 extinct species per million species per year, whereas the suggested boundary was 10 extinctions. As for the nitrogen cycle, humans remove today approximately 121 million tons of nitrogen per year from the atmosphere, whereas a safe rate would be a maximum of 35 million tons. In these three areas, therefore, this analysis suggested that humankind had pushed the earth system past planetary boundaries and possibly dangerous levels, into a new—and unknown—world.

Although the term planetary boundaries was coined and popularized in 2009, the concept itself is not new, but follows a broader line of research in earth system science. In the broadest sense, the framework builds on long-standing debates on limits on planet Earth (for reviews, see 4, 5), including widely read studies such as Kenneth E. Boulding's intervention "The Economics of the Coming Spaceship Earth" (6) or the 1972 report by the Club of Rome, *The Limits to Growth* (7). Also, more general studies on critical transitions and tipping points in the earth system relate to the planetary boundaries approach (8–11), and experts on critical transitions in complex systems such as Timothy Lenton and Marten Scheffer contributed to the 2009 paper.

More specifically, the planetary boundaries approach is not that different from the guard rails and tolerable windows concept developed in the late 1990s by the German Advisory Council on Global Change (12, 13) in collaboration with the Potsdam Institute for Climate Impact Research, both led by German physicist Hans-Joachim Schellnhuber (also a coauthor of the 2009 paper). As argued then by the German Advisory Council (13, p. 135), the "concept of tolerable windows . . . is characterized by the normative stipulation of non-tolerable risks, termed *guard rails*. . . . The purpose of limiting tolerable developments of climate change by means of guard rails is to prevent the climate system from moving dangerously close to possibly unstable states, which, considering the extremely high potential for damage, could lead to dramatic climatic hazards." One quantified guard rail named at that time is the target of a maximum average global temperature increase of 2°C (14), which has become formally accepted by governments in the 2015 Paris Climate Agreement. Although the 2°C target differs from the boundary suggested by Rockström and colleagues in 2009, conceptually it is very similar as a boundary condition for human survival on Earth.

Expansion of the Original Proposition

Six years after the original publication of Rockström et al. (1), an update of the planetary boundaries framework was published in 2015 (3). Will Steffen (the co-lead of the original article) now led the team of 18 authors, again mainly from the natural sciences. Although the 2015 paper was presented as an update, it is noteworthy that only 5 out of the 29 authors of the original 2009 article also coauthored the update.

The 2015 expansion of the original planetary boundaries framework consisted of a scientific update (e.g., adjustments in boundary values) as well as slight modifications to the boundaries themselves. These were made considering a range of criticisms of the 2009 paper, which we discuss below in more detail. For example, the authors now implemented a "two-tier approach" for boundaries on biogeochemical flows of nitrogen and phosphorous, land-system change, and freshwater use, "reflecting the importance of cross-scale interactions and the regional-level heterogeneity of the processes that underpin the boundaries" (3, p. 1). Maps were now included to show subglobal distributions and the status of the control variables.

Furthermore, the 2015 update emphasized the dynamic relationships between planetary boundaries. Steffen and colleagues made an extra effort to highlight that planetary boundaries interact, arguing against misunderstandings that the boundaries are static and independent (see also 15, 16). But this time, they made a new claim that planetary boundaries are hierarchically ordered, with climate change and biodiversity being at the core, such that these two boundaries connect to all other boundaries.

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Another point that the 2015 update underscored is that the planetary boundary research is a work in progress. The original nine boundaries are not to be seen as fixed and final but as a living framework to be further developed in earth system science. This means that more fundamental earth system processes could be discovered in the future, or their parameters or boundary positions could be adjusted. In relation to this point, the update makes it explicit that the planetary boundaries framework "does not dictate how societies should develop," which Steffen et al. acknowledge as "political decisions that must include consideration of the human dimensions, including equity" (3, p. 736), which are not incorporated in the framework itself. Rather, the authors hope that the framework will make "a valuable contribution to decision-makers in charting desirable courses for societal development" (3, p. 736).

CRITIQUE

Since 2009, the planetary boundaries approach and its key publications have found not only much praise, but also a wide range of critique from both natural and social sciences, humanities scholars, as well as the broader public and policy community. Criticisms are targeted at the framework itself as well as its implementation. We focus here on three strands of critique: from within earth system science, from the field of development studies, and from what can be broadly defined as science and technology studies.

Critique from Earth System Science

To start with, the original proposition of 2009 has met many criticisms from other earth system scientists. Already at the moment of publication, *Nature* printed the original paper together with no less than seven commentaries in its sister journal *Nature Reports Climate Change*, in which other scholars expressed skepticism over the planetary boundaries framework as being too long-term oriented (17, 18), some of the global limits being too generous (19, 20), and the definition of some boundaries being inadequate (21–23). In its editorial, *Nature* also expressed a concern over the possibility that the boundaries may be misused by policy-makers to "justify prolonged degradation of the environment up to the point of no return" (24, p. 448; see also 25).

In following this debate, many scientific debates addressed specific boundaries and the threshold values that were advanced in 2009. We can give here just a few illustrations of these discussions within earth system science. One example is the exact boundary value for freshwater consumption. Jaramillo & Destouni for instance argued here that the boundary suggested in 2009 was too conservative and that the freshwater boundary had in fact already been transgressed (26; for a response see 27). Other debates revolved around the phosphorus and nitrogen boundaries (28–30). There have also been several attempts to fill gaps left by the 2009 framework, especially in relation to boundaries for which no clear safe operating space was suggested, such as chemical pollution (31–34).

