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Planetary boundaries and earth system governance: Exploring the links

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ABSTRACT

This article discusses the concept of planetary boundaries that has been advanced by a group of leading experts around Johan Rockström. I place the concept of planetary boundaries in the larger framework of the emerging research paradigm of earth system governance, welcoming it as a crucial contribution that defines the overall goals of governance. Yet I also elaborate on the political conflicts that surround the identification of planetary boundaries, which are, in the end, a social construct. I then explore the policy and governance responses that may follow from the planetary boundary approach. In the conclusion, I point to several research challenges that flow from the current state of knowledge on planetary boundaries.

1. Introduction

Over the last two hundred years, humankind has evolved into a planetary force that influences global biogeochemical systems. No longer is the human species a spectator that merely needs to adapt to the natural environment. Humanity itself has become a powerful agent of earth system evolution. In particular global warming is proceeding rapidly. The snowfields on the Kilimanjaro might melt within a few decades, and the ice cover on the Arctic Ocean has shrunk by over 30% since satellite observations begun in 1979. Some scientists warn that major disruptions in the earth system could occur within this century (Steffen et al., 2004). The evidence of human influence on all planetary systems is such that stratigraphy experts are prepared today to formally classify the present time as a distinct epoch in planetary history, the "Anthropocene" (Zalasiewicz et al., 2008, 6, drawing on Crutzen and Stoermer, 2000).

This development poses one of the largest governance challenges ever. Policy-makers in the twentieth century gained much experience in managing confined ecosystems, such as river basins, forests, or lakes. In the twenty-first century, they are faced with one of the largest political problems humankind has had to deal with: protecting the entire system earth, including most of its subsystems, and building stable institutions that guarantee a safe transition and a co-evolution of natural and social systems at planetary scale. This challenge is increasingly referred to as earth system governance (Biermann, 2007; Biermann et al., 2009, 2010a, 2010b).

For this political task, the concept of "planetary boundaries", as suggested by Rockström et al. (2009), is a crucial contribution. Rockström et al. (2009) define inductively a number of 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. The threshold values are, to use a related concept, the "tipping points" in the system. Rockström et al. (2009) suggest boundaries for nine earth system processes, based on inductive research: 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. Eventually, this approach shall allow for the quantification of threshold parameters, which is then expected to guide political responses.

For some planetary boundaries, our current knowledge appears still too uncertain to allow for quantification. For other boundaries, however, Rockström et al. (2009) feel confident enough to suggest a numeric threshold value. In this endeavor, they err on the side of caution and a strict interpretation of the precautionary principle: where they see remaining uncertainties, Rockström et al. (2009) suggest the lower values for the boundary that they identify. Taken together, the nine planetary boundaries define what Rockström et al. (2009) describe as a "safe operating space for humanity".

An important insight of their assessment is that three threshold values have been crossed: Regarding climate change, we have reached atmospheric carbon dioxide concentrations of 390 ppm (compared to 280 ppm in preindustrial times), whereas the threshold value proposed by Rockström et al. (2009) would lie at 350 ppm. Regarding biodiversity, the current extinction rate is over 100 extinct species per million species per year, while the suggested threshold would be 10 extinctions. As for the nitrogen cycle, humans remove today about 121 million tons nitrogen per year from the atmosphere, while a safe rate would be, according to the planetary boundary concept, a maximum of 35 million tons. In these three areas, therefore,

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humankind has pushed the earth system past tipping points into a new—and unknown—world.

The approach by Rockström et al. (2009) is part of a broader line of research in the earth system sciences. The approach is similar, for example, to the earlier notion of "guard rails" and "tolerable windows" that was developed in the late 1990s by the German Advisory Council on Global Change (1997, 2000) in collaboration with the Potsdam Institute for Climate Impact Research. As argued then by the German Advisory Council (2000, 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 guardrail had been the target of a maximum average global temperature increase of 2 °C, which is today accepted by most governments. More broadly, all current work on critical transitions and tipping points in the earth system closely relates to the planetary-boundaries approach. Tipping elements are defined as parts of the earth system that can be switched by small perturbations under certain circumstances into a qualitatively different state (Lenton et al., 2008, 1786). Tipping points refer to the critical values at which the state of the system is qualitatively changed. At present, our knowledge about such tipping points is preliminary at best, and substantial research is directed at the identification of early-warning signals for such critical transitions in the earth system (Scheffer et al., 2009).

