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Learning from generations of sustainability concepts

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Learning from generations of sustainability concepts

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'*The environment does not exist as a sphere separate from human actions, ambitions, and needs, and attempts to defend it in isolation from human concerns have given the very word "environment" a connotation of naivety in some political circles. The word "development" has also been narrowed by some into a very limited focus, along the lines of "what poor nations should do to become richer", and thus again is automatically dismissed by many in the international arena as being a concern of specialists, of those involved in questions of "development assistance"*'. Gro Brundtland (United Nations 1987).

Abstract

Background: For decades, scientists have attempted to provide a sustainable development framework that integrates goals of environmental protection and human development. The Planetary Boundaries concept (PBc) – a framework to guide sustainable development – juxtaposes a 'safe operating space for humanity' and 'planetary boundaries', to achieve a goal that decades of research have yet to meet. We here investigate if PBc is sufficiently different to previous sustainability concepts to have the intended impact, and map how future sustainability concept developments might make a difference.

Design: We build a genealogy of the research that is cited in and informs PBc. We analyse this genealogy with the support of two seminal and a new consumer-resource models, that provide simple and analytically tractable analogies to human-environment relationships. These models bring together environmental limits, minimum requirements for populations and relationships between resource-limited and waste-limited environments.

Results: PBc is based on coherent knowledge about sustainability that has been in place in scientific and policy contexts since the 1980s. PBc represents the ultimate framing of limits to the use of the environment, as limits not to single resources, but to Holocene-like Earth system dynamics. Though seldom emphasized, the crux of the limits to sustainable environmental dynamics lies in waste (mis-)management, which sets where boundary values might be. Minimum requirements for populations are under-defined: it is the *distribution* of resources, opportunities and waste that shape what is a safe space and for whom.

Discussion: We suggest that PBc is not different or innovative enough to break 'Cassandra's dilemma' and ensure scientific research effectively guides humanity towards sustainable development. For this, key issues of equality must be addressed, un-sustainability must be framed as a problem of today, rather than projected into the future, and scientific foundations of frameworks such as PBc must be broadened and diversified.

Introduction

Over the last decade, the Planetary Boundaries concept (PBc) (Rockström *et al* 2009a, 2009b) has been highly cited in academic contexts (Downing *et al* 2019); it has been widely applied as a framework for sustainable business and sustainability campaigning (e.g. https://houdinisportswear.com/en-se/sustainability/planetary-boundaries-assessment ; https://www.weforum.org/agenda/2015/01/9-ways-to-pull-our-planet-back-from-the-brink/ ; https://www.loreal.com/sharing-beauty-with-all-living/assessing-the-footprint-of-our-products/a-new-tool-to-assess-the-environmental-and-social-impact-of-our-products); frequently raised in policy forums (Galaz *et al* 2012) – and also sometimes strongly contested (Montoya *et al* 2017, 2018, Rockström *et al* 2018). We view the framing of 'boundaries' in R2009 as a vital part of the reason for the impact of the concept.

The limits (or boundaries) presented in the PBc separate an environmental 'danger zone' – where thresholds to Earth system dynamics are likely to exist – from a Safe Operating Space (SOS) for humanity. The SOS represents Holocene-like Earth system dynamics, where Earth system processes continue to function as they have over the past ±12 thousand years while human societies have developed and thrived to become the dominant shapers of Earth system change (Rockström *et al* 2009a, Steffen *et al* 2015). In bringing together both Planetary Boundaries and a Safe Operating Space for humanity, the PBc brings to culmination centuries of work on the dependencies of societies on their environment, that has often been framed as a duality of nature protection goals in contrast to human development goals.

Greek mythology tells the story of a princess of Troy – Cassandra – who was gifted with prophecy but cursed that she would not be believed. Though she warned of the invasion and fall of Troy, she could not prevent it, and may have been blamed for it. In a similar way, centuries of research that carry a seemingly consistent message: 'human impacts outpace the natural environment's ability to support humanity' have yet to yield necessary changes (Oreskes and Conway 2014).

The first intergovernmental "Biosphere Conference" held in Paris in 1968 marked a shift in international perspectives on development (Unesco 1968). Here, the word 'Biosphere' appeared on the world stage and was anchored into everyday language. Humans, including their social interactions, were recognized as an integrated part of the biosphere, and a key factor in modifying the biosphere. The conference's most marking output was the recognition that environmental protection and human development go hand in hand. This message was repeated in the United Nations conference on the Human Environment in Stockholm 1972; and the Brundtland report (UN 1987). Forty years on, the publication of PBc indicates that the goals of these conferences are still far off.

In this article, we ask if PBc has what is needed to break Cassandra´s dilemma. We seek to identify how PBc differs from existing sustainability frameworks and research and what novel perspectives it brings. With the aim of better informing the design and implementation of future sustainable development research, we here compile centuries of knowledge on human impacts on their life support system. We highlight path-dependencies of ideas that have informed PBc and point to potential gaps that could be explored in future concept developments.

We first build a 'genealogy' of the literature the Planetary Boundaries article cites as foundations, i.e. literature that is listed in 'the three branches of scientific inquiry' (Rockström *et al* 2009a) as well as the body of science upon which these branches rest. We review the science that informs the PBc to understand how the environmental and human components of sustainable development have been brought together, analysing how the PBc builds on and importantly *distinguishes* itself from two centuries of research on the perceptions of the limited capacity of the environment to support societies (since Malthus, 1798).

We support this analysis with insights from two seminal and a new consumer-resource models. Our purpose in using these models is didactic. They are an illustration of the overarching duality between conservation and poverty alleviation perspectives. Furthermore, they highlight interdependencies between aims of 'conservation' and 'poverty alleviation' and thus suggest a new perspective from which to build future integrated social-ecological sustainability concepts. Indeed, these models are part of the basis of the research on which the PBc is built (e.g. Lotka 1925) and they provide a caricatural yet analytically tractable analogy to human-environment relationships. In seminal consumer-resource models, limits are typically framed in two ways (see Box 1 for details): either as the maximum population size a resource base can support - often referred to as the carrying capacity (K) (Verhulst 1838), or as the minimum amount of resources consumers need to survive and produce a next viable generation - often referred to as Tilman's R* (Tilman 1982). This minimum amount of resource captures a key component of the Malthusian catastrophe (1798) which postulates that ultimately human population size will be limited by famine.

Box 1 Two seminal consumer-resource models

Logistic growth of the human population sensu Verhulst

The mathematician and demographer Verhulst (1845) was the first to explicitly model the limits to human population size with what he called the logistic curve:

$$\frac{dC}{dt} = r_{Cmax}C\left(1 - \frac{C}{K}\right) \Longrightarrow C^* = K$$

where C is number of humans (population unit), r_{Cmax} is maximum per capita birth rate (rate unit), C^* is maximum number of humans that can be sustained (population unit), which is equal to carrying capacity K (population unit). The model describes the shift from a positive feedback of population size on itself at low numbers towards a negative feedback of population size on itself at high numbers. Whereas the positive feedback at low numbers leads to an initial exponential growth phase, the negative feedback at high numbers makes population size settle at carrying capacity.

