ENVIRONMENTAL RESEARCH
LETTERS

TOPICAL REVIEW • OPEN ACCESS

Matching scope, purpose and uses of planetary boundaries science

To cite this article: Andrea S Downing *et al* 2019 *Environ. Res. Lett.* **14** 073005

Environmental Research Letters

OPEN ACCESS

RECEIVED
27 November 2018

REVISED
10 May 2019

ACCEPTED FOR PUBLICATION
20 May 2019

PUBLISHED
9 July 2019

TOPICAL REVIEW

Matching scope, purpose and uses of planetary boundaries science

Andrea S Downing[1,2], Avit Bhowmik[1], David Collste[1,3], Sarah E Cornell[1], Jonathan Donges[1,4], Ingo Fetzer[1,2], Tiina Häyhä[1,5], Jennifer Hinton[1,3], Steven Lade[1,2,6] and Wolf M Mooij[7,8]

1 Stockholm Resilience Centre, Stockholm University, SE-10691 Stockholm, Sweden
2 Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden
3 Centre d'Études et de Recherches sur le Développement International, CERDI, Université Clermont Auvergne, Clermont-Ferrand, France
4 Potsdam Institute for Climate Impact Research, PO Box 60 12 03, D-14412 Potsdam Germany
5 International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1—A-2361, Laxenburg, Austria
6 Fenner School of Environment and Society, The Australian National University, Australian Capital Territory, Canberra, Australia
7 Department of Aquatic Ecology, Netherlands Institute of Ecology (NIOO-KNAW), PO Box 50, 6700 AB Wageningen, The Netherlands
8 Department of Aquatic Ecology and Water Quality Management, Wageningen University, PO Box 47, 6700 AA Wageningen, The Netherlands

E-mail: andrea.downing@su.se

Keywords: planetary boundaries, resilience, global sustainability science, human dimensions, footprints approach, life cycle analysis, safe operating space

Supplementary material for this article is available online

Abstract

Background: The Planetary Boundaries concept (PBc) has emerged as a key global sustainability concept in international sustainable development arenas. Initially presented as an agenda for global sustainability research, it now shows potential for sustainability governance. We use the fact that it is widely cited in scientific literature (>3500 citations) and an extensively studied concept to analyse how it has been used and developed since its first publication. *Design:* From the literature that cites the PBc, we select those articles that have the terms 'planetary boundaries' or 'safe operating space' in either title, abstract or keywords. We assume that this literature substantively engages with and develops the PBc. *Results:* We find that 6% of the citing literature engages with the concept. Within this fraction of the literature we distinguish *commentaries*—that discuss the context and challenges to implementing the PBc, articles that *develop* the core biogeophysical concept and articles that *apply* the concept by translating to sub-global scales and by adding a human component to it. Applied literature adds to the concept by explicitly including society through perspectives of *impacts, needs, aspirations* and *behaviours*. *Discussion:* Literature applying the concept does not yet include the more complex, diverse, cultural and behavioural facet of humanity that is implied in commentary literature. We suggest there is need for a positive framing of sustainability goals—as a Safe Operating Space rather than boundaries. Key scientific challenges include distinguishing generalised from context-specific knowledge, clarifying which processes are generalizable and which are scalable, and explicitly applying complex systems' knowledge in the application and development of the PBc. We envisage that opportunities to address these challenges will arise when more human social dimensions are integrated, as we learn to feed the global sustainability vision with a plurality of bottom-up realisations of sustainability.

Introduction

Achieving sustainability is a global concern because many environmental processes that shape and influence humanity, such as climate change, operate globally and connect across multiple temporal and spatial scales (Liu *et al* 2013, 2007). Science informing sustainable development must therefore be a concerted effort with a global vision.

The planetary boundaries concept (PBc), by Rockström *et al* (2009a, 2009b) represents such an effort. Indeed, PBc authors identify changes (climate change, disturbance to nutrient cycles, land use changes), uses (freshwater use, biodiversity loss) and absorption processes (ocean acidification, atmospheric aerosol loading, stratospheric ozone depletion and chemical pollution) for which there are limits to what the Earth can support while maintaining Holocene-like functioning. Global limits are quantified based on the precautionary principle, to avoid a rising risk of creating and/or reaching large-scale biophysical Earth system thresholds (Box 1; Rockström *et al* 2009a, Steffen *et al* 2015). According to the PBc, the relatively low variability in Earth system dynamics that was characteristic of the Holocene epoch represents a global safe operating space for humanity. Achieving sustainability is understood as an increasingly pressing concern, as four critical Earth system processes have already overshot their boundary values.

The initial aim of Rockström *et al* (2009b) was to establish an agenda for global sustainability research, but the concept has become prominent in sustainability governance and science-policy initiatives (Galaz *et al* 2012b), even inspiring the mission statement of the United Nations 2030 Agenda (UN 2015). The PBc has also been debated extensively within academia, with more than 3500 academic citations (source: Web of Science, May 2019).

This concept is in line with today's dominant scientific and political discourse: for already more than thirty years, global sustainability policy (UN 1987) has recognized how the environment supports and shapes humanity, and how humanity in turn influences its environment. PBc serves as a tool with which to relate human impacts to biogeophysical dynamics that are ideal (or aspirational) for humanity (i.e. Holocene-like dynamics). In the concept, humanity implicitly underlies critical Earth system processes, for example land use change, which is seen entirely as anthropogenic. Also, humanity is an important driver of the control variables behind each Earth system process. However, though the PBc points to the clear need for constraints on the human perturbation of global environmental processes, it has a limited articulation of links between its biophysical processes and more specific human processes. Indeed, society—the social organisations that act and react to their environment—is absent from these Earth system processes.

Here, we analyse the PBc's development and uses, to determine how it is being applied, with a particular focus on missing human dimensions. We relate applications of the concept to articles that discuss and review its context and challenges (labelled commentaries—viewed as the concept's evolving mandate) and to developments of the concept's core framework (the concept's scope). This analysis informs us how PBc needs to develop to fulfil its mandate and thus points to new research directions and specifications to render the PBc operational.

Box 1. Planetary boundaries—semantics and science.

The concept is rooted both in Earth system science and in 'resilience thinking', the notion that systems can exist in functionally and structurally different dynamical states, and that a system can change state relatively suddenly in response to even gradual changes in conditions. As a system approaches a state transition, its resilience erodes (Berkes *et al* 2003). State transitions—or regime shifts—are not always directly or even at all reversible. Boundaries presented in the PBc are set at a cautionary distance from potential Earth system tipping points. Science has yet to uncover the conditions under which tipping points of each critical Earth system process might exist, or what lies beyond such tipping points (Hughes *et al* 2013). This knowledge is masked by another key characteristic of the concept: the recognition that all Earth system processes are connected and dependent, within and across spatio-temporal scales.

In 2015, Steffen *et al* (2015) published an updated analysis of the PBc, reviewing the state of the art in the respective research fields of individual boundaries, expanding the arguments and rationale for setting large-scale boundaries, and including original model-based analysis.