Despite some differences in approach, perspective and research trajectory, all of these notions of planetary boundaries, guardrails, tipping points and critical transitions come down to the same basic idea: the attempt at a quantified identification of the boundaries of the safe operating space of humankind on planet Earth.

In this article, I discuss the value of the concept of planetary boundaries from the perspective of earth system governance research. Section 2 places the concept of planetary boundaries in the larger framework of the earth system governance research agenda. In Section 3, I discuss the politics of identifying planetary boundaries, while Section 4 then explores the policy responses to this approach. Section 5 concludes and points to some research challenges that flow from the current state of knowledge on planetary boundaries. This contribution seeks to essentially provide a commentary on the widely received concept of planetary boundaries. For a more extensive treatment of the governance challenges and research needs in this area, see Biermann et al. (2009, 2010a, 2010b).

2. Earth System Governance and the Concept of Planetary Boundaries

From the perspective of earth system governance research, the main contribution of the notion of "planetary boundaries" lies in the crucial specification of environmental target indicators.

Earth system governance builds on the assumption that humankind, having become inadvertently an agent in the earth system over the last 200 years, has now to develop the governing mechanisms to purposefully steer its own agency. Earth system governance is of course not about "governing the earth", or about managing the entire process of planetary evolution. Earth system governance is concerned with the *human impact on planetary systems*. It is about the societal steering of human activities with regard to the long-term stability of geobiophysical systems. But the latter is non-trivial: What *precisely* are the goals of earth system governance? In what *concrete* directions should human agency develop? What are the normative assumptions that underlie earth system governance?

The traditional approach in political discourse is the reference to sustainable development as the final goal of governance. The most influential definition of this concept, widely accepted today, has been elaborated by the World Commission on Environment and Development (1987): "Humankind has the ability to make development sustainable—to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs". Yet this definition is broad, and was meant to be broad (Robinson, 2004). As summarized by Kates et al. (2005, 10), "[t]his malleability allows programs of environment or development; places from local to global; and institutions of government, civil society, business, and industry to each project their interests, hopes, and aspirations onto the banner of sustainable development". To provide more focus, it is common to distinguish three pillars of sustainable development. For example, the Johannesburg Declaration adopted at the 2002 World Summit on Sustainable Development posited a "collective responsibility to advance and strengthen the interdependent and mutually reinforcing pillars of sustainable development—economic development, social development, and environmental protection—at local, national, regional, and global levels". Yet how these three pillars are to be weighted and defined in concrete cases—for example climate change or biodiversity depletion—remained undefined, and there is hardly any consensus about this in either academic or political communities.

It is here, I argue, where concepts such as "planetary boundaries", "guardrails", and "a safe operating space for humanity" become useful. The nine planetary boundaries suggested by Rockström et al. (2009) define an overall environmental target corridor for earth system governance.

Importantly, within this overall target corridor, the nine boundaries leave human societies ample space for different political choices and socio-economic development trajectories. These socio-economic development trajectories—within the safe operating space set by the planetary boundaries—are left open to the democratic political process and intergovernmental negotiation. In this sense, the nine planetary boundaries are just one element of the overall policy objective of sustainable development. They define the broad boundaries and "guardrails" for human development. They are in principle neutral towards human values and aspirations, in the sense that they represent a set of (increasingly supported) hypotheses about causal relationships in the earth system, for instance about the likelihood of the shut-down of the thermohaline circulation under certain greenhouse gas concentrations. The planetary boundaries do not determine any "limits to growth", but set limits to the total human impact on planetary systems.

In fact, many political trajectories for societies are conceivable to stay within the target corridor as defined by the nine boundaries. In theory, the non-violation of the planetary boundaries could be achieved even by Malthusian, totalitarian, plutocratic or oligarchic political systems, or any combination of them. Yet such political systems would conflict with important other policy goals such as democracy, human rights, and human freedom. In such circumstances, therefore, environmental effectiveness would be incompatible with important goals such as human development and social justice, which are usually seen as part of the broader notion of sustainable development. In short, the concept of planetary boundaries defines the environmental target corridor within the larger context of sustainable development, and serves as policy target only with this broader social context. (A related question that cannot be expanded here is whether democratic deliberation and the protection of human rights are *an essential prerequisite* for effective environmental protection, which would make them an *inherent part* also of the strive for non-violation of planetary boundaries; see here for example Dryzek and Stevenson, 2011).