Human population size constrained by resource scarcity sensu Malthus

The strength of the logistic growth model is that it provides the limitations to population growth in its most condensed form. However, by being a heuristic model, it provides little insight into the mechanisms through which the negative feedback happens. For this we need an explicit consumer-resource model:

$$\frac{dR}{dt} = r_R R_{res} - l_R R - r_C q_{R\to C} C$$

$$\frac{dC}{dt} = r_C C - l_C C$$

with

$$r_C = r_{Cmax}\frac{R}{R + H_R}.$$

This model has two dynamically modelled state variables and seven parameters. R represents the available resources (resource unit), C the number of consumers (population unit), R_{res} the reserve from which resources are made available to consumers (resource unit), r_R the proportional rate at which resources are made available to consumers from the reserve (rate unit), l_R the background rate at which the available resources are lost without being consumed (rate unit), $q_{R\to C}$ the conversion from available resources to consumers (resource unit/population unit), r_{Cmax} the maximum per capita birth rate of consumers (rate unit), H_R the resource availability at which the realized per capita birth rate of consumers equals half of their maximum per capita birth rate (resource unit) and l_C the per capita mortality rate of consumers (rate unit). The auxiliary variable r_C represents the realized per capita birth rate of consumers as function of resource availability.

The model has two equilibria that we named a ‘pristine world’ (PRW) – in which resource density (R^*_{PRW}) is controlled by other processes than consumption and consumers (C^*_{PRW}) cannot exist or have not yet invaded the system:

$$R^*_{PRW} = \frac{r_R}{l_R}R_{res}$$

$$C^*_{PRW} = 0$$

and a ‘resource limited world’ (RLW) in which the sustainable number of consumers C^*_{RLW} is limited by the resource availability R^*_{RLW}:

$$R^*_{RLW} = \frac{H_R l_C}{r_{Cmax} - l_C}$$

$$C^*_{RLW} = K = \frac{r_R R_{res} - l_R R^*}{l_C q_{R\to C}}$$

One of the major outcomes of this model is that when the consumer population has reached its maximum sustainable size at carrying capacity $K = C^*_{RLW}$, the resource availability is reduced to a critical low value R^*_{RLW} that allows individual consumers to produce offspring at replacement level. Remarkably, this minimal resource availability R^*_{RLW} is not dependent on the size of the resource reserve R_{res} from which resources are extracted or the rate at which this happens r_R. Together, these findings seem to capture the essence of the Malthusian catastrophe (1798) that irrespective of any conceivable advancement in agricultural production, consumer population growth will always be able to catch up until the resources are again depleted to the same level as before and starvation once more limits offspring to replacement level. We can generalize the advancement in agricultural production on which Malthus focused to any technological innovation in society that increases its access to resources. Sensu Tilman (1982), the model can be expanded to capture the competition between individual consumers, or groups of consumers, that differ in their ability to acquire resources, i.e. the topic of inequality.

Whereas the seminal consumer-resource models of Box 1 capture the population dynamics of many organisms, its Malthusian assumption that scarcity in resources directly translates into increased consumer mortality is unrealistic in the context of contemporary societies. Moreover, when we started applying the K-R* analysis to each of the PBc's nine Earth system processes, we noted that at least six of the nine Planetary Boundaries relate to processes of waste accumulation rather than resource limitation (table 1). For these reasons, we interpreted the PBc in terms of a new Resource-Producer-Consumer-Waste (*RPCW*) model. Acknowledging that in modern societies, resource acquisition and limitation is driven by economics, we make a distinction between the production and consumption of resources and move from expressing consumers in terms of numbers into expressing them in terms of the resource they possess (Box 2). Moreover, the new model captures the deleterious impacts of waste accumulation on human consumption. We use the analogies with the seminal and the new consumer-resource models to analyse the evolution of limits in the concepts on which the PBc is built.

Methods

Genealogy of literature

We first create a genealogy of the literature on which the Planetary Boundaries is built by selecting the work cited in Rockström *et al* (2009a) as the three *'branches of inquiry*'. These branches of inquiry are: (a) the scale of human action in relation to the capacity of the Earth to sustain it; (b) understanding essential Earth System processes and (c) framing of resilience (See table SA1). From these 22 direct references, we use a 'snowball' approach to identify secondary sources. In each direct reference, we select the sources to the core ideas being developed (Figure 1). For example, Bretherton (NASA Advisory Council 1986, Earth System Sciences Committee 1988) cite Newton, Hutton, Lyell and Darwin as the founders of the Earth system science that is built upon. Similarly, Holling (1973) builds on analyses of diversity and stability by May (1971), Lewontin (1969) and MacArthur (1955)(*inter alia*). We do not select all possible secondary references, but we build a comprehensive library of 58 direct and secondary references. Finally, we analyse the relationship between these references, in a systematic 'who-cites-who' approach (see table SA2). Unfortunately, not all older secondary references were directly searchable. Also, we here emphasize that the approach is not sufficient for a quantitative or systematic analysis of the network of references, since the referencing method and style of individual authors, types of publications (journals, reports or books) are very different and somewhat arbitrary (Borgman 2015). Furthermore, some concepts and ideas are often not (or mis-) attributed (e.g. the concepts of carrying capacity or cybernetics for instance), and a search for references can be murkied when an author name is common (e.g. Thomas), confusable (e.g. E. P. Odum, vs. H. T. Odum) or a common verb or noun (e.g. May and Marsh).

Consumer-resource models

Here we present a new Resource-Producer-Consumer-Waste *(RPCW)* model that deals with the shortcomings of the earlier mentioned seminal consumer-resource models (see box 1 for details on these models) to illustrate some dynamical aspects of the Planetary Boundaries. The model identifies four pools of resources of which three are modelled dynamically. In the model resources (*R*) are used by producers (*P*) to make goods for consumers (*C*) who then turn these goods through usage into waste (*W*). For example, oil may be extracted from an underground resource reserve R_{res} and after refinery become part of the stocks held by producers *P*. From there it will enter the stocks held by consumers *C* through retail and finally be emitted to the atmosphere as waste *W* through combustion. To keep the model as simple as possible we defined each state variable in the same unit so that we can leave out conversion factors between resources in the reservoir, held by producers and consumers and in the waste compartment. For the oil example this would imply that all pools would be expressed in masses of carbon. For details on the *RPCW* model see box 2.

