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# Approaches to defining a planetary boundary for biodiversity

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ABSTRACT

The idea that there is an identifiable set of boundaries, beyond which anthropogenic change will put the Earth system outside a safe operating space for humanity, is attracting interest in the scientific community and gaining support in the environmental policy world. Rockstrom et al. (2009) identify nine such boundaries and highlight biodiversity loss as being the single boundary where current rates of extinction put the Earth system furthest outside the safe operating space. Here we review the evidence to support a boundary based on extinction rates and identify weaknesses with this metric and its bearing on humanity's needs. While changes to biodiversity are of undisputed importance, we show that both extinction rate and species richness are weak metrics for this purpose, and they do not scale well from local to regional or global levels. We develop alternative approaches to determine biodiversity loss boundaries and extend our analysis to consider large-scale responses in the Earth system that could affect its suitability for complex human societies which in turn are mediated by the biosphere. We suggest three facets of biodiversity on which a boundary could be based: the genetic library of life; functional type diversity; and biome condition and extent. For each of these we explore the science needed to indicate how it might be measured and how changes would affect human societies. In addition to these three facets, we show how biodiversity's role in supporting a safe operating space for humanity may lie primarily in its interactions with other boundaries, suggesting an immediate area of focus for scientists and policymakers.


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## 1. Introduction

The identification of global-scale thresholds underpins the planetary boundaries concept introduced by Rockstrom et al. (2009a, 2009b). Nine boundaries were proposed, representing specific thresholds of climate change, ocean acidification, stratospheric ozone, global nitrogen and phosphorus cycles, atmospheric aerosol loading, freshwater use, land-use change, biodiversity loss, and chemical pollution (Rockstrom et al., 2009a) that collectively delimit 'a safe operating space for humanity'. While some of the proposed boundaries were relatively simple to define because local inputs or changes make a predictable contribution to global processes with known thresholds, others (such as land-use change and biodiversity loss) are recognised as complex human system-ecosystem processes not easily associated with known global or continental thresholds (Rockstrom et al., 2009a).

Transgressing any of the nine boundaries is expected to lead to an increased risk to one or more aspects of human wellbeing, or would undermine the resilience of the Earth system as a whole. While some boundaries operate in a top-down manner driven by systemic global processes (e.g. climate change), others may be bottom-up processes driving large-scale responses so that the processes might be local or regional only, but sufficiently widespread to have significant aggregate consequences at the global-scale (e.g. N and P nutrient pollution) (Rockstrom et al., 2009a).

The planetary boundary for biodiversity has been particularly problematic. The original analysis emphasised the difficulty of describing and quantifying a boundary for biodiversity loss, noting that it is a slow process without known global-level thresholds, that there is incomplete knowledge on the role of biodiversity for ecosystem functioning across scales, and that the suggested boundary position was therefore highly uncertain (Rockstrom et al., 2009a). However there are more fundamental problems with the biodiversity boundary than just setting its position. Brook et al. (2013) questioned the existence of a global biodiversity threshold, noting the large spatial heterogeneity in the drivers and responses associated with biodiversity loss, the lack of abrupt shifts at global scale, and the absence of the large-scale interconnectivity that would be needed to propagate local ecosystem regime shifts globally. In contrast, Hughes et al. (2013) suggest that local changes could scale up to regional or global-level, especially given the interconnectedness of human systems, and Barnosky et al. (2012) note that slow drivers over human timescales can still lead to thresholds. The extent to which a biodiversity boundary might be experienced at local, regional or global scales, and indeed whether accumulations of local biodiversity change can imperil large-scale processes, is currently unresolved.

The discussion of a biodiversity boundary is also clouded by confusion over the use of the term 'biodiversity', which can simply mean species richness, but is often used for functional or ecosystem diversity, or more generally to represent the whole variety of life on Earth, sometimes with connotations of naturalness or intactness (Convention on Biological Diversity, 2010; DeLong, 1996; Fischer and Young, 2007). Biodiversity loss is generally manifested as a reduction in species numbers (ultimately to global extinction rates), but it is more often the extent and biomass of the biosphere that has a dominant influence on Earth system processes and the ecosystem services on which people depend (Díaz and Cabido, 2001; Díaz et al., 2006; Mace, 2005; Mace et al., 2012). The broad definitions of biodiversity in current usage do not allow such distinctions to be drawn, despite their importance.

Discussions of thresholds for biodiversity are further confused about whether the proposed threshold is intended to represent (i) changes in elements of biodiversity that cause a large-scale change in other processes in the Earth system, (ii) physical or biogeochemical changes in the Earth system that cause rapid, large-scale biodiversity change, or (iii) localised ecosystem changes that may propagate and scale up to large-scale or even global biodiversity change. There is some evidence that each of these takes place (Barnosky et al., 2012; Leadley et al., 2010; Lenton and Williams, 2013), but none is quite what is defined by the planetary boundaries concept with its clear implication that the boundary position is set by the level of a driver (in this case biodiversity loss) where there is a raised risk of impact on human welfare.

Here, we review the current biodiversity boundary as determined by Rockstrom et al. (2009b). Drawing on recent research we develop a conceptual basis for a biodiversity boundary which proposes alternative approaches that could delimit the safe operating space for humanity. We use this conceptual basis to identify key research directions needed to move towards the identification of actual metrics and quantitative boundaries or thresholds.

## 2. A critique of the biodiversity boundary

According to the planetary boundaries concept, all boundaries are defined in terms of response and control variables (Fig. 1) (Rockstrom et al., 2009a). Response variables are measures of Earth-system responses relevant to humans. Control variables represent the metric(s) related to the specific boundary that determines the Earth system response, while the boundary is defined as a human-determined level of the control variable set at a "safe" distance from a global threshold or a potentially dangerous level. Currently the planetary boundary for biodiversity uses ecosystem functioning as the response variable and the global species extinction rate as its control variable. The boundary is set at 10 times the average background extinction rate, which is 10 extinctions per million species per year (E/MSY), roughly equivalent to Holocene rates. Species extinction rate is arguably the most fundamental measure of global biodiversity loss, but not an ideal metric in this context for a number of reasons. First, it tends to be estimated most often for vertebrate species (an unrepresentative <2% of all described species). Second, it is insensitive to important changes in species abundance, community composition and distribution of species (Balmford et al., 2003; Millennium Ecosystem Assessment, 2005; Pereira et al., 2012). Third, it is hard to estimate with high certainty until long after the extinction has occurred (Heywood et al., 1994). Finally it is not clear how global species extinction rates will influence ecosystem functioning at scales relevant to the safe operating space.

Recent reviews of the relationships between species richness and ecosystem functions show that as species loss increases and the system approaches a monoculture, ecosystem processes such as primary production and decomposition on average decline, but also show a strongly increasing variance in response (Cardinale et al., 2012; Hooper et al., 2012). These reviews are based on multiple experimental studies where the effects of biomass and sampling of species are controlled so that the effects can be attributed to richness alone. The best monoculture often outperforms the most diverse system because certain species are very effective at a particular process on their own, but in general, especially at intermediate levels of richness, lower species richness leads to reduced ecosystem functions (Cardinale et al., 2012). Such composite relationships however have only limited applicability to the broader issue concerning the impact of biodiversity loss on people because they are based on controlled mesocosm or field experiments, usually conducted in relatively simple ecosystems over years or – occasionally – decades. They cannot represent the additional contributions from richness or diversity to ecosystem functions over time (Reich et al., 2012) and place (Godbold et al., 2011; Spehn et al., 2005) or the fact that, although certain species may appear redundant when a particular function is considered