THE PLANETARY BOUNDARIES HYPOTHESIS

A REVIEW OF THE EVIDENCE

BY TED NORDHAUS
MICHAEL SHELLENBERGER
AND LINUS BLOMQVIST

BREAKTHROUGH INSTITUTE

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Ted Nordhaus, Chairman

Michael Shellenberger, President

Linus Blomqvist, Policy Associate,
Conservation and Development Program
(linus@thebreakthrough.org)

Graphic design and layout by Dita Borofsky
(ditaborofsky@comcast.net).

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BREAKTHROUGH
INSTITUTE

436 14TH STREET, SUITE 820, OAKLAND, CA 94612
PHONE: 510-550-8800 WEBSITE: WWW.THEBREAKTHROUGH.ORG

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EXECUTIVE SUMMARY

Since its publication in 2009, the planetary boundaries hypothesis has become a leading framework for thinking about global environmental problems. Authored by prominent earth scientists and published in *Nature* and other scientific journals, the planetary boundaries hypothesis posits that there are nine hard, global biophysical limits to human development — land-use change, biodiversity loss, nitrogen and phosphorous levels, freshwater use, ocean acidification, climate change, ozone depletion, aerosol loading, and chemical pollution — and suggests that crossing any of these boundaries may have catastrophic consequences for human welfare.

The planetary boundaries hypothesis has been embraced by the United Nations High-Level Panel on Global Sustainability and nongovernmental organizations such as Oxfam and WWF, is included in the UN Environment Program's Global Environment Outlook 5, and underpins a reform proposal for global environmental institutions by the Earth System Governance Project. It has also been proposed for inclusion in the outcome document of this year's United Nations Conference on Sustainable Development in Rio de Janeiro.

In this report, we review the empirical evidence for the planetary boundaries hypothesis, drawing upon an extensive literature review and informal peer review by leading experts.

KEY FINDINGS

- **SIX OF THE "PLANETARY BOUNDARIES" — LAND-USE CHANGE, BIODIVERSITY LOSS, NITROGEN LEVELS, FRESHWATER USE, AEROSOL LOADING, AND CHEMICAL POLLUTION — DO NOT HAVE PLANETARY BIOPHYSICAL THRESHOLDS IN THEMSELVES.** Real, global biophysical threshold elements exist in the global climate system, and partly also for ocean acidification (same driver as climate change, carbon dioxide), ozone depletion (regional tipping point averted), and phosphorous levels (tipping point extremely far off). But for all the remaining "boundaries," there are no global tipping points beyond which these ecological processes will begin to function in fundamentally different ways than they do at present or have historically. Hence the setting of boundaries for these mechanisms is an arbitrary exercise. A lax boundary may result in more degradation. A strict boundary less. But there is no evidence that exceeding the boundary will result in a fundamentally different magnitude of impacts associated with human activities.

- **ASIDE FROM THEIR IMPACTS ON THE GLOBAL CLIMATE, THESE NON-THRESHOLD "BOUNDARIES" OPERATE ON LOCAL AND REGIONAL, NOT GLOBAL, LEVELS.** This means that no global boundary can be meaningfully determined. For example, freshwater use, land-use change, or nitrogen levels in one region are ecologically independent of these processes or their impacts in other regions.

- **THERE IS LITTLE EVIDENCE TO SUPPORT THE CLAIM THAT TRANSGRESSING ANY OF THE SIX NON-THRESHOLD BOUNDARIES WOULD HAVE A NET NEGATIVE EFFECT ON HUMAN MATERIAL WELFARE.** While there may be many reasons to limit degradation and constrain human activities that impact upon natural resources and ecosystems, impacts of environmental change on human material welfare are typically both positive and negative, and the net benefit or cost varies with place, socioeconomic conditions, and many other factors. Hence, the same type of environmental change may in one place result in a net benefit for human material welfare, and in a different locale, a net loss.