Methodology—literature search and categorisation

We used Web of Science to identify references that cite the original PBc publications by Rockström *et al* (2009a, 2009b)—777 and 3108 references respectively—accessed on 6 May 2019. We selected those that use terms 'planetary boundaries' or 'safe operating space' in title, abstract, and/or keywords. We manually excluded a foreign language reference, a reprint, as well as references that only summarily mention the concept. We added references we are aware of, that cite the concept and/or are themselves cited in this context—but that do not appear in Web of Science (e.g. Raworth 2012, Crépin and Folke 2014, Fanning and O'Neill 2016). We obtained a total of 224 references (figure 1—note that 2 response articles are excluded from the count). Our assumption is that we in this way selected only articles that explicitly apply and build on the PBc. Although our literature search potentially missed some relevant research, we believe that our selection gives a comprehensive overview of academic research carried out on the PBc.

Figure 1 shows how we categorised the literature. 54% of the literature published to date discusses the PBc without advancing the scientific basis or applying the concept in practical or policy contexts. We labelled this category 'commentaries'. 14% of articles focus on further advancing the scientific underpinnings of the PBc *as a biophysically-expressed framework*, and 32% seek to *use* the concept to evaluate sustainability at sub-global scales. We group these last two categories—development and uses—as 'applications' of the PBc (see table S1 in supplementary materials, available online at stacks.iop.org/ERL/14/073005/mmedia).

We made simple word-clouds of keywords (when available) from commentary (figure 2(a)) and applied articles respectively (figure 2(b)). We omitted the terms

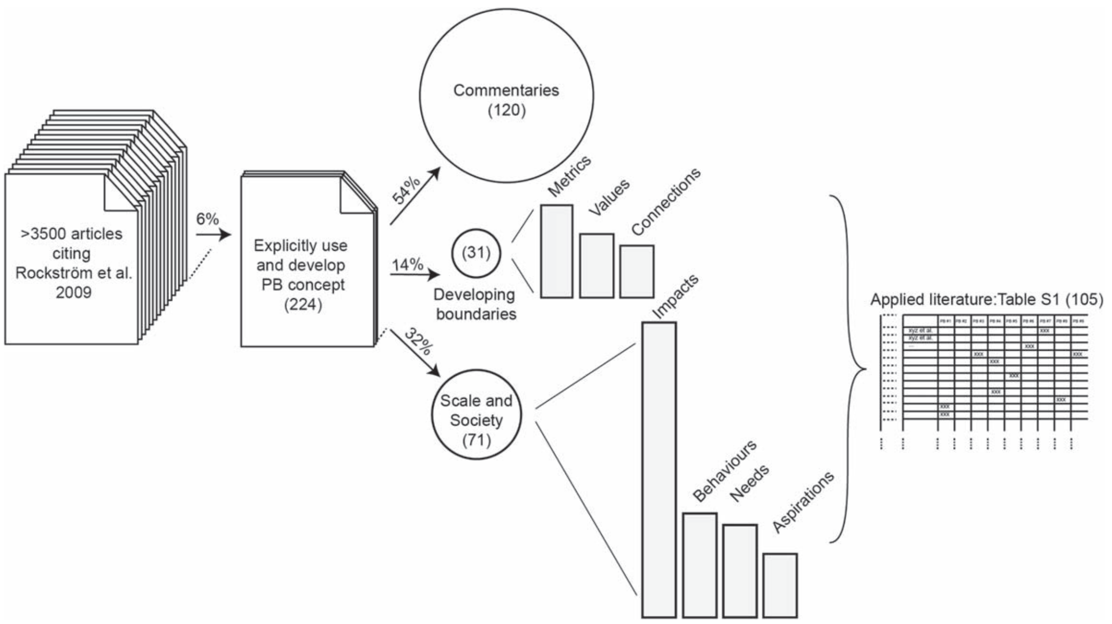

Figure 1. Literature categorisation. In brackets: the number of articles represented (see supplementary materials for the full lists of articles selected and their categorisations).

'Planetary Boundary(ies)' and 'Safe Operating Space' from the keyword analyses, because they were the selection terms for all the articles in the first place. We filtered for words that appear at least twice. Font-size reflects absolute frequency of the terms (see supplementary materials). This analysis gives semi-quantitative confirmation that commentary articles prioritise different facets of the PBc than the articles focused on the further development and application of the concept (figures 2(a) and (b)).

Results—tracking the progress of PBc research

Most citations of the Rockström *et al* (2009a, 2009b) articles use the term 'planetary boundaries' as shorthand for issues of global unsustainability, whereas 6% of the literature that cites the concept engages explicitly and substantively with the framework. This is the fraction of the literature that we delve into here.

Commentaries: a new global sustainability debate

From a structural perspective, articles categorised as commentaries (120 articles of the 224 identified, or 54%) focus mainly on the concept of the safe operating space, and much less on the boundaries themselves (i.e. the processes, proposed control variables and their boundary values). Dominant keywords of commentary articles are 'Anthropocene', 'resilience', 'sustainability' and phrases including 'governance' (figure 2(a)). These papers highlight a global context in which the PBc is evolving, issues that might prevent it becoming operational, and the needs it might be expected to fulfil. In this literature, we find that the humanities have recently engaged with the PBc (Brown 2017), discussing how to navigate today's framing of sustainability and the Anthropocene (e.g. Bennett and Teske 2017, Stubblefield 2018, Wakefield 2018), as well as the values and risks of the PBc framing (McAllum 2018), narratives (Kunnas 2017) and visualisations (Morseletto 2017).

Several articles focus on new governance challenges that the PBc's Earth system perspective brings. They point out that for institutions to support global sustainable development, they need to better understand the dynamics of critical Earth system processes, how they connect, and the scales at which they operate (Bogardi *et al* 2012, Galaz *et al* 2012a, 2012b, 2016, Pereira *et al* 2015, Nash *et al* 2017), as well as a need to understand how different institutions are themselves structured and connected (Galaz *et al* 2012b, Reischl 2012, Ahlström and Cornell 2018). Further governance challenges lie in identifying viable, compatible goals (Biermann 2012, Pereira *et al* 2015), and in the ability to manage transformative change (Folke *et al* 2011, Galaz 2012, Pereira *et al* 2015). From this perspective, there is a call for change: in order to navigate pathways towards resilience and global sustainability, governance should encourage learning and innovation, be flexible to uncertainty and encompass indicators and review mechanisms for the complex global processes that Earth system science now illuminates (Galaz *et al* 2012a, Hepburn *et al* 2014). These lines of enquiry have been reframed and emphasized since 2015 and the adoption of the United Nations' 2030 Agenda. 'Sustainable Development Goals' is a frequent keyword (figure 2(a)), and nearly a quarter of the review literature discusses the Sustainable Development Goals, despite Agenda 2030's relative youth.