Three issues have been brought forward as possible problems regarding the concept of planetary boundaries, but seem unlikely to limit the concept's value: lack of precision, lack of reversibility, and complexity and interlinkages. The problem of interlinkages I discuss in Section 4 in more detail.

Irreversibility of change is about whether a system can return to a previous state after a major perturbation. The systems covered under the nine planetary boundaries differ in this respect. Yet for the purposes of guiding human behavior and protecting human interests, this difference in irreversibility of change is less relevant. Even if system parameters would return after major disruptions at some point to the "Holocene state", harm to human societies would likely be dramatic and irreversible.

The overall lack of precision in the scientific basis for some boundaries will be less important as long as the boundaries are supported by a wide consensus among scientists and policy networks. In fact, it is part of the strength of the concept of planetary boundaries to try to quantify planetary boundaries despite uncertainties and problems. Even though quantification of planetary boundaries will always be based on scientific foundations that may become more certain but never fully certain, the suggested quantification of the nine boundaries has the potential of evolving into a powerful political narrative, comparable to other policy domains. The success of the world trade regime, for example, is related to the simplicity of its commitments, including its quantitative targets for the reduction of custom obligations. In the environmental sphere, the 2-degree Celsius target for global warming may defy any precise calculation and reasoning, but became nonetheless a powerful narrative for change and for galvanizing action at local and—despite the current stalemate in negotiations—global levels. Other simple indicators, for instance the presence of certain species as indicators of healthy ecosystems (tigers, salmon), have become simple yet powerful symbols that have oriented political action towards resolving much more complex underlying issues, such as river pollution or ecosystem degradation.

Nonetheless, at present the political use of the concept of planetary boundaries is probably still limited. More integrated scientific assessments will be needed to translate the concept into a basis for concrete political negotiations. So far, the nine planetary boundaries identified by Rockström et al. (2009) offer an important conceptual framework for a research and assessment program, rather than a clear guideline for political action. Rockström et al. (2009) readily admit that the science behind the quantification of target values along the nine planetary boundaries is still contested, and several boundaries are identified but not quantified. This limits their use, at present, for political decision-making, even in the core realm of climate change, where the scientifically suggested target of 350 ppm might conflict with the emerging current consensus within the political system that appears to be more risk-taking. However, this is not a conceptual but an empirical problem. In the longer term, the framework suggested by Rockström and colleagues is likely to develop into a powerful political narrative.

3. The Politics of Planetary Boundaries

Let me add some water to the wine. While the concept of planetary boundaries is normatively neutral, its operationalization is not. The scientific determination of planetary boundaries is, as most scientific assessments (Jasanoff and Long Martello, 2004; Mitchell et al., 2006), a political process. It has to be understood, and to be analyzed, as such. I discuss two examples.

First, the exact definition of planetary boundaries depends on normative assumptions about the risks that we, as humankind, are taking. Planetary boundaries assume the actions of the human species as a collective that is able, and willing, to take joint action. Yet the human species, as main driving force of the Anthropocene, is in itself utterly divided in wealth, health, living standards, education, and most other indicators that define wellbeing. Three billion people live on less than 2.5 USD per day (Chen and Ravallion, 2008). According to the World Bank, the richest 20% of humanity account for 76.6% of total private consumption. The world's richest people—the 946 billionaires—are worth 3.5 trillion USD (Kroll and Fass, 2007), which equals around 6% of global gross domestic product and is more than double the gross domestic product of India or of the entire African continent. On the other hand, the poorest 20% of humanity account for just 1.5% of global wealth. The life of this "bottom billion" of humanity is harsh, with 850 million people being undernourished. The poorest 25% of humanity—including 706 million South Asians and 547 million Africans—has still no access to electricity (UNDP, 2007).