EARTH SYSTEM PROCESS	SCALE OF PROCESS	GLOBAL-SCALE THRESHOLD
LAND-USE CHANGE	Local and regional	No
BIODIVERSITY LOSS	Local and regional	No
NITROGEN CYCLE	Local and regional	No
PHOSPHOROUS CYCLE	Possibly global	Speculative
GLOBAL FRESHWATER USE	Local and regional	No
OCEAN ACIDIFICATION	Global	Yes
CLIMATE CHANGE	Global	Yes
STRATOSPHERIC OZONE DEPLETION	Global	Partly
ATMOSPHERIC AEROSOL LOADING	Regional	No
CHEMICAL POLLUTION	Local and regional	No

IMPLICATIONS FOR SCIENCE AND POLICY

1. GLOBAL LIMITS MAY RISK MISLEADING LOCAL AND REGIONAL POLICY CHOICES.

For the six environmental processes that lack global biophysical thresholds, limits or boundaries cannot be set with reference to science alone. Changes in these systems necessarily entail continuous political and economic trade-offs between positive and negative impacts on human welfare, nearly all of which exist on local and regional, not global, scales. Specifying regional and local systems as global may in many cases result in misguided policies at the local and regional levels. Two cases illustrate this:

- Synthetic fertilizer — the main source of human nitrogen additions to the environment — boosts food production but may, if used excessively, cause groundwater pollution and "dead zones" in the coastal ocean. In some places, where nitrogen is used excessively, the negative impacts are substantial, and a reduction may be warranted. At the same time, there are other areas, notably many parts of Africa, where increased use of nitrogen in agriculture would yield very significant benefits for human welfare. Moreover, limiting nitrogen use in Africa would in no way mitigate the impacts of excessive nitrogen use in other regions. As such, the positing of a global boundary is of little use to policy makers in either those regions that underutilize nitrogen fertilizers, or those that overutilize them.

- Freshwater extraction meets direct human needs for consumption and irrigation, but may compromise riverine ecosystems. Just as there are places where water is scarce, and reducing human use may be preferred, in many rivers around the world, especially where population density is low, moderate increases in water extraction would not endanger ecosystem health. Furthermore, limiting human use of water in one river basin or aquifer does not ameliorate water scarcity elsewhere, thus making a global limit meaningless.

2. ENVIRONMENTAL FACTORS ARE AMONG MANY THAT INFLUENCE THE CLIMATE.

Most of the non-threshold systems interact with climate change in one way or another, putting greenhouse gases at the center of all the planetary systems. For example:

- Nitrogen can increase growth rates in plants and thereby stimulate faster uptake of carbon from the atmosphere.

- Land-use change is the source of a large share of global greenhouse gas emissions.
- Freshwater levels influence the ability of the terrestrial biosphere to act as a carbon sink.
- Carbon dioxide is the key driver of ocean acidification.

While no climate strategy is complete without accounting for environmental factors such as nitrogen, land-use change, and freshwater use, assigning them global boundaries confuses means (factors that influence the level of greenhouse gases in the atmosphere) with ends (climate stability). The fact that environmental processes can affect the level of greenhouse gases in the atmosphere and therefore constitute *means* to climate change mitigation does not mean that there is any absolute *boundary* for them.

3. ECOLOGICAL DEGRADATION HAS THUS FAR SHOWN LITTLE CORRELATION WITH GLOBAL MEASURES OF HUMAN MATERIAL WELFARE.

The planetary boundaries hypothesis rests on the assumption that environmental variables are closely linked to human welfare, and that, consequently, loss of ecosystem services or natural capital implies declining human welfare. This assumption, however, has thus far not stood up well to observed trends with regard to both human welfare and ecological degradation. Over the last few decades, human welfare has improved significantly on a global level, even as a majority of ecosystem services have declined.

4. WITH THE NOTABLE EXCEPTION OF CLIMATE, THERE IS LITTLE REASON TO ASSUME THAT OTHER CONDITIONS THAT CHARACTERIZED THE HOLOCENE ARE PARTICULARLY IMPORTANT TO HUMAN MATERIAL WELFARE.