The biodiversity boundary has been heavily scrutinized (35), especially for using extinction rates as the sole control variable in the 2009 paper. Some argued that rates of extinction have been highly variable through time, that underlying data on abundance and distribution is limited, and that the usefulness of a single variable for all of biodiversity was not clear (23). Mace et al. (36), together with some of the original authors, proposed the use of phylogenetic diversity, functional diversity, and biome integrity in determining a planetary boundary for biodiversity, an argument that was taken up in the 2015 update, which also added a caveat that these are "interim control variables until more appropriate ones are developed" (3, p. 4). Montoya et al. (37, p. 71) went as far as claiming that "notions of planetary boundaries add no insight into our understanding of

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the threats to biodiversity and ecosystem functioning, have no evidence to support them, are too vague for use by those who manage biodiversity, and promote pernicious policies." Rockström et al. (38) dismissed Montoya et al.'s claim as a misrepresentation of their planetary boundaries framework. In their view, such "ill-informed and misguided attacks" (38, p. 232) on the planetary boundaries framework are recurring largely because scientists conflate planetary boundaries and tipping points.

Other scholars have highlighted what is fundamentally missing from the current set of nine planetary boundaries, proposing to add entirely new issues or earth system processes. Nash et al. (39), for instance, argued that marine systems are underrepresented in the planetary boundaries framework. They hence suggested expanding the scope of the land-system boundary to include the seafloor as an earth surface change boundary. Another earth system process for which they saw the need for a planetary boundary involves "changes in vertical mixing and ocean circulation patterns" (39, p. 1632). Similarly, Running (40) suggested adding a boundary for terrestrial net primary (plant) production, so that human consumption of Earth's biological resources stays below net primary production. This boundary would then integrate five planetary boundaries—land-use change, freshwater use, biodiversity loss, and global nitrogen and phosphorus cycles—and has been argued to be more easily measurable on a global scale. This debate also shows the progress within the earth system sciences on defining boundaries: Even though this particular suggestion was not taken up in the 2015 update (for commentaries, see 41, 42), a similar logic was applied in revising a boundary from rate of biodiversity loss (1) to change in biosphere integrity (3).

A more fundamental line of criticism of the planetary boundaries framework has been its inclusion of subglobal-scale, nonsystemic, and aggregate processes that have shown little evidence of threshold behavior so far (43, 44). Examples here include land-system change, freshwater use, and, again, biodiversity loss. The proponents of the planetary boundaries framework would argue here that such processes provide the underlying resilience of the earth system and also interact with global processes. However, we still lack understanding of whether subglobal tipping points can lead to global transitions (45). The central use of the generic term threshold throughout the 2009 *Nature* paper has resulted here in critique by some earth system scientists who argue that the selection of the boundaries and their boundary values is arbitrary. The 2015 update made it therefore explicit that a "planetary boundary as originally defined is not equivalent to a global threshold or tipping point" (3, p. 1), and that not all earth system processes included in the planetary boundaries framework have "singular thresholds at the global/continental/ocean basin level" (3, p. 2).

Critique from Development Perspectives

In addition to these debates within earth system science, the planetary boundaries approach has met wide criticisms from the development studies community and from scholars and commentators from the Global South. This is not surprising given that the focus of the planetary boundaries framework, in its implementation, might constrain economic growth and potentially the development prospects of vast areas in Africa, Asia, and Latin America. In its original definition, the planetary boundaries framework was not designed to account for the regional distribution of causes and consequences of earth system transformations, historical patterns, or societal issues broadly defined. The boundaries were seen as planetary, with no concern for global inequality and social justice. The framework instead sought to establish a global limit on the extent to which humanity as a whole could perturb Earth's subsystems or processes. Although the framework is, according to the 2015 update, supposedly science-driven, apolitical, and silent on the "deeper issues of equity and causation" (3, p. 8), it is not free from political consequences for global equity. For example, the

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original suggestion to convert no more than 15% of global land to cropland has been controversial and has been changed in the 2015 update to maintain at least 75% of original forest cover globally. And yet, this new variable can be seen as equally controversial given the imbalance between currently still forested countries and those countries, for example in Europe, that had cut down their forests and turned them to agricultural land many centuries ago. Also, domestic inequalities within countries remain outside the purview of the planetary boundaries framework (46).

One widely cited normative critique came from an international nongovernmental organization, Oxfam, in their so-called doughnut framework, which suggested a safe and just operating space (47; see also 48). This doughnut framework combines planetary boundaries as so-called environmental ceilings with social foundations that consist of basic human needs and values such as housing, social equity, or education. Later, Oxfam author Kate Raworth turned the doughnut metaphor into a cottage industry of related concepts and publications, notably the so-called doughnut economics (49), which restate tenets and findings from the field of ecological economics in an attempt to reorient economic policy toward global and local ecological and social boundaries.

This critique of global inequality and injustice led to a burgeoning interdisciplinary literature that involved both natural and social scientists. At the most general level, there is now broad agreement that global equity and environmental sustainability should be made compatible, and that it is—as argued by Steffen & Stafford Smith—"in the self-interest of wealthy nations to achieve a more spatially equitable world in terms of access to resources and ecosystem services" (50, p. 403). Yet, the concrete implications are still fiercely debated.

Critique from Science and Technology Studies

Such normative underpinnings and implications of the planetary boundaries framework have been discussed by scholars from especially the social sciences, humanities, science and technology studies, and so-called critical approaches in the social sciences. One key concern has been the relevance of the planetary boundaries framework for actual governance and the problem of agency; in short, who is deciding on the precise values of boundaries that are to be protected?