It is in this global situation of large inequalities in resources and entitlements in which the definition of planetary boundaries needs to be agreed upon. Global inequalities could translate, for example, into conflicting perspectives on the underlying uncertainties and risks. Richer societies might prefer a risk-averse approach, conserving the world as it is, and preventing any harm. Poorer societies, on their part, might be more risk-taking, prioritizing economic development to alleviate poverty. Yet the interest constellation, if differently framed, could also be the other way round. Conservative threshold values—such as the 350 ppm threshold in atmospheric carbon dioxide concentration that Rockström et al. (2009) suggest—will require most efforts first from those who pollute most, that is, the richer societies in the North. On the other hand, system disruptions because of violated planetary boundaries will cost most, in relative terms, to poorer societies, which are most vulnerable and have the least means to adapt. It is thus the poorer island developing countries that are often most demanding in international climate negotiations, pushing for the lowest possible concentration targets for greenhouse gases. In short, the negotiation of the exact planetary boundary in any of the nine domains identified by Rockström et al. (2009) is not simply a matter for scientists—it is also a *political* boundary that needs to be negotiated by political actors who have to weigh scientific evidence and degrees of uncertainty with their own assessment of the risk to be taken and the costs to be endured. The planetary boundaries are, despite all accuracy in our measurement, in the end also a social construct.

As a second example, the definition of boundaries is more complex, and politically more problematic, in some areas than in others. Stratospheric ozone depletion gives societies relatively little freedom; here, the scientific assessment should, and in fact has, directly led to political action. Yet in the case of land use change, for example, the value that Rockström et al. (2009) suggest—at most 15% of global land cover should be converted to cropland—could be more debatable, given that every day, twenty-thousand children die because of poverty and about a third of all children in developing countries are underweight (UNICEF, 2004). Also the planetary boundaries for global freshwater use seem problematic and are surely a question of sufficient access and fair allocation. Today, one billion people lack sufficient access to water. 2.6 billion people have no basic sanitation (UNDP, 2006). Also the definition of the acceptable planetary boundaries needs to be seen in this light.

Given that the translation of the concept of planetary boundaries from assessment to action needs to be done in political negotiations and agreements, the role of scientists is affected, too. Since the assessment of planetary boundaries is inherently political, scientists involved in this process become inadvertently also political actors. This raises fundamental questions about the legitimacy and accountability of scientific assessment processes (see the contributions in Mitchell et al., 2006). The history of the Intergovernmental Panel of Climate Change, which evolved from a small group of mainly natural scientists from industrialized countries into a vast, highly institutionalized network of thousands of experts, is the best known example, where science became intermeshed with governmental oversight, geographic quotas, political conflicts, and in the end very fundamental questions about what science is, and who may count as a scientist (Siebenhüner, 2002a, 2002b; on the most recent developments see Berkhout, 2010).

4. Consequences for Governance

The systems defined by the nine planetary boundaries are interrelated. Rockström et al. (2009) emphasize that failure in addressing one boundary might negatively affect others. In the interlinked social and ecological systems of planet earth, nothing remains independent, and complexities and interconnections abound. But how does this relate to the governance of these systems? I argue here that interconnections between issues do not necessarily need to translate into general, all-encompassing institutions, nor into special institutions to govern the interactions and connections.

To start with, the graphical representation of the nine planetary boundaries might suggest that for each boundary, a distinct institutional response is needed. From the current empirical experience in earth system governance, however, such institutional reorganization does not seem convincing. Instead, the effective governance of specific types of social behavior that may contribute to the violation of a planetary boundary can—and in many cases should—be limited in scope and cover only parts of the overall human impacts. For example, the 1971 Convention on International Trade in Endangered Species of Wild Fauna and Flora—which is part of the overall effort of limiting loss of biodiversity—has proven to be relatively effective, despite governing only a limited set of species and only one activity (that is, trade). The 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter was equally powerful despite its limited scope. Even more limited has been the regime on protecting polar bears, involving only very few nations. Thus, it is unlikely that a targeted approach that follows the notion of planetary boundaries—for instance, one global institution for each boundary—would prove overall more effective. Issue-specific, tailor-made solutions appear in general more promising.