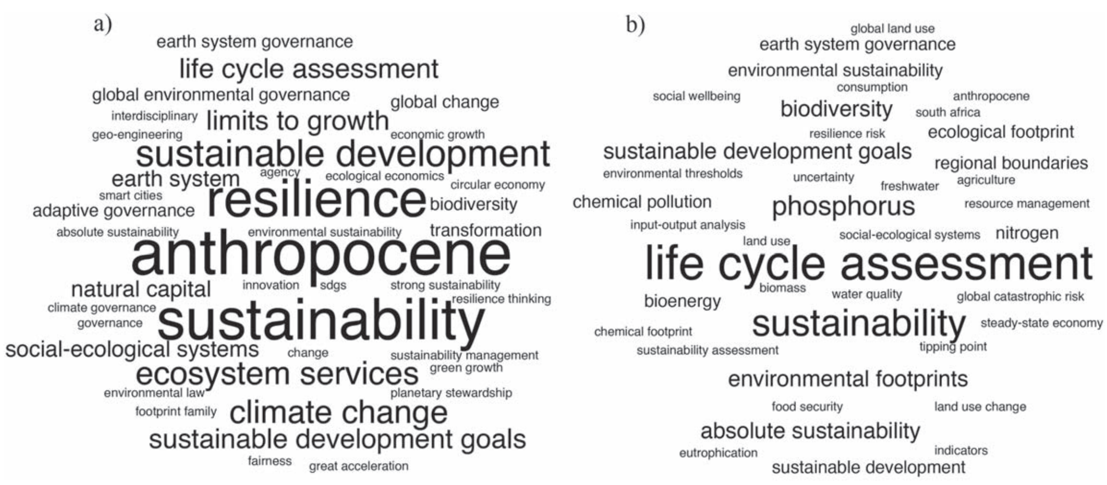

Figure 2. Word clouds created with keywords of articles (when available) (a) in Commentary articles and (b) in Applications articles. Font sizes reflect absolute frequency of appearance of words in article keywords (note: we excluded the terms 'planetary boundary(ies)' and 'safe operating space' as well as keywords that appeared only once—see supplementary materials for details).

Another area of focus addresses the practical and political challenges to applying the PBc (Mouysset et al 2018), such as perceived trade-offs between society and the environment (Messerli et al 2015, Saunders 2015), between economic growth and sustainable environmental and/or social development (Hepburn et al 2014, Gómez-Baggethun and Naredo 2015, Saunders 2015, Cumming and von Cramon-Taubadel 2018, Velenturf and Jopson 2019), and between differing North-South perspectives on development priorities, values, needs and rights (Kim and Bosselmann 2015, Saunders 2015, Figueroa-Helland et al 2016). The need for interdisciplinary research better linking human drivers and social and biophysical impacts is also highlighted (van Vuuren et al 2016). A further line of attention addresses scientific realities and challenges to applying the PBc, such as the global scale at which boundaries are defined, connectedness between boundary processes across spatial and temporal scales, uncertainty associated with connectedness, and current limits to our scientific knowledge of Earth process dynamics (Rockström et al 2014, Liu et al 2015).

Scientific development of the PBc

We found three main areas of boundary development: firstly (re-) defining the metrics and control variables for the fundamental Earth system processes in the framework. For example, Mace et al (2014) challenge the usability of biodiversity loss rates as a metric and suggest loss of genetic and functional diversity as well as biome condition as variables that better reflect changes to core Earth system functioning. A second area of development lies in (re-) evaluating boundary values Gerten et al (2013), for instance, propose a new value for the freshwater boundary by including environmental flow requirements to the assessment, concluding that rates of human use of freshwater should be lower than previously estimated. The third line of development of the concept focuses on understanding interactions between Earth system processes or between Earth system states (Anderies et al 2013, Larsen et al 2014, Heitzig et al 2016, Hellmann et al 2016), which serves as a preamble to reassessing boundary values by accounting for the interdependencies of processes.

Biodiversity, land use and water use boundaries have received most constructive critique (Table S1, supplementary materials). Of the two unquantified critical Earth system processes, only chemical pollution has spawned further research (Persson et al 2013, Sala and Goralczyk 2013, Handoh and Kawai 2014, MacLeod et al 2014, Villarrubia-Gómez et al 2018), whereas atmospheric aerosol loading has not been developed. Although our classification does not give a fine-grained content analysis, we find that nearly half the articles that develop the concept address more than one boundary process, many of which address the broader set of processes (see table S1). Some recent publications seek to develop the 'safe operating space' concept, exploring how humanity can navigate between different dynamic operating spaces—rather than remaining within static boundaries—and devising techniques to map the numerical and theoretical stability of potential safe operating spaces (Heitzig et al 2016, Hellmann et al 2016).

Applications: the missing social dimensions

A growing branch of research seeks to advance the applicability of the PBc by explicitly addressing the human dimensions of the biogeophysically expressed boundary processes. Studies point out that implementing the PBc will always encounter the need to deal with society's decision-making and action scales (Häyhä et al 2016), for example at national and regional scales (e.g. Kahiluoto et al 2015), or at the level of production systems (e.g. Sandin *et al* 2015). Studies present different methods for 'translating' the concept to sub-global levels, including such novel approaches as in Cole *et al* (2014) that proposes a decision-based methodology for the national level, or Dearing *et al* (2014) that links social well-being and sustainable resource management on a regional scale.

In the science advancing the applicability of the PBc, four terms emerge from the content analysis, these are: *needs*, *aspirations*, *behaviours* and *impacts*. We use these four terms to categorise the applied literature following these human perspectives (figure 1, table S1), and describe each one in the following text.

Needs

Needs look at how boundary values match against basic human necessities for life resonant with well-established conceptualizations of sustainable development in (UN 1987, Max-Neef 1991, O'Neill 2011). Water and food are the dominant topics in the needs perspective. Literature here highlights that projected human needs for water will overshoot the PB (e.g. Grafton *et al* 2015)—also for nitrogen—but see de Vries *et al* (2013) for a countering view. Rockström *et al* (2012) identify that freshwater availability does not suffice to feed humanity and to sequester carbon to curb climate change, and conclude that for water to be sufficient for human needs, humanity must limit climate change by reducing its carbon emissions. Bogardi *et al* (2013) use the freshwater boundary process to exemplify that a framework of planetary, ecosystem-based and social needs, is necessary to achieve sustainable resource use. Here humanity's purely functional freshwater needs are related to societal aspirations, which are seen as materialistic and currently unsustainable. de Vries *et al* (2013) re-estimate the nitrogen boundary by adding a measure of *per capita* dietary nitrogen needed to feed humanity to the limit of nitrogen that the biosphere can process. Looking at nitrogen and phosphorus flows, Kahiluoto *et al* (2014) find nutrient uses exceed boundary values, but highlight the spatial disparity in nutrient excesses and needs, implying that local targets and resource redistribution, in addition to behavioural changes in diets, waste and recycling are necessary to implement sustainable resource use (Kahiluoto *et al* 2015). The needs perspective relates boundary processes and human use of resources in a functional and pragmatic way. For instance, O'Neill *et al* (2018) connect the basic needs approach, as framed in (Raworth 2017) with the planetary boundaries using 'provisioning systems' that represent links between resource use and social outcomes. In this way 'humanity' as seen through the needs perspective—even in scaled sub-global models—reflects a generalised global human. Indeed, resource distributions as well as societies' production and consumption patterns are revealed, but not explicitly addressed.