The planetary boundaries hypothesis presupposes that the Holocene — the geological epoch spanning from the end of the last ice age to the Industrial Revolution — represents the most desirable state of the environment for human welfare.

While there are of course very good reasons to prefer the *climate* of the Holocene, which was relatively warm and stable, there is little evidence that land cover, nitrogen levels, biodiversity, or any of the other non-climate systems had in themselves a stability or level that was particularly beneficial for human development. In many ways, the human population and the level of material welfare that exist today fundamentally depend on the fact that some of the non-climate systems do not remain at Holocene levels. This would suggest that it is not the environmental conditions of the *Holocene* that have enabled human development in the past two hundred years, but the environmental conditions of the *Anthropocene*. For example:

- Nitrogen, in the form of synthetic fertilizers, and increased freshwater withdrawals for irrigation were of critical importance to the enormous increase in food production over the past century.
- Land-use change has been fundamental to expanding agriculture and thus feeding the world.
- *Until now*, the net benefit in terms of human welfare of using fossil fuels and thus emitting carbon dioxide to the atmosphere has been immense.

5. THE RELATIONSHIP BETWEEN HUMAN MATERIAL WELFARE AND ECOLOGICAL SYSTEMS IS BETTER EXPLICATED THROUGH TRADE-OFFS THAN BOUNDARIES.

The claim that the planetary boundaries represent "non-negotiable" limits upon human activities, development, or consumption that "exist irrespective of peoples' preferences, values, or compromises based on political and socioeconomic feasibility" is not supported by empirical evidence on either ecosystem functioning or the relationship between environmental change and human welfare. Instead, our review of the nine "planetary boundaries" suggests that there are multiple costs *and* benefits of human impacts on the environment, and that balancing these is an inherently political question — not one that science alone can resolve. Suggesting otherwise may harm the policy process, as it precludes democratic and transparent resolution of these debates, and limits, rather than expands, the range of available choices. The important role of the earth sciences in informing management of environmental problems would be enhanced by shifting focus to identifying and explicating various possible courses of action and the trade-offs they entail, as well as exploring both negative and positive impacts of environmental change on human welfare.

INTRODUCTION

The concept of planetary boundaries was described in a 2009 paper in *Ecology and Society*, written by a group of prominent scientists, including lead author Johan Rockström, Hans Joachim Schellnhuber, Will Steffen, Katherine Richardson, Jonathan Foley and Nobel Laureate Paul Crutzen. An edited, non-peer-reviewed summary was also featured in *Nature*, accompanied by online supplementary information.[1] Attempting to define environmental preconditions for human development, Rockström et al. identify key Earth system processes, quantifying for each process "the boundary level that should not be transgressed if we are to avoid unacceptable environmental change" (see Table 1).[2] Moving outside this "safe operating space for humanity" may, it is claimed, be "deleterious or even catastrophic for human well-being."[3] The baseline for the nine proposed planetary boundaries — the "desirable planetary state" — is defined as the environmental conditions of the Holocene, the geological epoch that lasted from the end of the last glacial period some 10,000 years ago until the Industrial Revolution. We now live in the Anthropocene, a novel epoch characterized by the dominant influence of humans on the Earth system.[4]

In the less than three years since its initial publication, the concept of planetary boundaries has come to assume an influential position in debates around global environmental sustainability. It featured prominently at the Planet Under Pressure conference in London in March 2012; was endorsed by the United Nations High-Level Panel on Global Sustainability; is included in the UN Environment Program's Global Environment Outlook 5; underpinned a much publicized proposal to reform global environmental institutions by the Earth System Governance Project; and has been embraced by nongovernmental organizations such as Oxfam and the World Wildlife Fund for Nature.[5] It was also proposed for adoption at this year's UN Conference on Sustainable Development in Rio de Janeiro.[6]

This report draws upon a wide range of scientific literature, as well as informal peer review, to critically assess the scientific validity of each proposed boundary — focusing, in particular, on land-use change, biodiversity, freshwater use, ocean acidification, and nitrogen. It also unpacks the key assumptions of the planetary boundaries framework, especially as it relates to the linkages between environmental conditions and human welfare.