Box 2: A new Resource-Producer-Consumer-Waste model

The aim of the newly developed Resource-Producer-Consumer-Waste (RPCW) model is to add waste limitation to the resource limitation that is key to the seminal consumer-resource model described in Box 1. Moreover, instead of modelling the number of consumers, we now model the amount of resources they have in their possession thereby keeping the unit of all state variables in the model the same. Finally, we acknowledged that in human society resources are not taken up directly from the environment but rather acquired from producers who themselves obtain these resources from the environment. We used the following color codes to link the RPCW model with the 'three branches of scientific inquiry' underlying the PBc. Terms that describe how producers and consumers interact with the Earth system are marked blue. Interactions among producers and consumers are marked purple and those terms in the model that make it nonlinear are marked orange:

$$\frac{dP}{dt} = r_P R_{res} - l_P P - r_C C$$

$$\frac{dC}{dt} = r_C C - l_C C$$

$$\frac{dW}{dt} = l_C C - l_W W$$

$$r_C = r_{Cmax} min\left(\frac{P}{P + H_P}, \frac{{H_W}^b}{W^b + {H_W}^b}\right)$$

The model has three dynamics state variables and nine parameters. We decided not to model the resource reserve dynamically, but rather keep this state at a constant level R_{res} to keep the model simple and avoid the need to make a distinction between renewable and non-renewable resources. In the model *P* is the pool of resources made available by producers to consumers, *C* is the pool of resources acquired by consumers, *W* is the pool of resources turned into waste by consumers, r_C is the realized rate at which consumers acquire resources (rate unit), R_{res} is the reserve from which producers extract resources to make them available to consumers, r_P is the rate at which producers extract resources from the reserve (rate unit), l_P is the loss rate of unsold extracted resources (rate unit), r_{Cmax} is the maximum rate at which consumers acquire resources if they were not limited (rate unit), l_C is the realized rate at which consumers turn acquired resources into waste through usage (rate unit), H_P is the level of resources offered by producers to consumers at which the realized rate of acquisition of resources by consumers is half the maximum rate of acquisition (resource unit), H_W is the level of waste experienced by consumers at which the realized rate of acquisition of resources by consumers is half the maximum rate of acquisition (resource unit), *b* is the shape parameter of the waste limitation function for consumers (unitless) and l_W is the rate at which waste is lost through natural decay or active waste treatment (rate unit).

The *RPCW*-model has three sets of equilibria. We named the first set a ‘pristine world’ (PRW) in which there are only resources and no consumers, the second set a ‘resource limited world’ (RLW) in which the acquisition of resources by consumer is limited by resource scarcity, and the third set a ‘waste limited world’ (WLW) in which the acquisition of resources by consumers is limited by waste accumulation as follows:

Equilibria	Pristine World (PRW)	Resource Limited World (RLW)	Waste Limited World (WLW)
P^*	$\frac{r_P}{l_P} R_{res}$	$\frac{l_C}{r_{Cmax} - l_C} H_P$	$\frac{r_P}{l_P} R_{res} - \frac{l_W}{l_P} W^*_{WLW}$
C^*	0	$\frac{r_P}{l_C} R_{res} - \frac{l_P}{l_C} P^*_{RLW}$	$\frac{l_W}{l_C} W^*_{WLW}$
W^*	0	$\frac{l_C}{l_W} C^*_{RLW}$	$\left(\frac{r_{Cmax} - l_C}{l_C}\right)^{\frac{1}{b}} H_W$

We studied the impact of changing each of the model parameters on the values of the equilibria. These bifurcation analyses also show how changing the parameters can induce switches between the pristine, the resource limited and the waste limited world and at which critical parameter values this happens. (See Supplementary materials B for detailed output of these analyses). Here we give an overview of the general patterns that we found:

<table>
<tr><th rowspan="2">Parameter value*</th><th colspan="3">Pristine World (PRW)</th><th colspan="3">Resource Limited World (RLW)</th><th colspan="3">Waste Limited World (WLW)</th><th rowspan="2">Parameter value*</th></tr>
<tr><th>P^*</th><th>C^*</th><th>W^*</th><th>P^*</th><th>C^*</th><th>W^*</th><th>P^*</th><th>C^*</th><th>W^*</th></tr>
<tr><td>r_P
R_{res}
l_P</td><td>↗</td><td colspan="2">0</td><td>=</td><td colspan="2">↗</td><td>↗</td><td colspan="2">=</td><td>r_P
R_{res}
l_P</td></tr>
<tr><td>l_W</td><td colspan="3">NA</td><td colspan="2">=</td><td>↗</td><td>↗</td><td>↘</td><td>=</td><td>l_W</td></tr>
<tr><td>r_{Cmax}
l_C</td><td>=</td><td colspan="2">0</td><td rowspan="2">↘</td><td colspan="2" rowspan="2">↗</td><td>↘</td><td colspan="2">↗</td><td>r_{Cmax}
l_C</td></tr>
<tr><td>H_P</td><td colspan="3" rowspan="2">NA</td><td colspan="3">=</td><td>H_P</td></tr>
<tr><td>H_W
b</td><td colspan="3">=</td><td>↗</td><td colspan="2">↘</td><td>H_W
b</td></tr>
</table>

For each of the nine parameters of the model we specify the impact of changing that parameter on the equilibrium amount of resource held by producers (*P**), held by consumers (*C**) and in the waste compartment (*W**) goes up (arrow upwards), stays equal (=), goes down (arrow down), equals zero (0) or cannot exist (NA) in the pristine world, the resource limited world and the waste limited world. The font size of the parameters on either side of the table shows whether we increased (e.g. from r_P to r_P) or decreased (e.g. from l_P to l_P) a given parameter to move from the pristine through the resource limited to the waste limited world.

The main findings of this analysis can be summarized as follows. With increasing the values of r_P, R_{res}, r_{Cmax} and b (± increased access to resources) and with decreasing the value of l_P, l_W, l_C, H_P and H_W we move from the pristine world through the resource limited world to the waste limited world. Within the resource limited world, consumers can increase the amount of resources they possess by increasing r_P, R_{res} and r_{Cmax} or by decreasing l_P, l_C or H_P with the other parameters having no effect. Within the waste limited world, consumers can increase the amount of resources they possess by increasing l_W, r_{Cmax} or H_W or by decreasing l_C or b with the other parameters having no effect. The main message is when technological development only focusses on making resource more available (i.e. increasing r_P and R_{res} while decreasing l_P) we necessarily end up in the waste limited world, as seems indeed the case with six of the nine Planetary Boundaries being caused by waste accumulation (Table 1). The best options to find a balance between a resource limited and a waste limited world are by technological advancement in the waste treatment rate (i.e. increasing l_W) or reducing the realized consumption rate (i.e. decreasing l_C).

Results

The scale of human action in relation to the capacity of the Earth system to sustain it.