This question revolves around whether such planetary threshold values are externally determined boundaries or politically decided targets. Rockström's team explicitly framed their approach as the scientific identification of pre-existing boundary conditions in the earth system. This is hence different from traditional environmental targets set by legitimized policy-makers according to agreed constitutional procedures; the boundaries in the 2009 article are framed as science, not politics. To give an example of the difference, the definition of the maximum discharge level of pollutants into a water body can be framed as an environmental target; then it will be up to policy-makers to balance the level of environmental pollution with other concerns, constituencies, and societal needs. Such levels, however, can also be framed as a "natural" boundary condition: In that case, the identification of the value would be in the realm of the expert. Moving parameters of earth system governance from policy targets to planetary boundaries hence implies a shift in responsibility, and political power, from the policy-maker to the expert. The only remaining task of policy-makers then is to ensure that the boundaries, identified by experts, are being respected and never transgressed.

This distinction between policy targets and planetary boundaries is less relevant in some cases, for example, the protection of the stratospheric ozone layer where political conflicts hardly arose about the target of complete restoration of the ozone layer as such. The distinction between policy targets and external, science-driven boundaries becomes relevant, however, in cases of global cumulative problems that are not marked by planetary interdependence, in areas with

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large regional differences, and in areas where human needs are fundamentally at stake. Examples are the cumulative and value-laden boundaries on freshwater use, land use, and possibly even climate.

Proponents of planetary boundaries admit that exact threshold values are uncertain and that boundaries follow the precautionary principle; they see boundaries, as it were, as fences around the cliff to prevent humanity from stepping near the cliff (that is, the tipping point). Yet again, this definition of precaution then depends on varying degrees of risk-taking and risk aversion in different societies (1), which should not—as critics argue—be left to experts from the natural sciences (51), which are also predominantly based in wealthy industrialized countries. Controversial here, again, is that boundaries are proposed by experts without stakeholder consultation or public participation and deliberation. The science and technology studies community has therefore objected to what it perceives as expert-driven, technocratic attempts at a sort of Platonian world of a "global expertocracy."

Is it then possible to make boundary-defining processes more democratic and yet science-based? This concerns the much broader debate around the compatibility between democracy and sustainability. Pickering & Persson (52, p. 59) (the latter being another coauthor of the 2009 paper) offer a forceful defense of the planetary boundaries framework by arguing that it allows for "an iterative, dialogical process to formulate planetary boundaries and negotiate 'planetary targets'." Yet, whether the framework can indeed form the basis for a democratically legitimate division of labor among experts, citizens, and policy-makers in evaluating and responding to earth system risks remains to be seen; we return to this discussion later in our review of the recent earth system targets concept.

APPLICATIONS FOR ASSESSMENT

Apart from these various lines of critique, numerous studies have also sought to further refine and implement the planetary boundaries framework. Here, we focus on two applications: downscaling the framework for local policy use and using it in environmental assessments at multiple levels.

Downscaling Planetary Boundaries

The original proposition of nine planetary boundaries addressed the earth system level of analysis: the planet as a whole. But what is a fair share of the burden of, for example, a specific country? What does the planetary boundaries approach entail for national or regional analysts and decision-makers? How can the spatial heterogeneity of control variables for planetary boundary processes be accounted for? The problem of downscaling planetary boundaries has been controversial. The 2015 update emphasized that the planetary boundaries framework was not designed to be "downscaled" or "disaggregated to smaller levels" due to the interdependent nature of the earth system processes (3, p. 8). But it nonetheless acknowledged the need to downscale to better align the framework with decision-making scales.

Yet, the global nature of the planetary boundaries framework limited its applicability at sub-global levels, even though it is here where policy action most commonly occurs. For example, the proposition of a planetary boundary for freshwater use has to be seen in the context of highly diverse geographical areas that either do not have enough water or are so humid that water shortage is no concern (53, 54). Uses of water differ between regions as well, with water also being embedded in traded goods, such as agricultural products. Here, global differences in regional and local availability, as well as questions of justice, restrictions in access, and inequality, become invisible in globally aggregated planetary boundaries (but see 55).

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Given such challenges, several studies looked into downscaling the concept of planetary boundaries to the national and regional level and to make it better applicable for decision-makers. One pioneering study is Nilsson & Persson's (56) attempt to downscale the boundaries in the context of the European Union to estimate the region's fair share. They argue, however, that such a burden-sharing approach is "neither feasible nor desirable" (56) for several theoretical and practical reasons and propose instead to focus on key regional drivers behind the planetary boundaries. Yet, others were more optimistic about the possibility of downscaling planetary boundaries. For example, Nykvist et al. (57) used a per capita approach in a study on Sweden that was pioneering at that time. Dearing et al. (58) created a downscaled version of the planetary boundaries framework and applied this on two low-income rural communities in China. Other studies designed, for instance, a national "barometer" for South Africa (59), proposed criteria for disaggregating planetary boundaries to national levels (60), developed a more general framework to translate the planetary boundaries into national fair shares of the earth's safe operating space (61), or proposed boundaries from a city's perspective to aid cities to play a more active role in global sustainable development (62). As a final and very regional example, Teah et al. (63) defined a "regional safe operating space" for a semiarid region in Western China. This paper, however, also shows some of the limits of downscaling planetary boundaries. Although Teah et al. built their work explicitly on the boundaries framework, they limited these earth system boundaries to a narrower set of boundary conditions that are applicable at the regional level, such as freshwater use, biogeochemical flow (measured by nitrate and phosphate concentrations), land-system change, atmospheric aerosol loading, and novel entities. Global boundaries that have regional impacts but cannot be regionally managed—such as climate change—were hence left out of the analysis. This regional application of the planetary boundaries concept was apparently well received by local officials in China, even though not integrated into policy-making.

Such studies raise the conceptual question of what is gained by the novel framing of planetary boundaries as opposed to earlier work on critical loads and local environmental targets. For example, water quality standards for rivers have long been part of traditional environmental policy, without necessarily needing an explicit reference to planetary boundaries, which might even be misleading given that local water pollution has limited planetary interconnectivity. Also, many local studies such as the one by Teah et al. do not account for international trade and exchange, which is important in the North-South context. Many rich, service-driven OECD economies have a global ecological footprint that by far exceeds their national footprint. Here, merely assessing the protection of a regional safe operating space might set incentives to export ecological degradation to other countries, effectively threatening the preservation of planetary boundaries.

