



Response to Rockström *et al.* 2009. “Planetary Boundaries: Exploring the Safe Operating Space for Humanity”

## On the System Properties of the Planetary Boundaries

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### THE PLANETARY BOUNDARIES

Rockström *et al.* (2009) identified a set of critical sustainability issues where perturbations resulting from human activities present a risk of unacceptable global environmental change. They attempted to quantify a boundary level for each one, using the range of variability observed during the Holocene as the marker for the safe operating space for humanity. Together, the set of boundaries (Table 1) represents an important conceptualization of global sustainability through the lens of resilience and Earth system science, already influencing research and policy agendas worldwide. Rockström *et al.*'s (2009) multidisciplinary expert deliberative process took into account several decades of Earth system research, and their text frequently signals the profound influence of systems approaches in their analysis (notably Supplementary Discussion 1). However, their article is not explicit about the system properties of the boundaries themselves, resulting in conceptual tensions, discussed below. Debates remain about the definitions of the boundaries and what kinds of measures should be control variables (e.g., Carpenter and Bennett 2011). Systems analysis approaches provide a theoretical containing structure for these debates as the boundaries are redefined or refined, and for the further development of the planetary boundaries concept.

The planetary boundaries include systemic processes that manifest themselves at the global scale, and environmental issues that become critical global problems when they are aggregated from the regional or local scale. Rockström *et al.* (2009) noted this scale aspect in their article. They also recognized that the issues they identified do not all show the same system character, so they further categorized the issues into those that show threshold behavior (that is, where change can trigger an abrupt, non-linear response), and slow processes that do not show clear thresholds. However, this categorization leaves us with awkward conceptual challenges for the kinds of issues that are local-to-regional in scale and threshold-less. These include social-ecological issues that have clearly manifest themselves as critical sustainability concerns at the global scale, such as biodiversity loss and chemical pollution. The simple scale/speed categorization means that the theoretical justification for a planetary boundary for these issues has remained comparatively weak. The inclusion of

slow processes for which there is “no current evidence of planetary scale threshold behavior” was justified on the grounds that they “provide the underlying resilience of the Earth system” by regulating the fluxes of carbon, water, nutrients, and minerals. While this is true, it does not explain why these issues were selected rather than any other locally problematic environmental issue, nor does it steer scientists towards identifying and remedying any strategic gaps in the overall evidence-base for humanity’s safe operating space. Extending the operationalization of the concept, both in research and as a policy engagement framework, requires this shortcoming to be addressed.

**Table 1.** The planetary boundaries (Rockström *et al.* 2009), their control variables, and the scale at which they are mainly observed.

Issue	Control variable	Scale
Climate change	CO <sub>2</sub> concentration and radiative forcing	Global
Ocean acidification	Surface ocean CO <sub>3</sub> <sup>2-</sup> saturation state	
Stratospheric ozone depletion	Ozone concentration	
Perturbed biogeochemical flows	Human-induced phosphorus inflow to ocean; fixation of atmospheric N <sub>2</sub> to bioavailable forms	Regional
Atmospheric aerosol loading	Not quantified (regional particulate concentration proposed)	
Global freshwater use	Annual volume of water used in human activities	
Land system change	Percent of Earth’s land converted to cropland	
Biodiversity loss	Global species extinction rate	Local
Chemical pollution	Not quantified (concentrations and effects considered)	

### APPLYING ECOSYSTEM ANALYSIS CONCEPTS

It may be helpful to revisit the system properties of the issues for which boundaries have been defined. Clarity about different system entities and their relationships is a prerequisite to any development of explanations of how the system may be influenced by internal or external events. However, part of the power of the planetary boundaries

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concept arises because it is not laden with structurally complex information (nor dense jargon). Its simplicity means it can be immediately and intuitively grasped. Ideally, theoretical developments to the concept will retain this operational and conceptual appeal, even as they enable a more dynamic understanding of the capacity of the natural environment to provide resources and services that meet human needs, directly or indirectly.

Here, simple concepts from environmental systems analysis as articulated in de Groot et al. (2002) are used to distinguish four system aspects: structure, process, function, and service (Table 2). De Groot et al. (2002) share a perspective with Rockström et al. (2009) in that they are concerned with global social-ecological sustainability. Indeed, this typology is well-known to several contributors to the original planetary boundaries article, and its tacit influence can often be seen (e.g., "...the importance of biodiversity for sustaining ecosystem functioning and services", p.14).