Aspirations

Framed as they are in the PBc and in the literature that builds on the concept, *aspirations* for humanity are global in scale, and are normative perspectives involving judgements about goals that people should collectively strive for, such as providing a resilient planetary system for future generations. In the literature analysed here, these aspirations for a 'global humanity' tacitly presuppose global policy; complementing social science perspectives of Okereke (2006) and Lockie (2016) that discuss wider implications of such a future-framing of global sustainability. Aspirations range from governments' social priorities (Raworth 2012, Dearing *et al* 2014), through Millennium Development Goals (Gerst *et al* 2013), to the Sustainable Development Goals that are now seen as the most up-to-date collective social targets and statements of humanity's aspirations (Hajer *et al* 2015). When *aspirations* are framed as positive levels to strive for, such as the safe and just operating space for humanity defined in 'Doughnut Economics' (Raworth 2012, 2017), they reflect a social minimum standard. When they aspirations are framed as catastrophes to avoid, for example the 'Boundary Risks for Humanity and Nature' framework (Baum and Handoh 2014), they reflect a maximum limit.

Behaviours

In this categorisation, *behaviours* are the means by which humanity can reach shared global targets and/or avoid catastrophes. The literature in this area adds a global dimension to existing sustainable behaviour research at the individual and community level (e.g. reviews in Barr and Gilg 2006, Heiskanen *et al* 2010) and on governance through global actions (e.g. Bäckstrand 2008, Hale 2008, Bernstein and Cashore 2012). Some PBc research focuses on the behaviours needed to drive humanity away from all boundaries. For example, Robèrt *et al* (2013) outline a framework to define and reach—through sustainability principles and guidelines—a socio-ecological safe operating space. Other articles discuss staying within a specific combination of boundaries from a governance perspective (e.g. Nilsson and Persson 2012) or through bioengineering methods (Heck *et al* 2016). Yet others focus on managing humanity's sustainable development with reference to a single boundary, recommending such actions by state and business communities as 'green chemistry' to remain clear of chemical pollution limits (Tarasova *et al* 2015). We here see the option of achieving global sustainability through lifestyle transformations—i.e. driven from individuals up through social systems—that lead to low carbon futures within the climate change boundary (Neuvonen *et al* 2014), or of assessing the scale of social and cultural transformation needed to reach a social-ecological safe operating space (Gerst *et al* 2013). *Behaviour* perspectives reflect a conscious, enabled, self-determining nature of humanity, and the

Figure 3. A framework combining social dimensions with which to continuously re-assess pathways and lifestyles within sustainability. In italics, examples of questions that link the four perspectives.

literature here describes humanity at many different resolutions: from differentiated cultural individuals, through social and governance systems to States and the generalised global Human.

Impacts

Impacts are the most common perspective we find in the literature (reflecting connections with well-established and diverse fields of environmental impact assessment and climate impacts research). Impacts are measures of the effects of human activities on the Earth system processes described in the PBc (e.g. Bringezu *et al* 2012, Heijungs *et al* 2014). They are mostly measured using either footprints or life cycle assessment approaches. A footprints approach consists of assessing the appropriation and use of a resource (for example carbon) by an individual, nation or globally (Hoekstra and Wiedmann 2014). A footprint is sustainable if the use of the resource enables it to regenerate at a rate sufficient to make it available and usable by future generations. Life cycle assessments focus on minimising the environmental impact of all different processes in the production of goods. When coupling these concepts with the PBc approach, footprints and life cycle assessments' maximum sustainable environmental impacts are derived from the boundary values of the relevant Earth system process. Whether these methods are suited to the PBc or not is still debated (Ryberg *et al* 2016)—as we discuss in the discussion section on scale.

Combined perspectives

A third of the literature that includes society addresses a combination of these four perspectives of needs, aspirations, behaviours and impacts (e.g. Gerst *et al* 2013, bridging *aspirations* and *behaviours* or Rockström *et al* 2012, Bogardi *et al* 2013, combining *needs* and *impacts*). All possible two-way combinations are represented (supplementary materials S1). We suggest that this indicates how the PBc (and its global biophysical framing) has catalysed discussions that bridge these social perspectives, and has raised fresh questions about sustainability. Indeed, we would argue that these four perspectives can and should inform one another more than they currently do. Put together, they have the potential to form a framework that deals with the missing human dimensions of the PBc (figure 3). This framework allows a continuous (re-) assessment of pathways to and lifestyles within sustainability.

Discussion—challenges ahead

The context and challenges of the global sustainability discourse are clear: humanity is leaving an environmentally safe space while still trying to reach a socially just place, and this journey is happening during the Anthropocene, an epoch where humanity finds itself at the helm of global environmental change, yet also at the cusp of unprecedented shifts in Earth system dynamics.

In the following section, we discuss mismatches in the mandate, scope and applications of PBc science along three topics that emerge from the literature reviewed here: Who is the human? What is the goal? And Where is the action? We then propose a plan for the development of PBc science with a framework for the integration and implementation of resilience thinking, acknowledging that different fields of study must connect and inform each other in order to make the messages of global sustainability science more useable.

Who is the human?

In much of the literature analysed, humanity is seen as a globally uniform biological and/or economico-political entity—as in the 'Anthropocene' (Stubblefield 2018): be it as an unspecified consumer and producer of resources (e.g. Kahiluoto *et al* 2014) or a global holder of basic human rights (e.g. Raworth 2012). For instance, O'Neill *et al* (2018)'s national-level assessments of social needs met versus environmental boundaries overshot reveal the heterogeneity in the realisations of the PB: few countries are equal in the needs met and boundaries transgressed. However, the 'human' remains generalised, and prone to exist either in a space where social needs are met at the cost of the environment, or within environmental boundaries but out of reach of basic needs. There is a disconnect between commentaries that discuss issues of fairness of resource allocations (Saunders 2015) and the understanding of governance as a complex, multi-scale system of systems (Galaz *et al* 2012c)—which imply diversity and heterogeneity of social organisation—and applications where humanity is simplified to a globally generalised entity subject to global policy. Yet it is this biological and economico-political organism that is seen as the potential operator of sustainable development. The only approach we uncovered that applies the PBc to best empower social actors to achieve sustainability is McLaughlin (2018), who downscales the PBc to a relatively homogeneous region from a biogeophysical perspective, and highlights the presence of diverse human actors within this region. Overall, most commentaries bring forward human dimensions that are only hinted at in applications of the concept. These dimensions underlies topics of fairness, subjective value, and ethics (Neuvonen *et al* 2014, Sandin *et al* 2015, Saunders 2015, Häyhä *et al* 2016, Mavrommati *et al* 2016). These dimensions are dynamic and evolving and complement biological and political human facets. They cannot be described by biological growth models or rulebooks and laws—and imply fundamental diversity in human aspirations, psychologies, needs, behaviours and thus impacts. We argue that it is primarily the absence of such human dimensions that prevents the effective realisation of global sustainability concepts at sub-global scales, as scaling the current global sustainability vision translates to top-down—and oftentimes North-South, wealthy-poor, industrialised-industrialising—control and decision-making (Saunders 2015). This dichotomy is made clear in the findings of O'Neill *et al* (2018). To make actionable the findings and inform action to reach safe operating spaces, it is essential to understand the diverse people underlying the PBc's generalised Humanity.