Some recent studies take this planetary dimension of regional boundaries explicitly into account. Dao et al. (64), for example, attempt to downscale the planetary boundaries framework in a country-scale assessment of Switzerland, but embed this analysis explicitly in a global assessment framework, noting that half of the environmental impact through the consumption of Swiss residents occurs abroad but needs to be included in a downscaled boundaries framework. On the basis of this starting assumption, they develop a novel method that integrates the planetary boundaries approach (with some revisions and adjustments) with a footprint approach that calculates national consumption limits based on a global assessment and, from an ethical perspective, the assumption of equal environmental rights per person. They propose that this method could be used to guide national assessments and policy-making, and potentially also international comparisons (for similar studies see 65, 66, and 67).

In addition, some scholars have tried to downscale the planetary boundaries framework not on geographical units but on industries, economic sectors, or products. Several studies advanced methodologies to bridge planetary boundaries with life cycle assessments (68) to assess, for

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example, the manufacturing of cosmetics (69) and clothing (70) with a view to their impacts on a planetary level; one study defined a safe operating space for inland recreational fisheries (71). Similar studies have focused on the impacts of companies (72). Such studies that couple life cycle assessments with the planetary boundaries approach make up a large part of all scholarly work on planetary boundaries (73). However, technical and theoretical challenges are still large in any serious attempt at operationalizing a planetary boundary-based life cycle assessment. Ryberg et al. (74), for instance, highlight that more research on downscaling is needed if we want to model the impact on allocation of and entitlement to the safe operating space. Others again are more optimistic and argue that this approach will help companies and policy-makers in promoting environmental sustainability (75).

Applications in Global and National Environmental Assessments

Despite the challenges associated with downscaling, the planetary boundaries framework has been referred to, or even used, in several assessments that estimate, in terms of planetary boundaries, different environmental impacts.

At the global level, examples include those on the planetary boundary for phosphate supply (76). At national to subnational levels, research projects focused on a wide range of areas, from entire sectors such as energy (77) to businesses and other commercial entities such as farms (78). As one exemplary insight, Algunaibet et al. (77) estimated that in the United States "the least cost energy mix that would meet the Paris Agreement 2°C target still transgresses five out of eight planetary boundaries" (p. 1890). In general, such studies point out the importance of "complex sustainability thinking" and consider the impact on multiple interdependent planetary boundaries rather than on one single environmental impact (78).

In addition, several authoritative global assessments of the state of the global environment have cited the planetary boundaries framework, including the *Global Environment Outlook* of the United Nations Environment Programme and the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. The planetary boundaries framework has been used in these reports in both assessing the state of the environment and proposing an outlook, emphasizing that the planetary boundaries framework provides "a quantification of safe levels of global environmental change, based on Earth-system science" (79, p. 478).

In general, many global and national assessments that use the planetary boundaries framework or the doughnut model conclude that we need to change how we govern our societies. This message is supported, for instance, in the work by O'Neill et al. (80), who conclude that "no country meets basic needs for its citizens at a globally sustainable level of resource use" (p. 88). Other policy conclusions in such assessments are the need to implement dietary changes; to increase waste prevention and nutrient recycling (81, 82); to globally redistribute nutrients in residues, soils, and sediments and rights to use nutrients (83); or that a reasonably good life within planetary boundaries is possible only at a much lower level of affluence than what richer countries enjoy today (84, 85). These studies hence point to the need for major transformations in earth system governance from local to global levels. We turn to some specific governance implications next.

IMPLICATIONS FOR GOVERNANCE

The definition of a safe operating space for humankind, defined by a set of planetary boundaries, has not only generated much critique but also stimulated many social scientists and international lawyers to explore what planetary boundaries thinking could imply for governance and the dominant paradigms of our time (e.g., 86–89).

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New Governance Arrangements

Three key clusters of governance implications of planetary boundaries are prominent in the academic debate.

First, the planetary boundaries framework implies that policy-makers must ensure that these boundaries are never compromised; the boundaries are advanced, implicitly or explicitly, as clear imperatives for political action by governments, parliaments, or courts. On the one hand, this is simply a renewed call by scientists for more effective governance and public policies on well-known challenges such as mitigating climate change, protecting biodiversity, or cleaning up the oceans. On the other hand, and more specifically, some scholars and civil society organizations have adopted the planetary boundaries framework as inspiration for a much more specific governance reform and realignment that revolves around the planetary boundaries framework. Some nongovernmental organizations have for instance submitted a "Draft United Nations Declaration on Planetary Boundaries" to the 2012 United Nations Conference on Sustainable Development in Rio de Janeiro (90). Some scholars went further by suggesting an international legally binding "framework convention on planetary boundaries" that would recognize planetary boundaries as "a necessary prior condition for the fulfilment of other objectives related to life and the well-being of humankind" (91). In the context of the Sustainable Development Goals, Costanza (a coauthor of the 2009 paper) and colleagues similarly argue that these Sustainable Development Goals should be hierarchically organized with those given priority that are most closely related to "staying within planetary boundaries" (92). Others again have argued that the planetary boundaries framework would be useful in identifying gaps in international environmental law (93) and to "bolster legal boundaries" (94).