This does not imply, however, that specific rules are not needed to address interactions. The most salient issue is the conflict between the Kyoto Protocol and the various institutions that protect biological diversity, notably regarding the governance of aforestation. These normative and institutional conflicts require urgent resolution; yet it seems likely that they can be better addressed by the development of overarching principles, coordination policies, or the influence and steering role of central international organizations than by creating new specific institutions at the interface of distinct planetary boundaries.

Important here is also the distinction between cumulative and systemic problems (Turner et al., 1990). Systemic problems often require larger actor coalitions at the outset of cooperation; stronger non-compliance management; and stronger incentives for less interested actors through positive side-payments. Cumulative problems can be governed, at least initially, by smaller coalitions of countries, in more fragmented governance systems, and they require less strict and powerful non-compliance mechanisms. However, problematic with cumulative problems is that they often require action only, or especially, by a small group of countries. If this group of countries lacks the means or the (relative) interest in taking powerful action, the provision of the overall public good is threatened unless other countries increase their efforts by means of support and side-payments. The deadlocks in the governance of the cumulative problems of desertification or deforestation—both centering on relatively small groups of often poor countries—are examples.

In sum, I argue that political institutions should follow social activities, not necessarily planetary boundaries. In some cases, social activities are directly related to the planetary boundary, as in the case of stratospheric ozone depletion. In some cases, global interdependencies might require a global "grand bargain" and hence a strong global institution in one area, as in the case of climate change. In other cases, however, issue areas are more disparate, conflict lines are overlapping, and causation diffuses. Here, as in the case of biodiversity or land use change, a network of focused institutions might be more effective.

There is one area, however, where institutionalization could, and should, follow the planetary boundaries. This is the area of scientific assessment. Here, the complexities of multi-causality and multiple consequences require indeed an integrated, interdisciplinary assessment. Assessment institutions such as the IPCC are highly valuable, and it is here where the concept of planetary boundaries requires an institutional response by means of the creation of distinct assessment processes for the nine boundaries. In a sense, Rockström et al. (2009) have done exactly this in the vast network of experts that they have consulted for their paper. This approach needs to be followed up by an even more intense research and assessment process to further define, and refine, the nine planetary boundaries that have been identified so far. One recent step in this direction is the creation in 2010 of an Intergovernmental Platform on Biodiversity and Ecosystem Services through the UN General Assembly, modeled somewhat on the success of the IPCC.

How to ensure the overall governance integration of all nine boundaries? Here, overarching principles are needed to govern the interaction between different institutions, to regulate norm-conflicts between these institutions, and to increase efficiency and effectiveness by providing for general standards of behavior (such as the principle of common but differentiated responsibilities) or general institutions and organizations (such as integrated funding mechanisms like the Global Environment Facility, or joint mechanisms of custom control). Many of the different issue areas of world trade law are regulated under the overarching principles enshrined in the Agreement on Establishing the World Trade Organization. Similar overarching agreements could also be conceived for the governance of the earth system and the protection of the planetary boundaries. However, this would take the form of general statements of principles and the set up of scientific assessment and advisory bodies rather than of a more detailed global framework agreement that covers all boundaries.

A special role will lie with international organizations as integrating actors. International organizations and their bureaucracies would have a key responsibility in assessing the interlinkages between the target corridors described by the concept of planetary boundaries and in advancing governance solutions if needed. The staff and governing bodies of such organizations could identify negative and harmful interactions between institutions, and propose, negotiate and implement counter-measures. They could identify un-governed yet important areas of social behavior that might threaten to contribute to a violation of planetary boundaries. They could also assess to what extent existing programs and measures are likely to guarantee that identified planetary boundaries are not violated—this task would be implemented, as mentioned, by the creation of issue-specific IPCC-like science-institutions.

The United Nations Environment Programme, as the "consciousness" and "catalyst" for environmental action within the UN system, is the obvious actor to be entrusted with such a set of tasks. However, given the existing shortcomings in the influence of the program, its transformation into a stronger specialized agency of the United Nations—as a World Environment Organization or United Nations Environment Organization (Biermann, 2000; Biermann and Bauer, 2005)—would increase the likelihood that this central actor could assist in identifying and addressing social behavior that threatens to violate planetary boundaries.