PLANETARY BOUNDARIES: THE THEORETICAL FOUNDATION

In addition to Earth Systems science, the planetary boundaries hypothesis draws on the notion — common within ecological economics — of Earth's "carrying capacity" in relation to the scale of human activities.[7] Rockström et al. argue:

> *…human activities have [now] reached a level that could damage the systems that keep Earth in the desirable Holocene state. The result could be irreversible and, in some cases, abrupt environmental change, leading to a state less conducive to human development.*[8]

The novelty of the planetary boundaries framework — and its central justification — stems from its foundation in complex systems theory, or "resilience thinking."[9] Ecosystems and by extension Earth systems are seen as complex adaptive systems, and as such frequently have tipping points.[10] If pushed beyond certain thresholds, such systems may change dramatically and "flip" into a different state, potentially endangering human welfare.[11] Linear changes in a complex system, in other words, may accumulate to produce non-linear or even exponential changes. Under these conditions, environmental management cannot be based on strictly linear dynamics, but instead has to adopt as its main priority the avoidance of these tipping points.[12] Rockström et al. explain:

> *The planetary boundaries approach … incorporates the role of thresholds related to large-scale Earth System processes, the crossing of which may trigger non-linear changes in the functioning of the Earth System, thereby challenging social-ecological resilience at regional to global scales.*[13]

For instance, in terms of the climate, it has been suggested that global average temperatures should be kept at no more than two degrees Celsius over pre-industrial levels. Whether temperatures are 0.5 or 1.5 degrees Celsius higher is less important; the key concern is to avoid the non-linear, "runaway" climate change that might occur beyond two degrees. In this view, then, warming of no more than two degrees Celsius would represent the "safe operating space" for humanity in terms of climate change.

SETTING LIMITS

Rockström et al. identify nine systems or processes as planetary boundaries (nitrogen and phosphorous are grouped together as one boundary). For each of them, one or several key "control variables" are identified — for the climate, it is atmospheric concentrations of carbon dioxide and radiative forcing; for land-use change, it is the percentage of land area converted to agriculture, etc. The authors then, where possible, identify a quantitative limit, within which "unacceptable environmental change" is avoided. The determination of this limit follows the precautionary principle:

> *Planetary boundaries are values for control variables that are either at a 'safe' distance from thresholds — for processes with evidence of threshold behaviour — or at dangerous levels — for processes without evidence of thresholds.*[14]

Three of these boundaries have already been crossed: climate change, the rate of biodiversity loss, and the global nitrogen cycle. The boundaries for global freshwater use, ocean acidification, and the global phosphorous cycle are close to being crossed. The boundary values for two out of the nine proposed boundaries, aerosol loading and chemical pollution, have not yet been determined.

TABLE 1

EARTH SYSTEM PROCESS	CONTROL VARIABLE	PLANETARY BOUNDARY	CURRENT STATUS
LAND-USE CHANGE	Percentage of global land cover converted to cropland	≤15	11.7
RATE OF BIODIVERSITY LOSS	Extinction rate (number of species per million species per year)	≤10	>100 (transgressed)
NITROGEN CYCLE	Amount of N_2 removed from the atmosphere for human use (Mt N/year)	≤35	121 (transgressed)
PHOSPHOROUS CYCLE	Quantity of P flowing into the oceans (Mt P/year)	≤11	8.5-9.5
GLOBAL FRESHWATER USE	Consumption of freshwater by humans (km^3/year)	≤4,000	2,600
OCEAN ACIDIFICATION	Global mean saturation state of aragonite in surface sea water	≥2.75	2.90