Problematic with such proposals is the diverse legal and institutional situation in each of the governance domains covered by a planetary boundary. For example, the boundary on stratospheric ozone depletion is regulated by the 1985 Vienna Convention for the Protection of the Ozone Layer and its 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, a broadly effective regime that led over time to the almost complete phase-out of production and consumption of ozone-depleting substances. Here, the identification in 2009 of a planetary boundary on ozone depletion does not add much, and in particular, no further regulation—for instance through a planetary boundaries treaty—is needed. Similarly, the climate crisis is addressed through the United Nations climate regime and many intergovernmental and private initiatives. Although the climate regime complex undoubtedly still lacks effectiveness, this will not be resolved by an alternative framing or novel additional governance process within a planetary boundaries framework, which would add complexity without helping resolve the impasses. In addition, a global approach to "planetary boundary governance" will not really help for those boundaries that are not global in scale, and the framework may hence "spread political will thinly" (44, p. 417). It might be counterproductive, in the sense that it might tempt scholars to argue for global regulation of freshwater or land use when this is politically pointless or at least problematic. In that sense, the planetary boundaries framework might suggest the need to regulate areas that are well institutionalized or that do not require (strong) global governance. For some processes, however, the planetary boundaries framework might help identify systemic processes that are poorly governed so far. Here, this research can, indeed, serve as an important agenda-setting and early-warning mechanism. One key example is nitrogen (e.g., 29, 95–98), and the resulting emphasis on the food system and agriculture as a major driver of earth system transformation (99, 100). Overall, the key governance conclusion should remain that "political institutions should follow social activities, not necessarily planetary boundaries" (101, p. 7).

Second, the planetary boundaries framework suggests the need for generally designing more adaptive institutions (102–104). Earth system processes are inherently dynamic, and any boundary

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positions change constantly and possibly abruptly, with large uncertainties about systemic threshold values. This highlights the need for governance arrangements that easily adapt to new information and warning signals at all levels of governance, from local to global (105, 106). Some observers suggested to go beyond reactive adaptation and engage instead with proactive anticipation, highlighting the potential role of anticipatory governance in exploring governance implications of planetary boundaries (e.g., 35) and in imagining plausible and desirable futures in the Anthropocene (107). But again, these processes have drawn critique, notably that the "tasks of governance thus become transformed, no longer seeking to imagine alternative futures but rather drawing out alternative possibilities that already exist in the present. Governance becomes increasingly an act of affirmation rather than a discourse of change and transformation" (108, p. 21).

Anthropocene: a proposed term for the current geological epoch in which humanity has become a global geophysical force

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Third, for some authors, the planetary boundaries framework emphasizes the need to govern the complex interactions between planetary boundaries (109, 110) and to create new institutional arrangements for that purpose. In this view, policies to reduce the pressure on one planetary boundary may have positive or negative side effects on other boundaries (111–114), which again poses challenges to earth system governance (115, 116). One prominent example is the relation between policies to protect climate change and the emergent risk of ocean acidification (117). The risk of trade-offs between planetary boundaries then highlights the need to address the increasing fragmentation of earth system governance and resolve multiple interacting environmental problems simultaneously. It also calls for attention to the overall or net effectiveness of earth system governance. Earth system governance scholars have made various proposals in response. They range from defining a *grundnorm* (115, 118, 119) to strengthening polycentricity (109) and mapping and designing bridging organizations (120). Also relevant here is the idea of governing through goals (121), where global goals are potentially instrumental in orchestrating existing institutions toward an overarching objective.

The challenge of governing boundary interactions becomes more pronounced when we account for the assumed hierarchy between boundaries as suggested by Steffen et al. (3). However, the current architecture of earth system governance does not reflect such hierarchy. All treaties at the international level, for example, are on an equal footing. In other words, the United Nations Framework Convention on Climate Change does not take precedence over the Vienna Convention for the Protection of the Ozone Layer. Although creating a strict and permanent hierarchy among international environmental institutions seems at this point neither possible nor desirable, a nested architecture for a more systematic implementation might be advisable considering the analysis of planetary boundaries and their interactions.

Implications for Dominant Paradigms

In addition to debates on "how to govern" planetary boundaries, this notion has given rise to a new strand of discussions that partially restage earlier debates around limits to human activities and development. We focus here on three potential implications: for the dominant growth paradigm in economics, for the legal understanding of national sovereignty, and for the debate around anthropocentrism versus ecocentrism.

First, whereas mainstream economic theory stays fixated on the need for economic growth, more critical ecological economists have long argued for alternatives, such as a-growth or degrowth (122). Here, the planetary boundaries framework has given rise to a series of studies that rechallenge the dominant growth paradigm, with some proponents linking the protection of planetary boundaries with the need to place boundaries on the dominant economic growth paradigm as well (123–125). Kate Raworth (49), mentioned above, has developed her original critique of the planetary boundaries approach in her emphasis on social boundaries—the "doughnut"—in the direction of "doughnut economics," which popularized some core ideas of ecological economics. Also, key proponents of resilience theory linked this approach to economic reform and new paradigms, for example, in Crépin & Folke's interpretation of planetary boundaries "as warning signs creating incentives for shifting development into new directions, new pathways, where growth in human well-being is the focus rather than growth in GDP" (126, p. 58). They call this new paradigm "biosphere economics," where we essentially recognize "economics as a subject area to the biosphere" (126, p. 66; see also 127).

Not all view a fundamental paradigm shift as necessary, however, and some argued that the "planetary boundaries literature does not explicitly challenge emerging notions around the 'green economy', nor indeed economic growth and mainstream development paradigms of recent decades" (4, p. 126). Rockström himself has much more strongly embraced global business and multinational corporations by seeking to develop earth system targets that business leaders could adopt and implement—an approach that stands opposite to the more radical positions from the degrowth community. More classical environmental economists continue to argue within the more traditional economic paradigm that clever design of effective policies (111) can help to protect planetary boundaries. In their view, environmental problems constitute market failures; protecting planetary boundaries hence primarily involves fixing misguided incentives for harmful activities. There is also a sizeable literature that seeks to use the planetary boundaries framework to advance the "greening" of big business and corporations (e.g., 128). In a highly cited paper, Whiteman et al. (129), for example, introduce the planetary boundaries framework to corporate sustainability scholars. These scholars seek bottom-up transformation by, for example, improving corporate reporting on their sustainability performance against planetary boundaries (130). Other papers in this line looked at the challenges for companies (131, 132), broader implications for management education (133), investment (134), accounting (135, 136), resource efficiency (137), entrepreneurship (138), or asset impairment (139).