An overarching thematic of this branch of inquiry lies in the closed, finite nature of the Earth system (Boulding 1966), and its resources (Costanza 1991), building on von Bertalanffy's (von Bertalanffy 1960) work on steady-states and systems theory (tables SA1 & SA2). The main emphasis of this branch of inquiry rests at sub-global levels, where carrying capacities are understood as dynamic and variable (Arrow *et al* 1995, Odum 1989), and where diverse contexts matter as well as the heterogeneity of distribution of resources and environmental impacts. In this branch of inquiry, the burden of quantification and balancing is on the economic system - as a tool for the management of natural resources – and the environment is valued qualitatively (Arrow *et al* 1995, Costanza 1991). Ecological economics focuses on the rules for the sustainable management of natural resources: non-renewables should be exploited at a rate no higher than the substitution of non-renewable to renewable resources; renewable resources should not be extracted at a rate higher than the rate at which they renew; and technology should focus on making the use of resources more effective, rather than on making their extraction more effective. Most of the PBc's Earth system processes are addressed, not in the interest of determining their limits, but to determine appropriate accounting for impacts on these processes in the economic systems (e.g. as intergenerational impacts; as costs to those who benefit from making impacts). A strong thematic, reinforced in the framework of the tolerable windows approach, is the capacity for human control of impacts to the environment.

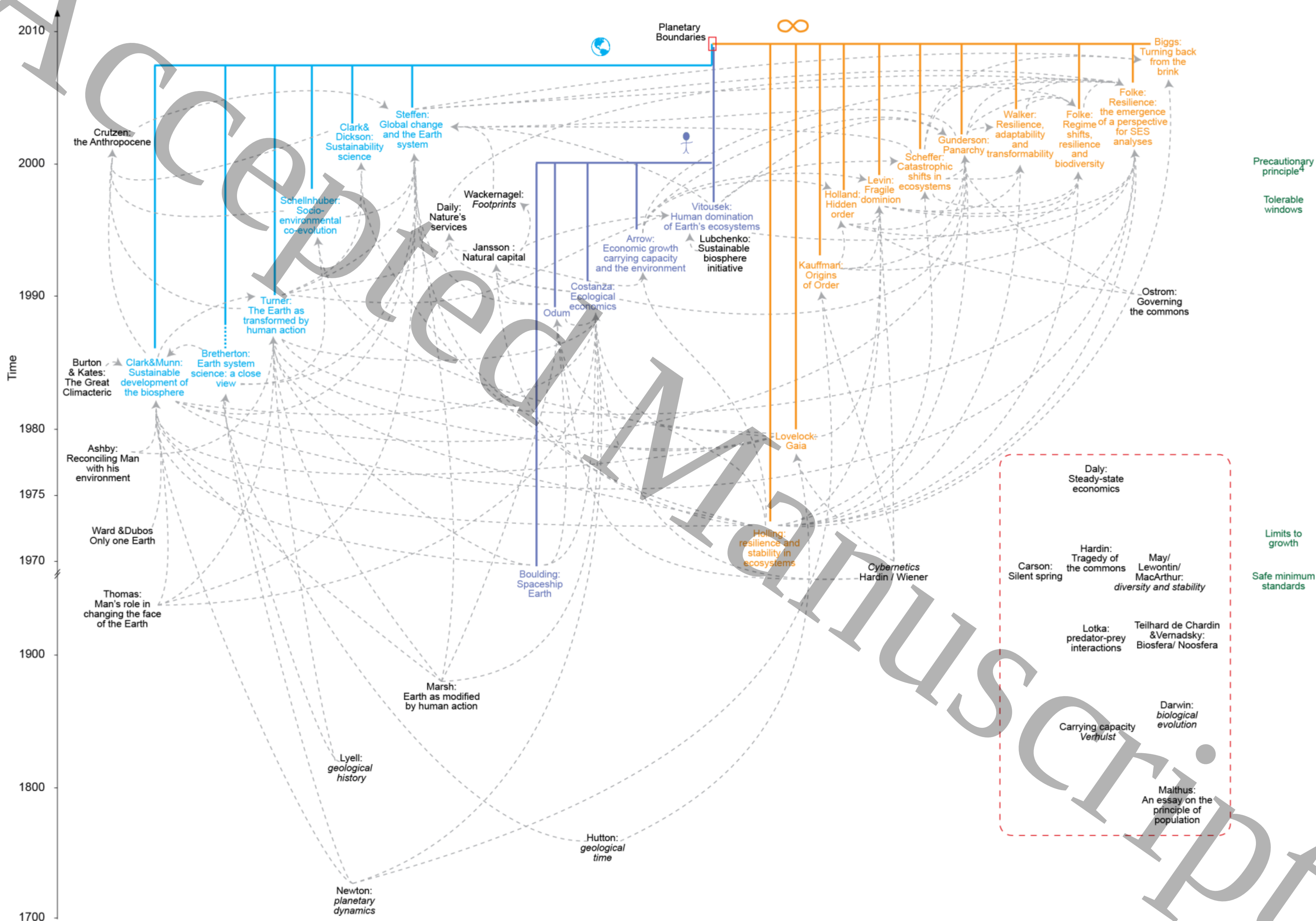

Figure 1: The genealogy of Planetary Boundaries science, references placed according to year of publication.. Couloured references represent those directly referenced in Rockström *et al* 2009. In blue, the branch of inquiry relating to understanding Earth system processes; in purple, the scale of human action in relation to the capacity of the Earth to sustain it; in orange, the framework of resilience; in green, the frameworks on which the PBc builds. In black are secondary references, i.e. those that shape the science on which the PB is built. For clarity, we have removed the lines representing citations between secondary references, and those for the secondary references that are cited more than 10 times (in red dashed box). For the full citation analysis, see table SA2.

Understanding essential Earth system processes

This branch of inquiry focused on understanding Earth system dynamics finds its roots as early as the 17th century, in Newton, then Hutton, Lyell, and Darwin. Turner *et al*'s book '*The Earth as Transformed by Human Action*' (1990) builds from Ashby's '*Reconciling Man with the Environment*' (1978), which in turn builds from Thomas *et al*'s '*Man's Role in Changing the Face of the Earth*' (1956), which itself finds roots in Marsh's '*The Earth as Modified by Human Action*' (1874) (figure 1, table SA2).

In this literature, the work of Clark and Munn (Clark *et al* 1986) has the broadest roots, drawing from economics (e.g. Boulding 1966), resilience (e.g. Holling 1973), and Earth system science to discuss not only sustainable levels of impacts, but also anthropological perspectives (e.g. contributions by Timmerman and Thompson 1986), on human perceptions and conceptions of sustainability, and ethics. 'Planet under Pressure' (Steffen *et al* 2004) follows on the approach and work of Marsh (1874), Thomas *et al* (1956), Ashby (1978), Turner *et al* (1990), Burton and Kates (1986), Bretherton (NASA Advisory Council 1986, National Research Council 1988) and Clark *et al* (1986) . Here the approach is to first understand and describe Earth system dynamics, then how impacts of humanity influence Earth system dynamics and finally, to address the critical questions regarding how Earth system change influences human well-being.