EARTH SYSTEM PROCESS	CONTROL VARIABLE	PLANETARY BOUNDARY	CURRENT STATUS
CLIMATE CHANGE	(i) Atmospheric CO_2 concentration (ppm by volume)	≤350 ppm	387 (transgressed)
	(ii) Change in radiative forcing (W/m^2)	≤1	1.5 (transgressed)
STRATOSPHERIC OZONE DEPLETION	Concentration of ozone (Dobson unit)	≥276	283
ATMOSPHERIC AEROSOL LOADING	Overall particulate concentration in the atmosphere, on a regional basis	To be determined	
CHEMICAL POLLUTION	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in the global environment, or the effects on ecosystem and functioning of Earth System thereof	To be determined	

SYSTEM CATEGORIES

Rockström et al. define "categories of planetary boundaries" along two axes. The first axis concerns the "boundary character" and distinguishes between "processes with global-scale thresholds" and "slow processes without known global scale thresholds." The second axis concerns the "scale of process" and distinguishes between "systemic processes at planetary scale" and what they call "aggregated processes from local/regional scale." Hence, the only systems that have planetary thresholds or "boundaries" are climate change and ocean acidification, with stratospheric ozone being intermediary as its thresholds are regional rather than global. The remaining systems — land-system change, biodiversity, nitrogen and phosphorous, freshwater, aerosols, and chemical pollution — operate on local to regional levels and do not have any known global-scale thresholds.

> *We distinguish between boundaries that are directly related to sharp continental or planetary thresholds … and boundaries based on "slow" planetary processes with no current evidence of planetary scale threshold behavior.*[15]

LAND-USE CHANGE

SYSTEM CHARACTERISTICS: Local- to regional-scale; no known global-scale threshold.

CONTROL VARIABLE: Percentage of global land cover converted to cropland.

PROPOSED BOUNDARY: ≤15%

CURRENT STATUS: 11.7%

MOTIVATION: Land-use change may trigger "irreversible and widespread conversion of biomes to undesired states." It also affects carbon storage and resilience via changes in biodiversity and landscape heterogeneity.[16]

NO GLOBAL THRESHOLD

Land-use change itself does not have a global biophysical boundary or tipping point — Rockström et al. say one is "unlikely."[17] Instead, the authors include it in the planetary boundaries framework because it provides the "underlying resilience of the Earth System."[18] This choice reflects a subjective preference concerning the global trade-offs between the costs and benefits of land-use. As Bass remarks:

> *The 15-per-cent figure is not a consensus value that can be validated in the research literature, but rather is based on a sensible — though apparently arbitrary — expansion factor ... If a figure of 15 per cent cannot be authenticated scientifically, policymakers will want to know why they should pay attention to it. Why shouldn't, say, 20 per cent of land surface be used for farming? Or indeed, why not 10 per cent?*[19]

IMPACTS ON OTHER "BOUNDARIES"

Rockström et al. justify limiting land-use change partly based on its impacts on biodiversity, climate, and the hydrological cycle. However, these systems are already boundaries themselves, and land-use change is therefore only one of many factors feeding into these systems.[20] This is partly recognized by Rockström et al.:

> *In setting a terrestrial land boundary in terms of changes in cultivated area, we acknowledge the limitations this metric entails given the tight coupling with the other boundaries of P [phosphorous] and N [nitrogen] use, rate of biodiversity loss, and global freshwater use.*[21]

There is no a priori reason why land-use change could not be traded off against other determinants of these three boundaries. This further warrants against setting an arbitrary cut-off point or boundary for this system.

A FLAWED ASSUMPTION

The authors assume that the conversion of land to agriculture leads to a "loss of ecosystem functioning and services" and that this in turn "risk[s] undermining human well-being and long-term sustainability."[22] In short, land-use change is seen as inherently undesirable, and should therefore be limited. However, this wholesale classification of land-use change stands up poorly to theory as well as empirical evidence. As Bass remarks:

> *Readers will want to know the basis for the authors' contention that land-use change undermines human well-being. If anything, the opposite has probably been more true: converting land for farming and for industry has clearly delivered a great deal of well-being, and populations will continue to find such land-use change both attractive and desirable.*[23]