Second, legal scholars and international governance experts emphasized the implications of the planetary boundaries framework on national sovereignty. Some argue here that planetary boundaries thinking gives an important new perspective on the international legal order created among European powers in the Westphalian peace of 1648, which reinforced—at least legally—the principle of national sovereignty (140). Scholars have proposed here a new vision "in which it is conceivable that maintaining the type and level of activities within and beyond our jurisdictional boundaries . . . may become conditional upon respecting certain overall, planetary-scale boundaries" (140, pp. 923–24). Theoretically, planetary threshold values—however defined—could also be linked to legal notions of *jus cogens*, that is, peremptory norms of international law that no state may ever derogate from (88, 101). If so, such threshold values would need to be defined through multilateral agreement and not directly by scientists. Maybe the 2°C target of the 2015 Paris Climate Agreement begins to assume such functions of a supranational legal standard in some national jurisdictions, given its recent influence on local courts when determining national political policies; a wider declaration of a higher legal status of the 2°C target might well seem conceivable.

Third, and partially related to the second point, the planetary boundaries framework brings profound implications for the long-standing debate between anthropocentrism and ecocentrism and the relative primacy of ecological concerns vis-à-vis human development. On the one hand, planetary boundaries thinking is unapologetically anthropocentric. The planetary boundaries aim at avoiding "unacceptable global environmental change," defined in relation to "the risks humanity faces in the transition of the planet from the Holocene to the Anthropocene" (2, p. 2). After all, the scientists selectively identified key earth system processes and quantified boundary levels with human development in mind (but see 141, 142). On the other hand, the planetary boundaries also are clearly conceptualized as limits for human endeavors in order to stay within the safe

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operating space. This, again, brings the approach closer to ecocentric approaches that prioritize the protection of nature.

At the core is the ethical question of what kind of world is still hidden behind the planetary boundaries concept—a core issue in the Anthropocene discourse that emphasizes the end of nature. If we accept that several of the planetary boundaries have been overstepped, we may soon trigger a regime shift into a so-called Hothouse Earth (143). This shift might be abrupt (on an ecological timescale), leaving no time for species—including ours—to adapt to the new conditions. Then the "natural" state of this Hothouse Earth will no longer be conducive to the survival of life as we know it. Here, ironically, living in harmony with Earth (that is, being ecocentric) will diminish the chance of survival of many species that currently exist. The Cartesian dualism between ecocentric and anthropocentric ethics becomes irrelevant. The integrity of the earth's ecosystem will no longer remain a global public good (144, 145).

What is then the ultimate purpose of earth system governance as we risk moving into the Hothouse Earth (146)? What planetary boundaries research might be telling us is that an irreversible transition from the Holocene to the Anthropocene might already be occurring and that we hence need to play the role of "planetary stewards" (e.g., 147–150). Such "planetary stewardship" would involve actively keeping a Holocene-like state in the Anthropocene, hence buying time for life on Earth to adapt to the transition to the Anthropocene. Earth system governance would increasingly involve actively seeking out what are plausible and desirable futures, and collectively choosing a future we want within the constraints of the earth system.

Such debates lead, unsurprisingly, to calls by scientists for more research. Van Vuuren et al. (151), for example, propose more interdisciplinary research to increase understanding by better linking human drivers and social and biophysical impacts. Others suggest more research on transformational change and how to achieve it by drawing, for example, on the transition management literature (152). Others again have used the planetary boundaries framework for developing socioeconomic pathways that would comply with planetary climate boundaries (153).

POLITICAL IMPACT

As we laid out, the planetary boundaries framework published in 2009 had its impact in scientific debate, as witnessed by the extraordinary citation impact of the core papers. But did it also leave any trace in politics and governance?

Some impact on policy is clearly traceable. According to Altmetric, the original proposition of planetary boundaries from 2009 (1) has been cited in 66 policy documents and the 2015 update in 31 documents (as of October 21, 2019) (3). The citing documents include publications from a few United Nations organizations, notably the World Health Organization, the Food and Agriculture Organization, the International Labor Organization, and the United Nations Environment Programme. Also, some business-related or financial institutions such as the World Economic Forum, the World Bank, and the African Development Bank have taken up the concept in some of their reports.

In global sustainability governance, the most recent major event where new reforms were debated and new actions were taken was the 2012 United Nations Conference on Sustainable Development, the "Rio+20" Earth Summit. Here, the planetary boundaries approach could have been influential and could have informed political decisions by world leaders. And yet, despite attempts (154) by nongovernmental organizations, science networks, and Rockström himself, the notion of planetary boundaries was not included in the final documents of the conference, the 2030 Agenda for Sustainable Development and its core agreement, the 17 Sustainable Development Goals and 169 targets that further specify these goals. Even more, it is fair to argue

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that the overall integrated and balanced structure of the Sustainable Development Goals is exactly the opposite of what proponents of planetary boundaries had originally intended. The focus of the Sustainable Development Goals is on human development, including the ending of hunger by 2030, the eradication of poverty, the reduction of inequality, and even economic growth and decent jobs. Ecological concerns are covered as well, of course, and surely more prominently than in the earlier Millennium Development Goals. But despite a series of papers in the run-up to the Rio conference, the Sustainable Development Goals remain as much about people as they are about the planet. A normative hierarchy that would put the planetary boundaries at the top of the Sustainable Development Goals was clearly not acceptable to governments—and here, especially, to representatives of the poorer countries.