Schellnhuber (1999, Schellnhuber and Kropp 1998) take a slightly different approach, focusing on the co-evolving feedbacks between social-ecological systems and the potential breaking points of these feedbacks - Nature and Humanity are more closely integrated. This work builds on the concept of Gaia (Lovelock and Giffin 1969, Lovelock and Margulis 1974) and the concept of cybernetics, self-regulation and co-evolution. Geocybernetics (Schellnhuber and Kropp 1998) follows the line of thought of Vernadsky and de Chardin's Noösphere (Vernadsky 1986, de Chardin 1955, Levit 2000): where the self-regulating processes expand and evolve, technology and geocybernetics are the next steps of social-ecological co-evolution. Despite these slight differences in perspectives – where the first approach predominantly aims to quantify processes and the cybernetics approach tends towards understanding mechanisms and qualifying changes – the approaches don't contradict each other. Their commonalities are crystallized in the framing of the Anthropocene (Crutzen 2002), which brings together the co-evolutionary, cybernetic visions of the Biosfera (Vernadsky 1986), Noösphera (de Chardin 1955), Gaia (Lovelock and Giffin 1969), and Geocybernetics (Schellnhuber and Kropp 1998), with the understanding of Earth system dynamics and impacts of Human action thereon (e.g. NASA Advisory Council 1986, Earth System Sciences Committee 1988, Turner *et al* 1990, Clark *et al* 1986). The Earth system branch of inquiry builds towards the global level (see supplementary materials C, and as exemplified in Schellnhuber 1999), where the branch of inquiry on human impacts brings out differentiated contexts. Clark and Dickson (2003) is not about Earth system sciences, but rather on science and technology as both are seen to '*take as their point of departure a widely shared view that the challenge of sustainable development is the reconciliation of society's development goals with the planet's environmental limits'*. The article is in large part a response to global policy events and documents (such as the world summit on sustainable development in 2002, and United Nations 1992, 1987) that call for more research into sustainable development.

Resilience

The resilience and complex systems framing branch of inquiry has a central commonality on feedbacks and systems thinking. Where the Earth system branch looks at what the Earth system processes and elements are, the resilience branch of inquiry investigates how they interact (e.g. Holland 1995, Kauffman 1993, Gunderson and Holling 2002). The first edition of Gaia (Lovelock and Giffin 1969) assumed self-regulation and homeostasis. In later editions however, Human action is framed as a disruption to self-regulatory, homeostatic processes, and the author thus calls to containing human activities (Lovelock 1991, 1989). This contrasts with Schellnhuber's framing, where the expansion of human technology and knowledge to respond to human-induced environmental degradation is part of self-regulating processes. Though this difference is subtle – resting on a normative assessment of where limits between self-regulation and deregulation might stand – it also reflects a difference in underlying assumptions. In the same vein as the Noösphere, geocybernetics' socio-environmental co-evolution (Schellnhuber and Kropp 1998) assumes a level of determinism and directionality to evolution that is not present in the later versions of Gaia. Cybernetics and feedback mechanisms are core to the branch of inquiry of Resilience and to the PBc concept, but the assumption of directionality and self-regulation for or towards human well-being is not. In this way, PBc also responds to the perspectives of the intergovernmental Biosphere conference, which cites limits to the 'plasticity' of ecosystems and risks of irreversible changes (Unesco 1968).

The branch of resilience builds on the adaptive cycle (Holling 1986, Gunderson and Holling 2002), focusing on why feedbacks are important for humanity: the risk of catastrophic shifts and irreversible changes (Scheffer *et al* 2001, Biggs *et al* 2009), and how societies manage or can be trapped in such dynamics (e.g. Walker *et al* 2004). Holling's seminal work (1973) permeates across branches of inquiry, specifically the focus on sudden changes in systems, as opposed to gradual changes, and on the notion of stability, as dynamic rather than static (May 1971, Lewontin 1969, MacArthur 1955). Where the Earth science and human impacts branches of inquiry primarily describe impacts to the Earth system, the resilience framing brings in the notion of limits, dynamic, context and scale specific.

The three branches of inquiry, though distinct in field and themes of focus, share much common ground. All are rooted in the central work of Holling (1973) and build a common school of thought. Indeed, many of the authors in the genealogy, e.g. Holling, Odum, Boulding, Clark, Costanza, Schellnhuber and Folke, to name but a few, are co-authors in each other's articles, co-editors of books and contribute chapters in each other's books. Of course, the genealogy is not comprehensive, and key scientists whose broader corpus of work have shaped the thinking behind PB and its genealogy do not appear explicitly here, such as for example C.S. Elton, E.O. Wilson, A.H. and P.R. Ehrlich and S.R. Carpenter. This stems in part from the fact that in some instances, the critical ideas are related to people and their broad corpus rather than to specific references.

*Interpreting the PBc in terms of K and R**

Already most of the PBc's nine (eleven if the subdivision of Biosphere Integrity and Biogeochemical Flows is included) Earth system processes were addressed in Meadow's *et al*'s limits to growth (1972), and by the Bretherton diagram in 1986, essentially all Earth system processes defined in the PBc had been brought to the fore.

In the genealogy, the early literature relating to Earth system science centres on determining changes in the Earth system's carrying capacity (K), with the underlying assumption or corollary that this interferes with humanity's basic needs. These needs (R*) however are not specified beyond the need for sustainability (Clark *et al* 1986). In much of this literature, human requirements are basic physiological needs: (clean) water and air, food. Steffen *et al* (2004) incorporate a more systemic nature of needs, i.e. need for a relatively stable and predictable environment, which is core to the PBc's definition of a Safe Operating Space. Throughout this literature, needs are seen as homogeneous, common to the whole of humanity, though Steffen *et al* (2004) cite the heterogeneous distribution of vulnerability.

The literature on the scale of human action is built on three sublines of inquiry (Rockström *et al* 2009a, see table SA1). Ecological economics (Costanza 1991) and Biophysical constraints to the economic system (Boulding 1966, Arrow *et al* 1995, and Daly 1991), are sublines that look not at humanity but the social sub-system of economics, and link it to ecology. The sum of ecological economics is to align economic system structure and function to the structure and function of ecological systems, the focus is thus on the carrying capacity aspect of the environment. Works of Odum (1989) and Vitousek *et al* (1997) constitute the subline of inquiry on human well-being. In Odum, well-being relates to the Earth as a life support system: producing food, recycling water, assimilating waste and purification of air. Vitousek does not mention well-being, but the Earth model used places human activities at the top and forefront, and elements described are those that are vital (carbon, nitrogen) or have become harmful to life (harmful algal blooms). R* is only vaguely addressed in this branch of inquiry and is common to the whole of humanity, it does not address issues of distribution and equality that are key to consumer-resource models (Box 1). The works of Odum (1989) and Costanza (1991) lead to concepts of Ecosystem Services (Daily 1997), Natural Capital (Jansson *et al* 1994), and Ecological Footprints (Wackernagel and Rees 1998): though these concepts are products of a similar body of research, the PBc distances itself from their approaches by removing the notion of values (ecosystem services and natural capital), and independent individual limits (footprints).