The Millennium Ecosystem Assessment (MEA), which set out a framework for ecosystem services, counts food — including crops and livestock — as a provisioning ecosystem service. Both of these have seen a "substantial production increase" over the last 50 years.[24] Other ecosystem services, associated with forests and other "natural" ecosystems, have declined in the same period.[25] According to this framework, then, land-use change implies that one set of ecosystem services has been replaced with another — an observation that does not imply that this is necessarily negative. Increased food production has been fundamental to rising human well-being and may plausibly outweigh other ecosystem services, especially regulating ones like air quality regulation and disease regulation, in terms of its effect on indicators of human well-being such as the Human Development Index.[26] Indeed, vast expanses of forest have been converted to agricultural land in Europe and the United States over the last centuries and millennia, allowing for growing populations and food supply. Hence, the claim that land-use change equals only the loss of ecosystem services, and has but negative impacts on human well-being, is unsupported even within the MEA framework.

In reality, there are multiple costs and benefits to any particular land-cover change, and the net of these is a political, social, and economic question.[27] These trade-offs cannot possibly be determined based only on the biophysical characteristics of the system, although that is of course one of the factors to account for in the decision. In many cases in the developing world, conversion to agriculture leads to expanded economic opportunities on local to national scales, even as a cost may be incurred on the global level — for example, in the form of biodiversity loss. Setting a limit to land-use change, therefore, represents a rather one-sided environmental constraint without adequate regard for human material welfare and the trade-offs inherent in land-use decisions. This is well illustrated by the fact that Rockström et al. suggest imposing restrictions on per capita food consumption, while promoting the preservation of "high conservation-value forests and other ecosystems in their current states."[28]

This is *not* to say that land-use change is inherently good or that it should be promoted: the negative effects on the environment and on human welfare are very real. Rather, we argue that planetary boundaries are simply not an adequate framework for dealing with the complex, multiscale interactions between land-use change, on the one hand, and biodiversity, food security, aesthetic values, and other factors, on the other.

A SUBJECTIVE PREFERENCE FOR PRISTINE NATURE

Given the mixed empirical evidence on the impacts of land-use change on human welfare, Rockström et al.'s assumption that land-use change is only negative or that it automatically implies "loss" is only possible based on a strict Holocene baseline, and a separation of notionally "natural" and "human" land-cover types, where the natural ones are seen as inherently superior. This separation between "human" and "natural" landscapes is empirically flawed, since humans dominate or influence nearly the entire ice-free surface of the planet.[29] Hence, in the vast majority of cases, land-system change implies a transition from one anthropogenic ecosystem to another, rather than a transition from natural to anthropogenic.

Perhaps more important, the authors leave unanswered the question as to why the Holocene baseline is superior. There is no evidence that land-use change at the Holocene baseline corresponds to the optimal state from a human welfare perspective. The Holocene baseline is in itself neither scientifically correct nor incorrect as it constitutes a value-laden, subjective judgment rather than any scientific fact. Lacking evidence for the desirability of the Holocene for human material welfare, the boundary boils down to an aesthetic or spiritual preference. Science alone cannot answer the question of which land cover there *ought* to be in any particular place.

BIODIVERSITY LOSS

SYSTEM CHARACTERISTICS: Local- to regional-scale; no known global-scale threshold.

CONTROL VARIABLE: Extinction rate, extinctions per million species per year (E/MSY).

PROPOSED BOUNDARY: ≤10 E/MSY

CURRENT STATUS: >100 E/MSY

MOTIVATION: Biodiversity loss "affects ecosystem functioning at continental and ocean basin scales." It also has an impact on many other boundaries, such as C storage, freshwater, N and P cycles, and land systems. Furthermore, massive loss of biodiversity, according to Rockström et al., is "unacceptable for ethical reasons."[30]

WHAT DOES GLOBAL AGGREGATE BIODIVERSITY MEAN FOR THE FUNCTIONING OF ECOSYSTEMS?