Although the planetary boundaries framework did not make its way into the United Nations norm-setting processes, it was met in several countries with interest and found some support from national and local policy-makers. For example, several "Making the Planetary Boundaries Concept Work" workshops were held in Geneva (2013), Brussels (2015), and Berlin (2017) and seem to have attracted increasing numbers of attendees from politics and even the private sector. The Swiss Sustainable Development Strategy, for instance, explicitly mentions the planetary boundaries (64). Several government agencies in other countries also reference the 2009 or 2015 papers on planetary boundaries in their policy documents, for instance, the PBL Netherlands Environmental Assessment Agency. However, according to Altmetric, the impact on national policy processes also does not extend much beyond a handful of countries in the Global North, such as Australia, The Netherlands, and the United Kingdom.

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EARTH SYSTEM TARGETS: OLD WINE IN A NEW BOTTLE?

A few years ago, a new term entered the debate, advanced again by Johan Rockström and a few of his colleagues and networks: "earth system targets," defined as "science-based targets" for the entire earth system. In essence, we are seeing here a reformulation of the original idea of the planetary boundaries of the early 2010s and the planetary guard rails and tolerable windows of the 1990s. A main difference between the planetary boundaries and the more recent earth system targets is the institutional embedding and procedures. The original planetary boundary approach was developed by a group of university professors—largely male, with natural science backgrounds, and tenured in leading positions in OECD countries. There is little doubt that this lack of inclusiveness has helped minimize the credibility and legitimacy of the approach, especially in the developing world (46), which could not find even one Southern scholar in the group of professors that wrote the original 2009 *Nature* article.

The new approach of earth system targets seeks to address this problem. Now, the earth system targets are to be defined not by a self-selected group of professors but by an Earth Commission, which should be supported by an Earth Headquarters based at the Potsdam Institute for Climate Impact Research in Germany and International Institute for Applied Systems Analysis in Austria. Despite the grandiose novel terminology, however, the Earth Commission is in no way legitimized by the United Nations and, in particular, developing countries. The Commission's main support comes from what is called the Global Commons Initiative, a network set up in 2016 by six organizations: the Global Environment Facility, International Institute of Applied Systems Analysis, International Union for Conservation of Nature, Stockholm Resilience Centre, World Economic Forum, and World Resources Institute. Three of these partners are research organizations based in industrialized countries and funded by Northern public funders or private donations. The Global Environment Facility is a funding body linked to the World Bank, set up in 1994 to support the implementation of a few major intergovernmental treaties, notably in the areas of climate, biodiversity, and land degradation. It is a financing body and as such not designed to set global environmental targets; instead, it shall work under the guidance of its governing council, with the conferences of the parties to the relevant multilateral treaties being the chief rule-setting bodies. Its new role as support of an Earth Commission to set earth system targets seems odd. Finally, the World Economic Forum is the not-for-profit foundation in Geneva that stands behind the Davos summits that bring each year corporate leaders, politicians, and selected civil society representatives together for informal meetings. It is governed by a group of individuals of which approximately half are representatives of the global business community and the others members of international organizations and civil society. Formally, the Global Commons Initiative works under the auspices of the global research network Future Earth, a hybrid platform that was formed around 2012 when funding agencies closed the then-existing four major global change research programs. Neither the Global Commons Initiative nor the Earth Commission is linked to those international institutions that are set up with the explicit purpose of defining the operating space for humanity: the conferences of the parties to the major multilateral environmental agreements, such as the United Nations Framework Convention on Climate Change—which agreed on a temperature target of 2°C maximum global warming—or the Convention on Biological Diversity with its separate set of targets. There is also no explicit link to the parallel set of 169 targets agreed under the 17 Sustainable Development Goals, the main outcome of the 2015 United Nations negotiations.

Despite the new terminology and broader approach, the basic concept of earth system targets is similar to the earlier planetary boundaries. Unlike the planetary boundaries, however, these new targets are planned to be disaggregated into specific, voluntary "science-based targets for Earth, specifically tailored to cities and companies" (**http://earthcommission.org**). The method of downscaling such earth system targets to smaller-scale actors such as cities or corporations is still to be seen. As research has shown repeatedly, such targets have been issues of major conflicts among nations that draw on different economic interests, social support, ethical values, and plain bargaining power.

At the time of writing, it is still unclear how this Earth Commission will eventually function: Will it engage in target-setting itself, function like a platform that plays a facilitative role, or simply publish global assessment reports similar to the *Global Environment Outlook* or those published by the Intergovernmental Panel on Climate Change? In the latter case, the question remains how the small commission will link up with the vast science networks working, for example, for the Intergovernmental Panel on Climate Change—who will soon provide the authoritative voice of science? Will the Earth Commission engage stakeholders in target-setting and how will those be chosen and legitimized? Will governments be involved in setting the global targets? Or, will these processes all feed into an intergovernmental process to politically decide on the targets? How will political conflicts between countries and regions be dealt with—for example, the conflict between the much more vulnerable low-lying island nations that see their own survival at risk by the 2°C global warming target that the community of governments has agreed as the main target in climate governance? What should and can science contribute in such value conflicts?

Despite all uncertainties around the eventual functioning of this new Earth Commission, two main conclusions seem appropriate to make. First, the institutional set-up and foundational documents behind this new Earth Commission still seem to follow a belief in value-free global change science: that science can conclusively resolve societal conflicts and set targets following the adage of "speaking truth to power." Second, it is striking that those organizations and institutions where developing countries have a key role to play—notably the intergovernmental institutions and the main United Nations agencies—seem to be effectively marginalized. Northern elite science (even if approximately one-third of the members of the Earth Commission are based

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in developing countries), major corporations—through the World Economic Forum—and World Bank facilities play a much larger role. Although the Earth Commission seems to be more oriented toward the Global South and more transdisciplinary than the group of professors that drafted the original 2009 planetary boundaries article, it is still debatable whether such a science-driven Earth Commission with an Earth Headquarters in Germany will generate in the capitals in Africa, Asia, and Latin America the much-needed legitimacy that effective earth system governance clearly requires.

