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Planetary boundaries revisited: a view through the 'water lens'

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The recognition of the limits of Earth resources is a key to understanding the capacity of our planet to support a large and expanding human population with aspirations for improvements in well-being. This paper contributes to the ongoing debate on Earth system limits through a water focused crucial review. We argue that the degree of human appropriation of abiotic planetary and biotic ecosystem-based resources offers a useful framework to define sustainability, once societal aspirations and technology are taken into account. In this context, a 'triangle' consisting of coupled planetary, ecosystem-based Earth resources, and the human appropriation and stewardship may offer a pragmatic conceptual model for planetary sustainability with respect to freshwater. Because of these linkages, we find this new approach better suited to support policymaking for sustainability than a series of single-valued planetary boundary (PB) thresholds. To demonstrate the utility of the proposed approach, we explore human appropriation of water in the food production, industrial and domestic water sectors considering and modifying previously reported assessments. We do this for freshwater resources in light of anticipated population and economic growth. We find that a significant intensification of human appropriation of water will be necessary to support anticipated basic services and wealth generation over the coming decades. Furthermore, we foresee a major expansion of degraded water systems unless conscious preventive investments or costly remediation of impaired water quality are implemented. In this context, we see the need not only for technical innovation but improved governance as well.

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Introduction

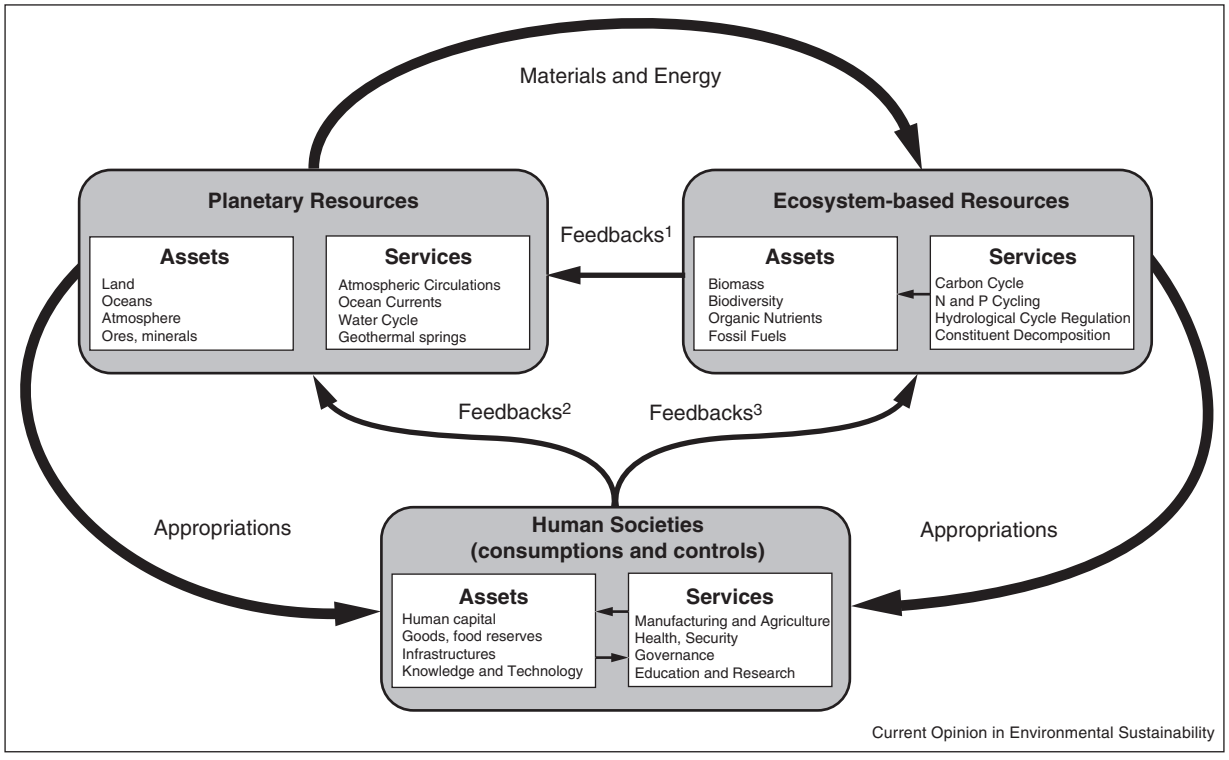
Collapses as a result of exhausting resources are not unprecedented in the history of human civilization, but occurred as isolated cases [1•,2]. The specter of a breakdown potentially affecting the whole planet represents a new challenge for humanity. The quest to identify the Earth's limits is almost as old as the realization that our planet is a 'sphere' and hence finite. From Malthus through the Club of Rome a number of scientists [3,4] warned about the dangers of surpassing the carrying capacity of our planet.