We suggest that an added human dimension could be represented into the four broad perspectives through which social applications of the PBc are currently addressed (figure 3). The four dimensions that emerge from our literature analysis have analogous dimensions that emerge from the social sciences, indicating that there are established tools and frameworks with which to address them. Attention to expanded framings of needs and impacts helps to articulate the rationale and motivation for taking a global viewpoint on sustainability, giving more depth and realism to the social component of sustainable development. Attention to aspirations and behaviours strengthen the bridge from knowledge of unsustainability to action-oriented research, and thus potentially inform new solutions and challenges to achieving sustainable lifestyles and societies. Using the reflective questions in figure 3 helps shed a light on people's agency in the context of global change (obviously while specifying who the 'we' and 'our' relates to), and can provide insight into possible ways of applying PBc science to reach safe operating spaces.

What is the goal?

The PBc set off to frame a Safe Operating Space for humanity, but instead of describing this space, current PBc research clearly focuses on thresholds: either boundaries that must be avoided at all cost (e.g. Baum and Handoh 2014), or basic targets that must be reached (e.g. Gerst *et al* 2013, Raworth 2012, 2017). There is little description of a social-ecological Safe Operating Space, encompassing system dynamics that lie both above social foundations and below environmental boundaries. The lack of any clear vision(s) of such a space (or *spaces*) is recognised as a problem for governance (Biermann 2012).

The United Nations' 2030 Agenda is taken as a consensus global goal framework, with worldwide legitimacy and accountability. Even though its social targets reflect a reality that is still far from humanity's situation today—in terms of poverty, education, health etc—they represent only some of the most basic social foundations and needs. We can easily assume that people aspire to more than having these needs met. The literature suggests that satisfying humanity's needs provides only a pass-mark; it fails to include the diverse, dynamic, complex and cultural aspects of societal ambitions. In Fauré *et al* (2016) for instance, the analysis of the tensions between the need to reduce environmental impacts while maintaining relatively high social welfare and participation levels in Sweden, perhaps illustrates how aspirations—when achieved—become seen as necessities. This perspective showcases how development pathways are shaped by fluid aspirations, not just fixed social foundations. There is risk in this realisation, for instance when the unsustainable lifestyles of many in the global North and of an extremely wealthy minority are aspirational goals. There is also opportunity perhaps, that aspirations of sustainability, combined with sound and specified scientific groundings of what is sustainable—and for whom—can effectively characterise the safe and just operating spaces for humanity and show way-markers for pathways through their terrain.

A critique of the PBc is that Earth system boundaries are presented as a maximum allowance (e.g. Heijungs *et al* 2014), rather than as a signpost to a fundamentally different and sustainable development route, which gives the impression that they might even be negotiable targets. This critique is neither new nor unique to the PBc: it is shared by carrying capacity (Verhulst 1838), global warming limits set by the Intergovernmental Panel on Climate Change and

UN climate agreements (IPCC 2014), the social foundations and environmental ceiling of Doughnut Economics (Raworth 2012, 2017) and the Sustainable Development Goals (UN 2015). It may be true that the focus specifically on boundaries constitutes a negative framing of the sustainability discourse, with strong potential for self-sabotage towards goals of sustainability. Indeed, using an analogy from climbing: a successful climber will remember to look up to her/his destination, not down the cliff-side.

A better understanding and integration of human dimensions in the PBc will help not only define sustainable aspirations that different people can strive for, but also help frame the sustainability discourse in a constructive way. To this purpose, we recommend shifting away from referring to the 'planetary boundaries' and instead talking more about the Safe Operating Space(s) (SOS).

Where is the action?

Implementing the SOS concept will always encounter the need to deal with society's decision-making and action scales (Häyhä *et al* 2016). We find that the scale at which humanity is being described is often unclear, which has repercussions on how well sustainability science can be translated into action (Reischl 2012, Galaz *et al* 2012b). Indeed, when seen as a generalised global human, 'humanity' is mostly seen as an object of global change, manipulated by global policy. However, when seen as an individual, community, organisation and society, humanity can be the subject and director of change. To understand and act upon global sustainability challenges we need both the bigger picture of the global human and its place on the planet as well as the detail on how social organisations (as biological, economic, political and social entities) shape and are shaped by the world around them.

The SOS concept is currently expressed at a global scale and in purely biophysical terms. This gives poor insights into how responsibility or rights over the Earth system processes are distributed. Furthermore, there is a disproportionate influence of the wealthy on processes such as climate change, paralleled with a disproportionate effect of climate change on the poor (Boonstra 2016). Aligned with this understanding of heterogeneously overlapping processes, research translating the SOS concept to the national level (Häyhä *et al* 2016) recommends scaling its biophysical, socio-economic and ethical aspects separately. This is mostly seen as a process of 'scaling-down' to the sub-global 'action' level. Another approach, by McLaughlin (2018), scales the SOS concept to a relatively homogeneous region from a biogeophysical perspective, but where the 'action'—implementing measures to redress human impacts—is then distributed across the diverse actors/stakeholders in the regions. In a way, this approach turns the SOS concept on its head, by homogenising the environmental context and diversifying 'Humanity'.

To integrate context-specific needs, behaviours, aspirations and impacts, with global sustainability challenges, there is a need to distinguish processes that are generalizable from those that are scalable, and to complement current top-down perspectives with bottom-up perspectives that span from local to global scales.

Where is resilience?

As a global perspective on sustainability, the PBc could ignore issues relating to the heterogeneous distribution of processes. The SOS concept pays heed to the fact that the processes and their interactions vary at sub-global scales, and as such its relation to resilience thinking (Folke 2016) becomes explicit.

Many authors use the footprints and life cycle assessment approaches to scale the concept to national levels. There are nonetheless fundamental differences that distinguish these approaches from resilience thinking. For example, the gradient of resilience (systems are more or less resilient, until they collapse) and the fundamental shift in functioning of systems underlying the planetary boundaries (box 1) are absent from footprint and life cycle assessment approaches to evaluate environmental (and social) impacts. Also, Earth system processes are interdependent, co-evolving and influencing each other within and across multiple scales (Watson 1999), thus leading to the global picture of a SOS that cannot be downscaled or disaggregated (Steffen *et al* 2015), and where Earth system thresholds are neither fixed nor predictable (Steffen *et al* 2018).