Rockström et al. state that "biodiversity loss occurs at the local to regional level."[31] This is, however, not entirely true. While global biodiversity has in all likelihood declined,[32] on local and regional levels the evidence is more mixed, and species diversity has in many cases *increased* on these scales during the Anthropocene.[33] The mechanism behind this is that — against the backdrop of global biotic homogenization[34] — in any one place, extinctions of native species have in most cases been fewer than the number of new arrivals, leading to a net increase in local species richness. On many oceanic islands, for example, the number of plant species has doubled as a result of species introductions.[35]

This has important implications for conclusions about the impact of changes in global biodiversity on ecosystem functioning and services. There is a consensus among ecologists that, at local sites, on average, "greater [plant] diversity leads to greater productivity in plant communities, greater nutrient retention in ecosystems and greater ecosystem stability."[36] Most of the evidence for this comes from laboratory studies or small patches of grassland, and the degree to which this can be scaled up (especially to a regional or global level) is possibly very limited. The commonplace inference from this is that global biodiversity loss — as currently witnessed — leads to a weakening of global ecosystems. However, this chain of reasoning is undermined by the evidence that global biodiversity loss has not in fact been paralleled by losses on local and regional scales, which is where ecosystem dynamics chiefly operate.[37] In an analysis of over 1,000 field studies, Vilà et al. showed that on average, "abundance and diversity of the resident species decreased in invaded sites, whereas primary production and several ecosystem processes were enhanced."[38] This appears to suggest that, on shorter timescales and averaged out over many places, the current trend of global homogenization and local increases in species richness may maintain or even enhance ecosystem processes, which is the exact opposite of what is generally predicted. It can be concluded, then, that the relationship between global aggregate biodiversity and ecosystem functioning is far from simple or direct[39] and that a single boundary that does not take the local, regional, and global dynamics into account will fail to adequately capture the trends and consequences of changes in biodiversity. It would be theoretically possible, for example, to halt biodiversity loss — and thus stay within the suggested limit — while ecosystem health continues to deteriorate in most places, and vice versa.

THE BOUNDARY RATE

Rockström et al. have set the boundary level for biodiversity loss to an extinction rate of 10 extinctions per million species-years. This corresponds to 1 percent of species going extinct per millennium, or roughly 0.1 percent of species per century. In other words, if the boundary rate was maintained until the year 2112, no more than 1 percent of biodiversity would have been lost. This rate would have to be maintained for 138,000 years to qualify as a mass extinction (commonly defined as losing 75 percent of species in a short geological period[40]). This is not only extremely precautionary, it also illustrates that a *rate* of biodiversity loss has little meaning without an explicit timeframe. Rockström et al. do admit that defining the boundary as a rate, rather than an aggregate level, is a weakness:

> *Ideally, a planetary boundary should capture the role of biodiversity in regulating the resilience of systems on Earth. Because science cannot yet provide such information at an aggregate level, we propose extinction rate as an alternative (but weaker) indicator.*[41]

Assumptions about human impacts on biodiversity that extrapolate beyond a few hundred years are scarcely useful, given the uncertainty about future human resource needs and the state of the Earth system. It is the absolute *level* of biodiversity that impacts Earth system functioning, not the rate of loss at the margin. This remains an important research challenge, but until it has yielded any answers, a rate of biodiversity loss cannot substitute for the lack of knowledge on the role of biodiversity in regulating the resilience of systems on Earth.