Resilience thinking in this genealogy has its origins in environmental sciences, but aims to integrate social and ecological processes and understands thresholds in both human and environmental systems. Thresholds in the social system encompass more than basic physiological needs, they can be thresholds in economic or political processes. In such integrated systems, where resilience is specified as 'resilience *of what, to what*?' (Carpenter *et al* 2001b), carrying capacities (K) and minimum resource requirements (R*) are highly contextual but are framed as more systemic limits to '*basins of attraction*' (Gunderson and Holling 2002), found where resilience reaches zero. The PBc builds heavily on this body of research: the Safe Operating Space of Holocene-like Earth system dynamics represents a social-ecological basin of attraction. The resilience of this Safe Operating Space is being eroded along multiple axes of environmental degradation - the PBc's eleven Earth system processes, most of which are 'slow variables' – that act to change the overall size/resilience of the basin of attraction. The selection of these processes comes from Earth system sciences and represent (human impacted) Earth system processes. Social system processes are not included in those that might erode the resilience of the Safe Operating Space.

Table 1: Interpreting the PBc in terms of the RPCW model. For each boundary we first identify whether it primarily involves resource scarcity (marked in blue) or waste accumulation (marked in orange) and identify the critical resource of waste involved. Moreover, we identify whether the PB is defined in terms of a process or a state. Next we identify the fundamental imbalance that leads to crossing the boundary and the resulting unsustainability in terms of the parameters and states of the RPCW model. Finally we express the solution for not crossing the PB - and hence staying in the Safe Operating Space - in terms of the model parameters. For the PBs caused by waste accumulation this solution lies in reducing consumption (= decrease in I_C) or improving waste treatment (= increase in I_W). For the Planetary Boundaries dealing with resource scarcity in water and topsoil this solution lies in reducing the rate at which producers extract resources from the reserve (= decrease r_P). The solution to PB9 dealing with biodiversity is outside the scope of the RPCW model.

PB#	Planetary Boundary	Primary problem	Critical resource/ waste	Defined in terms of	Fundamental imbalance	Resulting unsustain-ability	Solution
PB1	Climate change	Waste accumulation	Greenhouse gasses	Process	$I_C\ C > I_W\ W$	Increase in W	Decrease in I_C or increase in I_W
PB2	Novel entities (chemical pollution)	Waste accumulation	Novel entities/ chemical pollutants	State	$I_C\ C > I_W\ W$	Increase in W	Decrease in I_C or increase in I_W
PB3	Stratospheric ozone depletion	Waste accumulation	Ozone-depleting substances	Process	$I_C\ C > I_W\ W$	Increase in W	Decrease in I_C or increase in I_W
PB4	Atmospheric aerosol loading	Waste accumulation	Fine particles/ droplets	Process	$I_C\ C > I_W\ W$	Increase in W	Decrease in I_C or increase in I_W
PB5	Ocean acidification	Waste accumulation	Carbon dioxide	Process	$I_C\ C > I_W\ W$	Increase in W	Decrease in I_C or increase in I_W
PB6a	Biochemical flows (nitrogen)	Waste accumulation	Nitrogen	Process	$I_C\ C > I_W\ W$	Increase in W	Decrease in I_C or increase in I_W
PB6b	Biochemical flows (phosphorus)	Waste accumulation	Phosphorus	Process	$I_C\ C > I_W\ W$	Increase in W	Decrease in I_C or increase in I_W
PB7	Freshwater use	Resource depletion	Water	Process	$r_P\ R_{res}$ unsustainable	Decrease in R_{res}	Decrease in r_P
PB8	Land system change (loss of topsoil)	Resource depletion	Topsoil	Process	$r_P\ R_{res}$ unsustainable	Decrease in R_{res}	Decrease in r_P
PB9a	Biosphere integrity (functional diversity)	Resource depletion	Functional diversity	State	R_{res} decreasing	Decrease in R_{res}	Not covered by the model
PB9b	Biosphere integrity (genetic diversity)	Resource depletion	Genetic diversity	State	R_{res} decreasing	Decrease in R_{res}	Not covered by the model

Interpreting the PBc in terms of resource scarcity versus waste accumulation

Four of the PBc's Earth system processes are resource depletion problems, and the remaining seven are waste accumulation problems (see table 1). For instance, the planetary rate of anthropogenic carbon dioxide emissions exceeds the biosphere's ability to sequestrate it (Anderies *et al* 2013, Hansen *et al* 2008) while aquatic ecosystems are receiving higher loads of nitrogen and phosphorus than they can absorb (Chang *et al* 2019).

In the genealogy outlined here, waste accumulation is first described as a geological process (Vernadsky 1986, Marsh 1874), not as a human impact on the Earth system threatening humanity's own existence. However, R. Carson's 'Silent spring' (Carson 1962) brings attention and interest in the problem of chemical pollution – her work is cited 13 times in this genealogy alone (see table SA2), is understood as a critical issue for the environment and people (Unesco 1968) and is seen as a turning point in the sustainable development policy world (Creech 2012). Waste accumulation – or pollution – as a systemic and global problem appears in Boulding (1966): "*Oddly enough, it seems to be in pollution rather than in exhaustion that the problem is first becoming salient. Los Angeles has run out of air, Lake Erie has become a cesspool, the oceans are getting full of lead and DDT, and the atmosphere may become man's major problem in another generation, at the rate at which we are filling it up with gunk. It is, of course, true that at least on a microscale, things have been worse at times in the past. The cities of today, with all their foul air and polluted waterways, are probably not as bad as the filthy cities of the pretechnical age. Nevertheless, that fouling of the nest which has been typical of man's activity in the past on a local scale now seems to be extending to the whole world society; and one certainly cannot view with equanimity the present rate of pollution of any of the natural reservoirs, whether the atmosphere, the lakes, or even the oceans*". Boulding blames pollution on a flaw in the economic system that could be regulated through taxes.

What characterises pollution or waste is not the same across references however. Lovelock (1979) frames waste as a necessary system dynamic throughput. A ban or tax on pollution would therefore be against natural order, but Lovelock blames a lack of sensibility for not '*putting industrial waste to good use*'. In Hardin (1963)'s understanding of cybernetic feedbacks, he addresses only natural waste, and calls for both its qualification and quantification. Limits to growth (Meadows *et al* 1972, 2004) call to not produce those substances that cannot be processed by the biosphere, reducing emissions rates of other substances, and re-using materials. The PBc thus builds on the science underlying systemic impacts of waste accumulation, and select the chemical pollution as boundary category (Rockström *et al* 2009a, – now labelled 'Novel entities' in Steffen *et al* 2015), representing both natural and synthetic matters . However, the PBc does not build on Boulding (1966) or Lovelock's (1979) perspectives to understand the social *processes* (e.g. taxation/economic system, incentives, 'sensibilities') that underlie excess, synthetic and/or toxic wastes, perhaps explaining why the ‘chemical pollution/novel entities’ category remains different to other PBc waste accumulation processes.