By introducing the concept of '*planetary boundaries*' (PBs) the seminal work of Rockström *et al.* [5••] triggered considerable scientific and public debate [6•,7••,8•,9]. Although not claiming to be exclusive measures of sustainability, PBs are recognized as (auxiliary) metrics defining a 'safe operating space' for humanity. How long, if at all, 'business as usual' can be continued? How can boundaries be defined and their transgression prevented? How many and which boundaries need to be defined and observed to keep the world on a sustainable track? These and similar questions can be answered through the perspective of PBs. Rockström *et al.* [5••,10••] identified ten dimensions and proposed (except for two dimensions) global indicators and threshold values.

The ten dimensions represent a practical compromise between the complexity of PBs and the desire to specify a 'safe operating space' that can be communicated to the public and policymakers. Blomqvist *et al.* [6•] argued that many of these dimensions have arbitrary limits and no obvious tipping points. Rockström *et al.* [10••] recognized that the selected dimensions are not independent. Through the hydrological cycle freshwater use is linked to arguably all other dimensions. Therefore, any single boundary estimate for water is particularly problematical. We see additional limits to the original concept applied to water [6•], including uneven distributions in time and space and entrenched local-scale management perspectives [7••]. The current absence of limits recognizing the impact of impaired water quality and/or technological interventions and governance concepts also limit the current PB concept as applied to water.

Although identifying PBs is essentially a scientific task, their acceptance is fundamentally a societal process reflecting human perspectives. PBs are inherently value judgments as they are associated with the preservation of a presumably desirable state. Consequently it is unlikely in our view that useful PBs could be established without explicit consideration of human activities, aspirations and

Figure 1



Balanced Triangle of planetary and ecosystem-based resources and human societies. Modern human society emerged as a dominating force in appropriating both planetary and ecosystem services and putting feedback pressures on these domains. Achieving sustainable human development will require a balance between the three services: provisioning planetary to ecosystem, planetary to human societies and ecosystems to human societies) and their impacts. (Assets and services listed are illustrative examples without the claim of completeness).

stewardship. The aim of this paper is to review the ongoing debate [9,11–15]. Although acknowledging the need for simple '*policy relevant*' concepts and corresponding '*actionable*' metrics, we will argue that PBs should be expressed as a balanced triangle whose vertices represent (i) planetary resources, (ii) ecosystem-based resources and (iii) societal needs, resources and aspirations (Figure 1).

This paper deliberately takes a water-centric view. We argue that water, as a key component of the Earth system, and almost all human activities and biological processes provides both a direct planetary service and through the action of biology an ecosystem service. Because of this centrality, it is eminently qualified to serve as a '*lens*' to scrutinize the usefulness and limitations of PBs.

Interaction between human society and the supporting planetary and ecosystem resources

We present here a conceptual model of PBs that we apply for fresh water (Figure 1). To define hard limits in Earth resources, we distinguish *Planetary* (abiotic), *Ecosystem-based* (biotic), and *Human Societal Resources* as assets and services. Assets are stocks while services are dynamic fluxes. *Planetary Resources* are created by energy that drives the great planetary cycles of climate and ocean dynamics, the hydrologic cycle, sediment and geochemical cycles, and over a much longer time horizon the geological forces creating minable assets and geothermal energy. *Ecosystem-based Resources* are created from — but importantly also modify–the mass and energy associated with *Planetary Resources*. Both ecosystems and human societies can create new assets or build up stocks and deplete them (i.e. for fossil fuels representing ancient net primary productivity).

We maintain that the water cycle (both marine and terrestrial) is fundamentally a planetary service that can exist and existed without ecosystems, but its regulation through terrestrial ecosystems is an ecosystem service [16].

Humankind can appropriate planetary and ecosystem resources through a number of pathways, therefore their respective limits are determined by how humanity satisfies its needs and the sensitivity of the donor systems (Figure 1). The distinction between stocks versus fluxes [17] (or assets versus services) can serve to define sustainability. Intuitively, stocks should be used only non-consumptively unless they are abundant beyond possible exhaustion, while renewable fluxes can be used