A final yet intriguing political consequence of the notion of planetary boundaries is relationship with traditional concepts of state sovereignty. What are the political consequences when full consensus of all nations is not attainable? How should one judge, from a theoretical perspective, the position of a minority of countries that do not seek to comply by certain measures to protect planetary boundaries that a majority of countries see as fundamentally required? In essence, this is the question of state sovereignty in the Anthropocene. While it seems neither feasible nor desirable to abrogate fully from

the sovereignty principle, it appears questionable whether full national sovereignty can be upheld for the most essential environmental standards that are needed to protect the planetary boundaries. One example is the prohibition of producing chlorofluorocarbons that destroy the stratospheric ozone layer. In such cases, one needs to differentiate between classes of international legal standards; namely, those that are so essential that no abrogation may be permitted, and those that nations can freely choose whether to adhere to. This argument could draw on existing concepts in international law such as peremptory norms, so-called *jus cogens*. The concept of *jus cogens* essentially restricts the sovereignty of states regarding the creation of international law (Verdross, 1966). Article 53 of the 1969 Convention on the Law of Treaties (1969) states that any treaty is void if it conflicts with a "peremptory norm of general international law". Those are norms that are "accepted and recognized by the international community of States as a whole as a norm from which no derogation is permitted and which can be modified only by a subsequent norm of general international law having the same character". Not every rule of customary environmental law will qualify for the status of *jus cogens*. This would blur the distinction between general custom and peremptory norms. Applying the criteria of article 53 to different types of environmental pollution, certain standards that are fundamental to preserve and protect the nine planetary boundaries would fall under the injunction of *jus cogens*. The emission of chlorofluorocarbons contrary to the provisions of the Montreal Protocol would be a case with widely agreed and quantified commitments. Importantly, obligations under the Montreal Protocol are differentiated between industrialized and developing countries.

The practical effect of endowing core norms of earth system governance with the superior status of *jus cogens* is difficult to assess. Such distinctions would apply if environmental conflicts were submitted to international tribunals or to the International Court of Justice, which seems at present to be rather unlikely. The notion of peremptory norms might also help galvanize action at the national or global level and increase pressure on countries that refuse to contribute to widely agreed global efforts for example of limiting greenhouse gas emissions. Such norms could also guide decision-making in other policy areas, for example when it comes to assessing the legality of environmentally motivated trade restrictions. Eventually, the high relevance of protecting the planetary boundaries and the safe operating space of humankind could also lead to a reconsideration of the procedural underpinnings of international negotiations towards (qualified and possibly weighted) majority voting (Biermann and Gupta, 2011). Yet regardless of the practical implications for present political processes, it is certain that the concept of planetary boundaries will eventually also have a major influence on both legal and political theorizing regarding limitations of the sovereignty of nations.

5. Taking the Planetary Boundaries Seriously: Further Research Questions

Finally yet importantly, one important consequence of the definition of planetary boundaries is that urgent action is required. If we take the assessment by Rockström et al. (2009) seriously, it is evident that at least three boundaries have been crossed by human action. Here, humankind has left its safe operating space and entered unknown territory. Especially regarding greenhouse gas emissions into the atmosphere, humankind is engaging in the largest collective experiment ever: pushing greenhouse concentrations to levels that are unprecedented throughout the entire period of human development in the last 400,000 years, and global mean temperatures to unknown heights. And as with all experiments, the outcome is unknown. This places three additional items on the research agenda.

First, we have to increase our efforts to understand global adaptation governance. To what extent are local, national and global systems of governance, as well as systems of production, distribution and consumption, prepared for a world characterized by parameters that differ from the 10,000 years of experience in the Holocene, which saw the rise of human civilization? While a substantial research trajectory has studied the adaptability of local and country-level social and ecological systems, this research is still in very early stages when it comes to the adaptability of global systems of governance, including the UN system. The current discourses range from a securitization of global climate change in the tradition of political realism to the search of avenues for further (global) institutionalization in this domain. More research in this area is clearly needed (Biermann and Boas, 2010).