Discussion

The inquiries

Holling sowed the seed of the Planetary Boundaries concept in 1973, as his work influences all the branches of inquiry. The Earth systems understanding behind the Planetary Boundaries was in place already in 1986: The Bretherton diagram (NASA Advisory Council 1986, Earth System Sciences Committee 1988) brought together all Earth system processes, Clark *et al* (1986) compiled essential impacts of humanity and questions relating to the needs for humanity. This work built on Spaceship Earth (Boulding 1966), that framed the ultimate global limit of the single Earth system and repercussions for economic systems. Burton and Kates' (1986) work ‘The Great Climacteric, 1798-2048: the Transition to a Just and Sustainable Human Environment’ also provided inspiration to the titles of modern day sustainability concepts (Rockström *et al* 2009a, Raworth 2012, 2017). The 1968 Biosphere conference already brought to light the risk of irreversible changes that would threaten the welfare of present and future generations (Unesco 1968). Since 1986, the cited science has provided consolidation and framing. Crutzen (2002) for instance put the Earth system science and social impacts work together in his framing of the Anthropocene, which in turn justifies the safe space of the concept as the Holocene. The resilience work, from Scheffer *et al* (2001) to Biggs *et al* (2009) outlines the possible scenarios of overshooting boundaries, and the efforts necessary to stay within them. Much of the knowledge behind this work was already explicit in Sustainable development of the Biosphere (Clark *et al* 1986), where Holling first presented the adaptive cycle delineating the system dynamic phases of collapse and reorganisation (Holling 1986).

Relative or absolute limits?

We have described more than two centuries’ worth of research aiming to constrain human activities within environmental limits, culminating in the PBc. Science has made great progress in understanding the scale, extent and consequences of unsustainable development. Nonetheless, continued increases in humanity’s negative impacts on nature – its life support system – justifies repeating and expanding the science. We now discuss some of the ways in which the different environmental limits have been relativized in practice, in a way which perhaps undermines the warnings that emerge from scientific research, and justifies ever more research to demonstrate that human impacts on the natural environment are deleterious to human well-being.

In ecological economics, the environment is often framed as natural capital. Under this framing, the extraction limit of non-renewable resources is set as the rate at which renewable substitutes are being created (Jansson *et al* 1994). This implies that the real limit is not the non-renewable stock, but the creation of renewable substitutes, which is a technological issue. According to Moore's law, the observation that computers double in power every two years, technological advances know no limits (Moore 2006).

Limits to the extraction of renewable resources are often quoted as set by the regeneration rate of resources and assimilation rate of waste (Jansson *et al* 1994). However, such 'maximum sustainable' rates are not a constant, but a dynamic, system property (Odum 1989, Arrow *et al* 1995, May 1971). Also, there is a tendency to overshoot such limits (Odum 1989), which in itself has consequences on the future dynamics of the resource in question and its broader system (Carpenter *et al* 2001a, 2008), and thus its maximum sustainable limit of extraction (Holling 1973, Clark *et al* 1986).

Furthermore, when systems reorganise and restructure in response to resource stock collapses, baselines against which we measure the desired ecosystem dynamics or novel ecosystem services used also shift. For example, leading to the mid 1980s, Lake Victoria saw the rapid extinction of hundreds of native fish species and the upsurge of introduced Nile perch. The food web of Lake Victoria's ecosystem has adapted to the absences and presences of species, and lakeshore societies have transformed to social-economic systems that depend largely on Nile perch and the new food web. Management is now designed to manage fishing to the sustainable limits of the introduced species, not to recover previous species (Downing *et al* 2014). This example illustrates that the parallel R*, the needs of the population — or the ecosystem and resources we aim to maintain – can also shift (Mooij *et al* 2019).

The relativizations described above have perhaps in part shaped the scientific enquiry in a 'Red Queen's Race', where for each limit overshot, shifted or relativized, a new context for which to make the limit absolute has been sought. Perhaps in part also, the scientific method has shaped this line of inquiry by rejecting the null-hypothesis: first seeking the contexts in which a certain limit does not apply, then seeking the limits to new and yet unbound contexts.

The apparent contradiction between relative – and therefore potentially extendable – limits at sub-global levels and the absolute limit of the single planet is partly resolved in the literature that the PBc builds on: limits to sustainability are not carrying capacities to individual resources, or ecosystems but thresholds to system *dynamics*. Sustainable development seeks to produce those system dynamics in which societies can fulfil their needs and reap necessary resources in a way that supports the environment's ability to provide to these needs over time

(United Nations 1987). There is only one Earth for humanity (Boulding 1966, Ward and Dubos 1972), and the Earth system is not self-regulating for human well-being (c.f. Lovelock 1979, Costanza 1991), especially not when human impacts affect precisely those processes that enabled human life to develop in the first place. Therefore, sustainable development is not – and most certainly not only - about limits, it is about the processes and interactions that shape long term human survival and well-being. Sustainable development isn't the answer to the question '*How much?*' but to the question *'How?'*. This is briefly explored in Odum (1989), who calls for an 'about-face' to focus on managing to improve system inputs rather than maximising system outputs. Bretherton, Rockström et al and Steffen et al. argue that determining how or what societies should do is beyond the remit of their disciplines (but see Rockström *et al* 2017, Steffen *et al* 2018). Yet, establishing what not to do has insufficient impact.

What is sustainable and what kind of sustainability do we want?

The system identified as sustainable in the PBc is one where Holocene-like Earth system dynamics prevail. The assumption that Holocene-like dynamics are safe is based on a) the relative stability of the Holocene, b) the knowledge that societies did develop and thrive during this epoch and c) research pointing to the Earth system dynamics produced by current trends as being inhospitable for humanity (Steffen *et al* 2015, Richardson *et al* 2011, IPCC 2018). However, the PBc only assumes that Holocene-like Earth system dynamics are safe for all of humanity: *how* 8 billion people and counting can all be safe in Holocene-like dynamics, and maintaining those dynamics in the long run remains to be analysed. In short, Holocene-like Earth system dynamics is Rockström *et al's* (2009a) answer to the question '*what is sustainable?'.*

What constitutes sustainability - or the contexts or system dynamics that one wishes to maintain – is a normative choice. As stated in Clark *et al* (1986): *'If we accept the garden image as a useful one, two questions arise: What kind of garden do we want? What kind of garden can we get? The first of the questions - "What kind of garden do we want?" - ultimately calls for an expression of values. The values on which we have based this study - the kinds of garden we want - are suggested in our choice of title:* The Sustainable Development of the Biosphere*. The common sense meaning of "sustainable" is a good first approximation of our intended meaning. We seek to distinguish gardening strategies that can be sustained into the indefinite future from those that, however successful in the short run, are likely to leave our children bereft of nature's support.´*

The main message of the PBc is that current unsustainable trends in the Earth's social-ecological system increase the risks of passing thresholds beyond which these systems dramatically change structure and function. These new structures and functions may not be suitable for human life. More importantly: they may not be suitable to providing equal and sufficient quality of life to all. With this point, we touch on the PBc's Achilles' tendon: The Safe Operating Space does not effectively address R* - i.e. the issue of resource distribution for all of humanity. R* is better represented in the social foundations of Doughnut economics (Raworth 2017), where equity, equality, justice and the distribution of resources to all feature as necessary complements to environmental limits. These social foundations however remain void of context, expressed at a global level, and are thus difficult to implement.