By ignoring resilience and interconnections between processes, the implicit assumption of many environmental impact assessment frameworks is that individual impacts can simply add-up to form a global assessment of impacts. However, while some processes might be independent overall, many processes in complex adaptive systems either enhance, (e.g. Kirby *et al* 2009), complement (e.g. Gable *et al* 2012) or cancel each other out (e.g. Yachi and Loreau 1999). There is clearly a need to refine the sciences of cross-scale dynamics and complex adaptive systems to make SOS science applicable across scales and systems (box 2).

Conclusions

There has been considerable academic interest around the planetary boundaries concept. The body of literature engaging with the concept is developing along coherent themes, where social dimensions are coming into clearer focus, and the PBc is increasingly presented as the embodiment of the Anthropocene and global sustainability agenda. However, we find that the concept's scope and mandate are not always aligned. Indeed, our literature search on this growing field highlights a rift between the science that analyses the

Box 2. Challenges to combining multidisciplinary data.

Though the PBc mentions resilience and multi-scale interconnectedness, these facets are not applied in the concept itself—the boundaries are presented as fixed and independent (de Vries *et al* 2013)—leaving resilience and multi-scale interconnectedness to be freely ignored in subsequent research. There are pragmatic reasons for these omissions. For example, different Earth system processes—and additional social values—are all expressed in different units that are often incompatible and incommensurate. Strategies to combine different fields of research tend to oversimplify the system being represented and seldom represent all fields on an equal footing (Stone-Jovicich 2015).

So far, most common methods include converting all units to a single one, for example carbon or a currency. This approach excludes the comparison of continuous versus discrete processes, reduces the resolution of existing data, adds uncertainty with regards to fluctuations in exchange rates and hides the variability in conversion factors. Another common approach is to average out different indicators as one index, such as the Human Development Index or the Ocean Health Index, which aim to characterise complex social-ecological systems with a single number. Though these indices have a clear pragmatic aspect, they are not sufficient to characterize the multitude of diverse facets of complex social-ecological systems. Attempts to raise or lower such an index risk yielding short-sighted, singular solutions that have unintended consequences on the overall system.

concept and the science that develops and uses it. Commentaries present explicit, dynamic and complex human dimensions and emphasize the importance of resilience thinking. Nonetheless, the core structure and elements of the PBs remain essentially the same: society is implicit, and resilience thinking purely theoretical. Uses rest in a middle ground, with an explicit but underspecified human, where resilience thinking is mostly ignored.

Through this review and analysis, we identify key avenues that SOS research should take in order for scope to match mandate, so it can stand out as an effective sustainability-informing concept. SOS research needs to explicitly take a *human* society on board its framework, joining forces with fields of humanities to better understand drivers of human behaviours in different cultural, historical and natural contexts. Our sustainability-assessing framework shows where this knowledge should be filled in, and this should happen at the smallest relevant action scale. Scaling-up from the action scale, connecting across and within scales and explicitly applying resilience thinking remain key scientific challenges. However, opportunities to address these challenges will arise when more human dimensions are integrated, as we learn to feed the global SOS vision with a plurality of societal realisations of sustainability.

Acknowledgments

This work was carried out as part of *Systemic Links and Interdependencies of the Planetary Boundaries*, a project funded by the Swedish Research Council Formas (project grant 2012-742). SJL received funding from the Swedish Research Council Formas (project grant 2014-589). ASD is supported by the GRAID programme at Stockholm Resilience Centre. This is publication 6746 of the Netherlands Institute of Ecology (NIOO-KNAW).

ORCID iDs

Andrea S Downing https://orcid.org/0000-0002-5206-9355
Avit Bhowmik https://orcid.org/0000-0002-7137-0741
David Collste https://orcid.org/0000-0002-4303-9744
Sarah E Cornell https://orcid.org/0000-0003-4367-1296
Tiina Häyhä https://orcid.org/0000-0002-9462-0408
Steven Lade https://orcid.org/0000-0001-9719-9826
Wolf M Mooij https://orcid.org/0000-0001-5586-8200

References

Ahlström H and Cornell S E 2018 Governance, polycentricity and the global nitrogen and phosphorus cycles *Environ. Sci. Policy* **79** 54–65
Anderies J M, Carpenter S R, Steffen W and Rockström J 2013 The topology of non-linear global carbon dynamics: from tipping points to planetary boundaries *Environ. Res. Lett.* **8** 044048
Barr S and Gilg A 2006 Sustainable lifestyles : framing environmental action in and around the home *Geoforum* **37** 906–20
Baum S D and Handoh I C 2014 Integrating the planetary boundaries and global catastrophic risk paradigms *Ecol. Econ.* **107** 13–21
Bennett P and Teske J A 2017 Varieties of knowing in science and religion *Zygon* **52** 764–76
Berkes F, Colding J and Folke C 2003 Navigating social-ecological systems: Building resilience for complexity and change (Cambridge University Press)
Bernstein S and Cashore B 2012 Complex global governance and domestic policies : four pathways of influence *Int. Affairs* **3** 585–604
Biermann F 2012 Planetary boundaries and earth system governance: exploring the links *Ecol. Econ.* **81** 4–9
Bogardi J J, Dudgeon D, Lawford R, Flinkerbusch E, Meyn A, Pahl-Wostl C, Vielhauer K and Vörösmarty C 2012 Water security for a planet under pressure: Interconnected challenges of a changing world call for sustainable solutions *Curr. Opin. Environ. Sustain.* **4** 35–43
Bogardi J J, Fekete B M and Vörösmarty C J 2013 Planetary boundaries revisited: a view through the 'water lens' *Curr. Opin. Environ. Sustain.* **5** 581–9
Boonstra W J 2016 Conceptualizing power to study social-ecological interactions *Ecol. Soc.* **21** 21
Bringezu S, O'Brien M and Schütz H 2012 Beyond biofuels: assessing global land use for domestic consumption of biomass. A conceptual and empirical contribution to sustainable management of global resources *Land Use Policy* **29** 224–32
Brown K 2017 Global environmental change. II. Planetary boundaries - a safe operating space for human geographers? *Prog. Hum. Geogr.* **41** 1–13

Bäckstrand K 2008 Accountability of networked climate governance: the rise of transnational climate partnerships *Glob. Environ. Polit.* **8** 74–102

Cole M J, Bailey R M and New M G 2014 Tracking sustainable development with a national barometer for South Africa using a downscaled 'safe and just space' framework *Proc. Natl. Acad. Sci. U. S. A.* **111** E4399–408

Crépin A-S and Folke C 2014 The economy, the biosphere and planetary boundaries: towards biosphere economics *Int. Rev. Environ. Resour. Econ.* **8** 57–100

Cumming G S and von Cramon-Taubadel S 2018 Linking economic growth pathways and environmental sustainability by understanding development as alternate social–ecological regimes *Proc. Natl Acad. Sci.* 201807026

Dearing J A *et al* 2014 Safe and just operating spaces for regional social-ecological systems *Glob. Environ. Chang.* **28** 227–38