Second, we have to advance our understanding of non-linear, rapid social transition processes and "social tipping points". Unless major technological breakthroughs materialize soon, it is likely that current patterns of production and consumption need to change fundamentally. Both command-and-control and economic instruments are unlikely to achieve these changes unless accompanied by large-scale transformations in life-styles and common perceptions of the good and rightful way of life. Such large-scale changes of life-styles are probably non-linear, which gave rise to the new terminology of "social tipping points" as a narrative to describe factors that initiate such changes. There are ample experiences in drastic changes in perceptions of good and rightful life-styles, often motivated by religion, national renaissance (for example, Gandhism), or philosophy. In Roman times, stoic philosophy led even an emperor, Marcus Aurelius, to sleep on a stone bench in order to comply with notions of a simple, or simplified, life. Environment-related changes in public perceptions of the good and rightful living include the public ban on smoking as inappropriate behavior for movie actors, politicians and other perceived role models; the change in perception of whale-meat consumption that is hardly affected by a recovery in species stocks; and the rising social movement of vegetarianism. Such large-scale transitions in social perceptions of good and rightful behavior are unlikely to be "manageable" by public intervention. However, how public policy can contribute to initiating such changes, and to help identify "social tipping points", remains a major research frontier. As also argued by Lenton et al. (2008, 1792), what we need is to study "potential tipping elements in human socioeconomic systems … especially to address whether and how a rapid societal transition toward sustainability could be triggered". In short: staying within planetary boundaries might require breaking through societal boundaries.

Third, more research on geo-engineering cannot be avoided. One may like it or—for reasons of a risk-averse, precautionary approach—dislike it, but the discourse on geo-engineering is certain to grow in resonance and relevance, largely because of the slow progress in current global negotiations on a successor agreement to the Kyoto Protocol. Should we massively pump iron into the Southern ocean to increase algae production, as Gribbin proposed twenty years ago (Gribbin, 1988)? Should we inject sulfur into the atmosphere to increase albedo, as Paul J. Crutzen (2006) and others have proposed? Research on the social, political, economic and environmental implications of such visions of large-scale geo-engineering is difficult and has hardly started. Among other complications, each proposed measure of geo-engineering entails different combinations of academic disciplines and bodies of knowledge in the social sciences, ranging from the specialist areas of the law of outer space to the law of marine dumping and use of the high seas. Nonetheless, such research will quickly gain relevance, not the least due to a political discourse that urgently requires scientific scrutiny and critique.

In sum, the concept of planetary boundaries is highly valuable for the larger purposes of earth system governance. It defines the operating space and core target corridors for human development, and is hence an important element in the study of earth system governance. Yet the intriguing precision and appearance of certainty in defining planetary boundaries should not let us forget that the political interpretation of boundaries will, in the end, have to remain with societies,

at both national and international levels. The concept of planetary boundaries does not necessarily require grand institutional designs, as they are sometimes found in op-eds and press announcements, or ideas of rational rule by scientists, reminding of Plato's philosopher kings. Research on planetary boundaries helps societies to understand the fundamental processes of planet Earth, and the likelihood that certain changes in system parameters might trigger large-scale perturbations. The political interpretation of this research is left to societies and their modes of deliberation and decision.

And in this deliberation, one crucial factor needs to be that the earth system is, and will remain, full of "surprises". It may bring about (possibly abrupt) changes based on system parameters that we do not yet fully understand (Lenton et al., 2008). The history of earth system research asks for humility in the accurateness and early-warning function of science. At the first major global environmental governance conference—the 1972 Stockholm Conference on the Human Environment—none of the major earth system challenges that we discuss today was on the agenda. And this was merely forty years ago. Hardly anybody talked then about ozone depletion, climate change, desertification, or the mass extinction of species. In the case of stratospheric ozone depletion, we already had a "near miss", that is, an (almost) crossing of a planetary boundary and sudden transition in a tipping element of the earth system that was only recognized at a rather late stage in the process. Our luck was that the planetary boundary was discovered late, but not too late. To quote one of the key actors in this drama, Nobel Laureate Paul Crutzen, "Do not assume that scientists always exaggerate; the ozone loss over Antarctica was much worse than originally thought" (Crutzen and Ramanathan, 2004, 280). Research on planetary boundaries is hence vitally important. It deserves the full attention of scholars and decision-makers alike.

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