An issue that remains to be resolved is thus in first focusing on the 'we' at sub-global levels, rephrasing Clark *et al* (1986)'s question to: *what gardens does* <u>*who*</u> *want*? To subsequently address the question of global sustainable development: *how* can the diverse and evolving understandings of sustainability be combined to achieve sustainable development for all? The combinations and compatibility of diverse and different perspectives of sustainability face many political and ethical challenges, and these are fields of research and knowledge that are absent from the PBc's genealogy. Indeed, even topics of equality and equity are hardly addressed in the genealogy (but see Majone 1986) and not in the PBc (Steffen *et al* 2015). It is important to recognise that the scientific genealogy that the PBc rests upon is deeply intertwined at its deepest roots: the authors of the work in the genealogy are part of a same school of thought, co-authors in each other's articles and books. A majority of the authors in this genealogy are male, from Europe and North America. This review – highlighting a stagnation in innovation since the 1980s – illustrates that little more progress can be made in understanding or guiding sustainable development without properly integrating the normative questions of resource and opportunity distribution. Addressing these questions appropriately must be done from a larger variety and diversity of perspectives than has shaped the PBc's genealogy.

The stories

Much of the literature presented here has been part of and influenced high level political fora, yet despite such high visibility the message has failed to yield sufficient response, much like Cassandra's dilemma.

One possible reason why scientific forecasts are seemingly ignored, could be - as outlined above - that they are not tackling the questions that can be acted upon: understanding *what* is sustainable (rather than what isn't) for a diversity of people, not just humanity, and *how* sustainability can be achieved.

A related issue lies in identifying human needs. Earth system sciences focus on needs for food, water and (clean) air. Multiple Earth system processes contribute to providing these resources, and human development ought not to compromise those supporting services. However, the direct quest to meet these needs is not the only nor the root cause of environmental degradation, but rather the social systems that have been designed around the provision of these environmental services: economic systems' unbounded growth, farming systems' pesticides, technological systems' waste for example. It is in the first place *how* basic needs are met that is unsustainable. Humanity's development comes with many complex and evolving needs. These needs are context specific, where contexts include past dynamics (e.g. the need for justice), local conditions, and external drivers (e.g. market prices for resources).

In addition, all needs have never been met by everyone: famine and the effects of drought have existed throughout the Holocene, as have poverty and conflict. Development during the Holocene was not sustainable, hence reaching a Safe Operating Space is not simply returning to Holocene-like dynamics, rather it is (re-)creating Holocene-like dynamics with transformed social-ecological system interactions and processes.

Finally, unsustainability is often framed as a problem of the future, that might be solved by technologies and knowledge of the future. Nonetheless, the processes that need to be transformed - of unsustainable extraction, waste production and of inequitable distribution of resources, power and opportunities - are problems of today. Silent spring (Carson 1962) and the hole in the ozone layer led to concrete actions (Creech 2012). Both of these described immediate existing problems. The risks and consequences of overshooting planetary boundaries are serious and would likely lead to a no-return: to engage change for sustainable development, we need to focus on why unsustainable development is a serious issue today.

We highlight above that part of the problem in effectively conveying the message of limits to sustainability, is that these limits are easily relativized and stripped of their contexts, and that baselines for what needs to be sustained also shift. Furthermore, the global perspective, in which all of humanity would theoretically be safe under Holocene-like dynamics, possibly only reflects a form of retrogressive development, in which few people see an improvement to their well-being and livelihoods. Issues of equality and fairness that are fundamental to sustainable development are absent in a single, global humanity: scaling and determining operating spaces that are safe and just to appropriate contexts is essential.

Sustainability is not about warning of what not to do, rather it lies in determining what to do, and sustainable development addresses *how* to do it: understanding the dynamics of systems and flows. Extractive, consumptive and production systems ought to be designed to support an economy based on re-generation, not (quantitative) growth (Raworth 2017). Technology ought to be designed to support and maintain flows of matter, for instance by minimising, re-using, or properly treating waste and thus slowing waste accumulation, not maximise extraction. Circular economic models that redesign today's dominant linear growth economic models have evolved in parallel to the development of the science behind PBc, and they are also largely inspired by Boulding's Spaceship Earth (Maitre-Ekern 2018). Such models, based on reducing raw material inputs and waste and pollution, are essentially supportive of an economy that reduces society's pressure on planetary boundaries. Yet circular economic models do not explicitly address sustainable levels of impacts. Importantly implementing these transformations in the design of sustainable social-economico-technical systems needs to account for social justice, distribution and inequalities (Odum 1989, Leach *et al* 2010, Raworth 2017).

Conclusions

As early as the 1960s (Carson 1962, Unesco 1968), and as late as the 1980s (United Nations 1987, Clark *et al* 1986, NASA Advisory Council 1986), all the messages of: a) irreversible damage of humanity's life support systems (at all scales) caused by human activities, b) the need for integrated interdisciplinary research to understand and achieve sustainable development and c) the crucial issues of equality and distribution for sustainability were well established in policy and scientific arenas. In this sense, the PBc rests on solid foundations. However, in this same sense, PBc does not appear to bring novel perspectives and solutions to the table. Scientific advances have allowed to decrease granularity and add some degrees of precision as to how unsustainable environmental degradation is and the risks posed by this degradation. However, by still not addressing the diverse and dynamic sources of social drivers and impacts on sustainability, PBc risks facing Cassandra's dilemma.

Defining and securing sustainable futures for all, across scales and reframing the narrative of sustainable development away from Cassandra's dilemma will require not only solid scientific foundations. It will also require broad foundations that are representative of the diversity of perspectives that shape and are shaped by (sustainable) development. It will require diverse and innovative perspectives, and one might argue that the first step in innovation is a step beyond the narrow box of perspectives so far included. Fields of ethics and humanities are mostly absent in the PBc, but are essential to tackling the challenges of determining sustainability across scales of space and time.

Understanding how social-ecological initiatives and processes combine and co-evolve to influence sustainable development ought to be within the mandate of scientific research: there is no evidence to suggest that scientists have been cursed in the same way as Cassandra, knowledge acquired through scientific research can and ought to be made useful to and usable by societies by both scientists and policymakers.

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Data availability statement

Any data that support the findings of this study are included within the article and its supplementary materials.

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