Fanning A L and O'Neill D W 2016 Tracking resource use relative to planetary boundaries in a steady-state framework: a case study of Canada and Spain *Ecol. Indic.* **69** 836–49

Fauré E, Svenfelt Å, Finnveden G and Hornborg A 2016 Four sustainability goals in a Swedish low-growth/degrowth context *Sustain.* **8** 1–18

Figueroa-Helland L E, Lindgren T and Pfaeffle T 2016 Civilization on a crash course? Imperialism, subimperialism and the political-ecological breaking point of the modern/colonial world-system *Perspect. Glob. Dev. Technol.* **15** 255–89

Folke C *et al* 2011 Reconnecting to the biosphere *Ambio* **40** 719–38

Folke C 2016 Resilience (republished) *Ecol. Soc.* **21** 44

Gable J T, Crowder D W, Northfield T D, Steffan S A and Snyder W E 2012 Niche engineering reveals complementary resource use *Ecology* **93** 1994–2000

Galaz V 2012 Geo-engineering, governance, and social-ecological systems: critical issues and joint research needs *Ecol. Soc.* **17** 434–43

Galaz V, Biermann F, Crona B, Loorbach D, Folke C, Olsson P, Nilsson M, Allouche J, Persson Å and Reischl G 2012a 'Planetary boundaries'—exploring the challenges for global environmental governance *Curr. Opin. Environ. Sustain.* **4** 80–7

Galaz V, Biermann F, Folke C, Nilsson M and Olsson P 2012b Global environmental governance and planetary boundaries: an introduction *Ecol. Econ.* **81** 1–3

Galaz V, Crona B, Österblom H, Olsson P and Folke C 2012c Polycentric systems and interacting planetary boundaries — emerging governance of climate change–ocean acidification–marine biodiversity *Ecol. Econ.* **81** 21–32

Galaz V, Österblom H, Bodin Ö and Crona B 2016 Global networks and global change-induced tipping points *Int. Environ. Agreements* **16** 189–221

Gerst M, Raskin P and Rockström J 2013 Contours of a resilient global future *Sustainability* **6** 123–35

Gerten D, Hoff H, Rockström J, Jägermeyr J, Kummu M and Pastor A V 2013 Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements *Curr. Opin. Environ. Sustain.* **5** 551–8

Grafton R Q, Williams J and Jiang Q 2015 Food and water gaps to 2050: preliminary results from the global food and water system (GFWS) platform *Food Secur.* 209–20

Gómez-Baggethun E and Naredo J M 2015 In search of lost time: the rise and fall of limits to growth in international sustainability policy *Sustain. Sci.* **10** 385–95

Hajer M, Nilsson M, Raworth K, Bakker P, Berkhout F, de Boer Y, Rockström J, Ludwig K and Kok M 2015 Beyond cockpit-ism: four insights to enhance the transformative potential of the sustainable development goals *Sustainability* **7** 1651–60

Hale T N 2008 Transparency, accountability, and global governance *Glob. Gov.* **14** 73–94

Handoh I C and Kawai T 2014 Modelling exposure of oceanic higher trophic-level consumers to polychlorinated biphenyls: pollution 'hotspots' in relation to mass mortality events of marine mammals *Mar. Pollut. Bull.* **85** 824–30

Heck V, Donges J F and Lucht W 2016 Collateral transgression of planetary boundaries due to climate engineering by terrestrial carbon dioxide removal *Earth Syst. Dyn. Discuss.* 1–24 (http://earth-syst-dynam-discuss.net/esd-2016-22/)

Heijungs R, De Koning A and Guinée J B 2014 Maximizing affluence within the planetary boundaries *Int. J. Life Cycle Assess.* **19** 1331–5

Heiskanen E, Johnson M, Robinson S, Vadovics E and Saastamoinen M 2010 Low-carbon communities as a context for individual behavioural change *Energy Policy* **38** 7586–95

Heitzig J, Kittel T, Donges J F and Molkenthin N 2016 Topology of sustainable management of dynamical systems with desirable states: from defining planetary boundaries to safe operating spaces in the earth system *Earth Syst. Dyn.* **7** 21–50

Hellmann F, Schultz P, Grabow C, Heitzig J and Kurths J 2016 Survivability: a unifying concept for the transient resilience of deterministic dynamical systems *Sci. Rep.* **6** 29654

Hepburn C, Beinhocker E, Farmer J D and Teytelboym A 2014 Resilient and inclusive prosperity within planetary boundaries *China World Econ.* **22** 76–92

Hoekstra A Y and Wiedmann T O 2014 Humanity's unsustainable environmental footprint *Science* **344** 1114–7

Hughes T P, Carpenter S, Rockström J, Scheffer M and Walker B 2013 Multiscale regime shifts and planetary boundaries *Trends Ecol. Evol.* **28** 389–95

Häyhä T, Lucas P L, Van V D P, Cornell S E and Hoff H 2016 From planetary boundaries to national fair shares of the global safe operating space—how can the scales be bridged ? *Glob. Environ. Chang.* **40** 60–72

IPCC 2014 *Climate Change 2014: Synthesis Report Summary for policymakers. Intergovernmental Panel on Climate Change* (Geneva, Switzerland) (https://ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf)

Kahiluoto H, Kuisma M, Kuokkanen A, Mikkilä M and Linnanen L 2014 Taking planetary nutrient boundaries seriously: can we feed the people? *Glob. Food Sec.* **3** 16–21

Kahiluoto H, Kuisma M, Kuokkanen A, Mikkilä M and Linnanen L 2015 Local and social facets of planetary boundaries: right to nutrients *Environ. Res. Lett.* **10** 104013

Kim R E and Bosselmann K 2015 Operationalizing sustainable development: ecological integrity as a grundnorm of international law *Rev. Eur. Comp. Int. Environ. Law* **24** 194–208

Kirby R R, Beaugrand G and Lindley J A 2009 Synergistic effects of climate and fishing in a marine ecosystem *Ecosystems* **12** 548–61

Kunnas J 2017 Storytelling: from the early anthropocene to the good or the bad anthropocene *Anthr. Rev.* **4** 136–50

Larsen F W, Turner W R and Mittermeier R A 2014 Will protection of 17% of land by 2020 be enough to safeguard biodiversity and critical ecosystem services? *Oryx* **49** 74–9

Liu J *et al* 2007 Complexity of coupled human and natural systems *Science* **317** 1513–6

Liu J *et al* 2013 Framing sustainability in a telecoupled world *Ecol. Soc.* **18** 26

Liu J *et al* 2015 Systems integration for global sustainability *Science* **347** 963

Lockie S 2016 Sustainability and the future of environmental sociology *Environ. Sociol.* **2** 1–4

Mace G M *et al* 2014 Approaches to defining a planetary boundary for biodiversity *Glob. Environ. Chang.* **28** 289–97

MacLeod M, Breitholtz M, Cousins I T, De Wit C A, Persson L M, Rudé C and McLachlan M S 2014 Identifying chemicals that are planetary boundary threats *Environ. Sci. Technol.* **48** 11057–63