CONCLUSION

How can we assess the overall impact of the planetary boundaries framework? In terms of pure citations and the breadth of debate, there is no doubt that this boundaries framework helped redefine the scientific discourse over the past decade. In a sense, the proposition of nine planetary boundaries reinitiated and clearly advanced older debates on planetary limits, and even though the core concept is no different from earlier notions of, for instance, guard rails, the planetary boundary idea added a new imaginary that reached beyond purely scientific papers to the world of policy-makers and civil society activists.

Numerous elements of the boundary concept helped in this success. The planetary boundaries provided a powerful visualization of a simple, intuitively understandable framework (155), helped by a powerful public relations team and eloquent proponents. The framework combined both positive and negative framings with a consolidating core message that, yes, there are boundaries that we must not surpass, but there is also a remaining operating space that can be safely navigated by societies and decision-makers. The rise of so-called planetary boundary thinking was also supported by the parallel emergence of the notion of the Anthropocene as the description of the current human-made epoch in planetary history. The planetary boundaries were actively propagated as the normative target corridor for human activities in the Anthropocene—if the Anthropocene discourse saw humans as the driving force on planet Earth, the planetary boundaries were framed as the direction, or rather, as the guard rails of the speed train of human development. The planetary boundaries had also a strong integrating impact on the global change research community by bringing together scientists who were before focusing separately on climate, biodiversity, land use, or ocean issues. Many scientists from diverse communities could find themselves and their work in the boundary framework, and if not, raised their voice and argued that *their* boundary was missing or misconstrued, which again led further support to the planetary boundary idea. As the normative frame for human actions in the Anthropocene, the planetary boundaries also found some support by social scientists, notably governance scholars and lawyers, who tried to think through how such boundaries could find their expression in actual governance and institutional practice.

But the concept of planetary boundaries has also shown its limitations and faces its own boundaries. Most importantly, it seems to lack strong political support from the Global South. The original concept was advanced by Northern professors, and the most recent incarnation as earth system targets set by an Earth Commission is unlikely to impress governments in developing countries. For governments in Africa or most regions in Asia, it is simply more helpful to leave the setting of global targets to those institutions where their voice matters and their vote counts, notably the conferences of the parties to global treaties and the United Nations agencies and committees. Most major treaty systems have established target-setting bodies (such as committees for scientific and technical advice) or are supported by bodies like the Intergovernmental Panel on Climate Change, and there seems to be no overriding reason for governments in the South to replace those intergovernmental processes controlled by their own diplomats and officials with

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earth system targets that groups of scientists now seek to define for freshwater use, biodiversity protection, land use, and forest cover.

In the end, the planetary boundaries concept and the more recent earth system targets cannot shed their conceptual links to the earlier discourses of limits, and all that comes with this discourse in terms of political critique and contestations. It still is a debate about who authoritatively decides on the societal operating space in the Anthropocene. Planetary-scale tipping points into dangerous new states of the earth system must be studied by science, and the science findings need to inform legitimized, widely accepted bodies such as the Intergovernmental Panel on Climate Change. The global targets that our societies will need to adopt, however, must be defined in political processes where all political stakeholders—especially from the Global South—are fairly represented. Although many proponents and researchers affiliated with the planetary boundaries approach simply seek to advance human understanding and help prevent global disaster, there is a danger that political processes that build on this concept create realities where the operating space of humankind is decided by professors, not by the people. Only when the planetary boundaries approach manages to clearly distance itself from planetary technocracy and a global limits discourse that is seen in the South as unfair given past colonialism and current Northern overconsumption will the justified debate on the risks of planetary tipping points gain the global political support that it needs.

SUMMARY POINTS

1. The planetary boundaries framework has been influential in generating academic debate and in shaping research projects and policy recommendations worldwide.
2. Numerous studies have sought to further refine and implement the planetary boundaries framework by downscaling planetary boundaries or applying the framework to global and national environmental assessments.
3. The definition of a safe operating space for humanity has stimulated many social scientists and international lawyers to explore what planetary boundaries thinking could imply for governance and the dominant paradigms of our time.
4. Yet the framework has also come under heavy scrutiny and been criticized from both natural and social sciences, humanities scholars, as well as the broader public and policy community.
5. In the end, the concept of planetary boundaries has shown its limitations in terms of political impact and faces its own boundaries. Most importantly, it seems to lack support from the Global South.
6. The experience with the planetary boundaries framework offers important lessons for the new Earth Commission with its work on setting earth system targets.

FUTURE ISSUES

1. More research is needed to explore implications of planetary boundaries for earth system governance and dominant paradigms such as economic growth.
2. Key research questions relate to the institutionalization, coordination, operationalization, and democratization of planetary boundaries.

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3. An important challenge remains regarding downscaling planetary boundaries to subglobal levels while taking global equity into consideration at the same time.
4. More attention could be given to governance challenges relating not only to staying within the safe operating space but also to muddling through the unknown and unsafe space outside planetary boundaries.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We thank for valuable comments on earlier versions of this article Aarti Gupta, Prakash Kashwan, Louis Kotzé, Chukwumerije Okereke, Marie-Catherine Petersmann, Carole-Anne Sénit, and the participants of a roundtable discussion at the 2018 Oaxaca Conference on Earth System Governance.

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Annual Review of
Environment
and Resources

Volume 45, 2020

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