**Table 2.** The de Groot et al. (2002) typology for the capacity of the natural world to meet human needs.

Structure	Process	Function	Service
The biotic and abiotic components that make up ecosystems (and the Earth system)	Flows of matter and energy mediated through the interactions of the biotic and abiotic parts of the system	The ecosystem's capacity to regulate and sustain its structures and processes	The benefits derived by humans from a well-functioning ecosystem

Using this typology, we can then more clearly categorize the kinds of Earth-critical issues to which the planetary boundaries concept can be applied. In the article, thresholds are defined more narrowly than they need be (c.f. Prigogine and Stengers' [1984] rich exploration of the behaviors of both simple and complex systems) as "non-linear transitions in the functioning of coupled human-environmental systems" (p. 2), around which a normative judgment can be made about the boundary. The de Groot et al. (2002) typology suggests complementary rationales for determining boundaries. For example, we can distinguish:

- aggregate structural effects causing essentially irreversible undesirable impacts on processes or ecosystem function (biodiversity loss, land use, cumulative pollution)
- run-away behavior in the process itself (climate and its biophysical feedbacks; ozone depletion as a chain reaction)
- critical thresholds in the functions affected by the changing process (biogeochemical perturbation leading

to ecological regime shifts; aerosol loadings altering climate patterns)

Explicitly making this distinction helps explain why certain issues really should be included as planetary boundaries—even though they may not show non-linear behavior—and helps in making the concept more operational. It enables us to treat the different kinds of system risks in more targeted ways: it points us towards the kinds of places where these risks may appear, and should inform our identification of better (more robust or sensitive) measures for tracking society's progress in reducing the planetary pressures that the boundaries represent. Specifically, it helps us focus on the kinds of indicators of change that are likely to be robust as control variables. Rockström et al. (2009) said their criteria were that the control variables should be "comprehensive, aggregated and measurable". The de Groot et al. (2002) categorization provides a way to determine what might be comprehensive or aggregated "enough", and to propose what might need to be measured in order to constitute a reliable, responsive control variable.

It also takes us a step towards clarifying what might be fundamental system entities in the current social-ecological configuration of our Earth, and those that emerge from the connections and dependencies between entities. If human interventions are going to have any positive effect on global sustainability, the dynamic behavior of the boundaries and their interactions needs to be understood. This approach lets us begin to consider system interdependencies that link the critical sustainability issues identified in the original planetary boundaries papers. We know these interdependencies exist and are likely to magnify the risks of transgressing any single boundary, but we still lack conceptual tools for the feedbacks and interactions between these global-scale concerns. An environmental systems analysis framing lets us state and explain why a functional change is contingent on a structural change, and to some extent lets us predict how structural changes will have consequences on processes, functions, and services. It can help us structure model investigations—and perhaps new global models—in ways that will let us explore the potential risks of multiple simultaneous stressors.

In a related area of concern, we are struggling conceptually with how to propose robust boundaries for issues that are spatially distributed heterogeneously around the world. Part of the answer relates to the potential geographic specificity of process and function—the primary concern is not the physical intervention in the structure itself. Thus for instance, deforesting the equatorial/tropical Amazon basin really might be more of a planetary cause for concern than land use change over an equivalent area elsewhere, not because of what it materially consists of nor the area involved, but because of the interplay of that particular patch of vegetation with the processes influencing global water and energy balance. Similarly, the human perturbation of biogeochemical flows of

essential nutrient elements matters more in places where ecosystem function is jeopardized (although we also need to be aware of the profound anthropocentricity of the judgments we make about places where there is too little nutrient), and in some places, these changes in function have global consequences. By distinguishing flows from functions (and indeed ecosystem services), we can start to refine our definition of an actual biophysical threshold and the normative boundary of the safe operating space for humanity.

Finally, this systems analysis approach also provides a framework for linking the planetary boundaries concept more explicitly to understandings of the human dimensions of global change. The original papers were framed almost exclusively in the language of biophysical changes, even though the critical sustainability issues identified are fundamentally the consequence of human action, and the reason they were identified as global causes for concern is that they present risks to the current configuration of the human enterprise. A substantial area of critique of the planetary boundaries concept focuses on this elision. The structure-process-function-service trajectory takes us from the biophysical to the social dimensions of global sustainability. It also reminds us that Earth's ecosystem services are fundamentally dependent on a well-functioning whole nature. Thus, an environmental systems analysis approach to the planetary boundaries concept can provide an important complement to the current ecosystem services discourse, which often seems to elide the biophysical reality, as evidenced in the much-discussed trade-offs of ecosystem services that implicitly assume that the multiple environmental benefits enjoyed by human society can both stand alone in some way and also be substitutable one for another (e.g., Rodríguez et al. 2006). Regardless of differences of opinion about the utilitarian slant of the ecosystem services discourse and the practical and geopolitical realities of its operationalization, it shares a powerful conceptual impact and politically mobilizing dynamic with the planetary boundaries concept. Finding more effective ways to link these concepts in a theoretically coherent way will present a valuable contribution to our collective efforts towards global ecological integrity, social equity, and economic well-being.

*Responses to this article can be read online at:*  
<http://www.ecologyandsociety.org/vol17/iss1/resp2/responses/>

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