Mavrommati G, Bithas K, Borsuk M E and Howarth R B 2016 Integration of ecological-biological thresholds in conservation decision making *Conserv. Biol.* **30** 1173–81

Max-Neef M A 1991 *Human Scale Development. Conception, Application and Further Reflections* (New York and London: Apex Press)

McAllum M 2018 Learning to live in toxic nature (toxicus natura) *J. Futur. Stud.* **22** 101–8

McLaughlin J F 2018 Safe operating space for humanity at a regional scale *Ecol. Soc.* **23** 43
Messerli P, Bader C, Hett C, Epprecht M and Heinimann A 2015 Towards a spatial understanding of trade-offs in sustainable development: a meso-scale analysis of the nexus between land use, poverty, and environment in the Lao PDR *PLoS One* **10** 1–19
Morseletto P 2017 Analysing the influence of visualisations in global environmental governance *Environ. Sci. Policy* **78** 40–8
Mouysset L, Doyen L, Léger F, Jiguet F and Benton T G 2018 Operationalizing sustainability as a safe policy space *Sustainability* **10** 1–9
Nash K L, Cvitanovic C, Fulton E A, Halpern B S, Milner-Gulland E J, Watson R A and Blanchard J L 2017 Planetary boundaries for a blue planet *Nat. Ecol. Evol.* **1** 1625–34
Neuvonen A, Kaskinen T, Leppänen J, Lähteenoja S, Mokka R and Ritola M 2014 Low-carbon futures and sustainable lifestyles: a backcasting scenario approach *Futures* **58** 66–76
Nilsson M and Persson Å 2012 Can Earth system interactions be governed? Governance functions for linking climate change mitigation with land use, freshwater and biodiversity protection *Ecol. Econ.* **75** 61–71
Okereke C 2006 Global environmental sustainability: intragenerational equity and conceptions of justice in multilateral environmental regimes *Geoforum* **37** 725–38
O'Neill D W, Fanning A L, Lamb W F and Steinberger J K 2018 A good life for all within planetary boundaries *Nat. Sustain.* **1** 88–95
O'Neill J 2011 The overshadowing of needs *Sustainable Development: Capabilities, Needs, and Well-Being* (London: Routledge) pp 25–43
Pereira L, Karpouzoglou T, Doshi S and Frantzeskaki N 2015 Organising a safe space for navigating social-ecological transformations to sustainability *Int. J. Environ. Res. Public Health* **12** 6027–44
Persson L M, Breitholtz M, Cousins I T, de Wit C A, MacLeod M and McLachlan M S 2013 Confronting unknown planetary boundary threats from chemical pollution *Environ. Sci. Technol.* **47** 12619–22
Raworth K 2012 A safe and just space for humanity: can we live within the doughnut? Oxfam Discussion Papers (Oxford: Oxfam)
Raworth K 2017 *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist* (London: Random House) (https://books.google.se/books?id=9euWCwAAQBAJ)
Reischl G 2012 Designing institutions for governing planetary boundaries—lessons from global forest governance *Ecol. Econ.* **81** 33–40
Robèrt K-H, Broman G I and Basile G 2013 Analyzing the concept of planetary boundaries from a strategic sustainability perspective: how does humanity avoid tipping the planet? *Ecol. Soc.* **18** 5
Rockström J *et al* 2009b A safe operating space for humanity *Nature* **461** 472–5
Rockström J *et al* 2014 The unfolding water drama in the anthropocene: towards a resilience-based perspective on water for global sustainability *Ecohydrology* **7** 1249–61
Rockström J, Falkenmark M, Lannerstad M and Karlberg L 2012 The planetary water drama: dual task of feeding humanity and curbing climate change *Geophys. Res. Lett.* **39** 1–8
Rockström J R *et al* 2009a Planetary boundaries: exploring the safe operating space for humanity *Ecol. Soc.* **14** 32
Ryberg M W, Owsianiak M, Richardson K and Hauschild M Z 2016 Challenges in implementing a planetary boundaries based life-cycle impact assessment methodology *J. Clean. Prod.* **139** 450–9
Sala S and Goralczyk M 2013 Chemical footprint: a methodological framework for bridging life cycle assessment and planetary boundaries for chemical pollution *Integr. Environ. Assess. Manag.* **9** 623–32
Sandin G, Peters G M and Svanström M 2015 Using the planetary boundaries framework for setting impact-reduction targets in LCA contexts *Int. J. Life Cycle Assess.* **20** 1684–700
Saunders F P 2015 Planetary boundaries: at the threshold… again: sustainable development ideas and politics *Environ. Dev. Sustain.* **17** 823–35
Steffen W *et al* 2018 Trajectories of the earth system in the anthropocene *Proc. Natl Acad. Sci.* **115** 8252–9
Steffen W, Richardson K, Rockström J, Cornell S, Fetzer I, Bennett E, Biggs R and Carpenter S 2015 Planetary boundaries: guiding human development on a changing planet *Science* **347** 1259855
Stone-Jovicich S 2015 Probing the interfaces between the social sciences and social-ecological resilience: insights from integrative and hybrid perspectives in the social sciences *Ecol. Soc.* **20** 25
Stubblefield C 2018 Managing the planet: the anthropocene, good stewardship and the empty promise of a solution to ecological crisis *Societies* **8** 25
Tarasova N P, Ingel' F I and Makarova A S 2015 Green chemistry as a tool for reduction of environmental risks from exposure to chemically hazardous facilities *Russ. J. Phys. Chem.* B **9** 406–11
UN 1987 *Report of the World Commission on Environment and Development: Our Common Future* (https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf)
UN 2015 *Transforming our world: The 2030 agenda for sustainable development* (https://doi.org/10.1007/s13398-014-0173-7.2)
Velenturf A P M and Jopson J S 2019 Making the business case for resource recovery *Sci. Total Environ.* **648** 1031–41
Verhulst P-F 1838 Notice sur la loi que la population suit dans son accroissement *Corresp. mathématique Phys.* **10** 113–21
Villarrubia-Gómez P, Cornell S E and Fabres J 2018 Marine plastic pollution as a planetary boundary threat—the drifting piece in the sustainability puzzle *Mar. Policy* **96** 213–20
de Vries W, Kros J, Kroeze C and Seitzinger S P 2013 Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts *Curr. Opin. Environ. Sustain.* **5** 392–402
van Vuuren D P, Lucas P L, Häyhä T, Cornell S E and Stafford-Smith M 2016 Horses for courses: analytical tools to explore planetary boundaries *Earth Syst. Dyn* **7** 267–279
Wakefield S 2018 Inhabiting the Anthropocene back loop *Resilience* **6** 77–94
Watson A J 1999 Coevolution of the earth's environment and life: goldilocks, gaia and the anthropic principle *Geol. Soc. London, Spec. Publ.* **150** 75–88
Yachi S and Loreau M 1999 Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis *Proc. Natl. Acad. Sci.* **96** 1463–8