THE CURRENT RATE OF EXTINCTIONS

Rockström et al. claim that current extinction rates are 100 to 1,000 times more than the natural background rate. This calculation is not well supported by evidence. The background rate is assumed to be one extinction per million species-year, corresponding to 0.1 percent of species going extinct per millennium. But less than 1 percent of all organisms are recorded to have gone extinct in the last few centuries, representing a rate only one order of magnitude higher than the background rate.[42] What is more, the vast majority of these extinctions have occurred on islands. Loehle and Eschenbach show that "only six continental birds and three continental mammals were recorded in standard databases as going extinct since 1500."[43] This yields continental extinction rates for mammals and birds of 0.89 – 7.4 times and 0.60 – 5.9 times the background rate, respectively. To arrive at higher extinction rates than that requires an assumption that some extant species are bound to go extinct and that, consequently, there exists an "extinction debt" that will take decades or centuries to play out. Even so, we appear to be relatively far away from anything like a sixth mass extinction. For example, Barnosky et al. calculate that "if extinction were limited to 'critically endangered' species over the next century and those extinction rates continued, the time until 75% of species were lost per group would be 890 years for amphibians, 2,265 years for birds and 1,519 years for mammals."[44] If we assume that all species that are currently critically endangered would go extinct over a 500-year period, it would take up to 10,000 years before it would qualify as a mass extinction.[45]

BIODIVERSITY AND HUMAN WELFARE

Last, but perhaps most important, Rockström et al. offer no discussion of or evidence for the assumed linkages between biodiversity and human well-being. In the absence of such evidence, and clearer causal linkages between global biodiversity and the functioning of ecosystems, the suggested planetary boundary for biodiversity appears to boil down to some combination of the precautionary principle and an intrinsic or aesthetic preference for high levels of biodiversity. These preferences are not in themselves invalid. They do not, however, necessarily imply a non-negotiable "urgent need to radically reduce biodiversity loss rates" for the sake of human material welfare.

GLOBAL NITROGEN CYCLE

SYSTEM CHARACTERISTICS: Local- to regional-scale; no known global-scale threshold.

CONTROL VARIABLE: Amount of N_2 removed from atmosphere for human use (Mt N/year).

PROPOSED BOUNDARY: ≤35 Mt N/year

CURRENT STATUS: 121 Mt N/year

MOTIVATION: Nitrogen "affects overall resilience of ecosystems via acidification of terrestrial ecosystems and eutrophication of coastal and freshwater systems."[46]

NO GLOBAL THRESHOLD

While "local to regional-scale interference with the nitrogen cycle … has induced abrupt shifts in lakes and marine ecosystems," Rockström et al. admit that there is no evidence for any global tipping point with regards to nitrogen.[47] This puts nitrogen in the same category of non-threshold systems as freshwater and land-use change, with similar implications. Lacking a global biophysical boundary, there is no scientific justification for the specific boundary level chosen.[48] What is more, several of the justifications for the planetary boundary for nitrogen really concern biodiversity and climate, and thus do not as such justify the existence of a separate boundary for nitrogen. There is no a priori reason why nitrogen — as one of many variables influencing climate and biodiversity — could not be traded off against other factors.

NET BENEFITS FOR HUMAN WELFARE AND THE HOLOCENE BASELINE

The overriding problem with the suggestion to cut nitrogen additions by nearly three quarters — as implied by the chosen boundary level — is its disregard for human material welfare. It is highly questionable whether it can be said that there is simply too much reactive nitrogen in the environment, and whether a reduction in global aggregate levels would translate into a net long-term improvement in human welfare. Without synthetic fertilizers — the main human source of reactive nitrogen inputs to the environment — "the enormous increase in food production over the past century, which in turn has sustained the increase in global population, would not have been possible."[49] According to Robertson and Vitousek, the net benefits of anthropogenic nitrogen additions to the environment are "huge."[50] This suggests that the Holocene baseline may not be an appropriate target for nitrogen.

NEGATIVE AND POSITIVE IMPACTS OF EXCESSIVE NITROGEN

Nevertheless, excessive nitrogen application in agriculture has "substantial and manifold" negative consequences.[51] These include: i) eutrophication of terrestrial and aquatic ecosystems, altering their biodiversity and functioning, often in the form of higher net primary productivity and lower species diversity;[52] ii) the development of hypoxic (oxygen-free) conditions in the coastal ocean and consequent elimination of deep-water organisms that require oxygen;[53] iii) acidification of soils and freshwater;[54] iv) formation of nitrous oxide which is a potent greenhouse gas, contributing about 6 percent of anthropogenic radiative forcing;[55] v) other forms of air pollution with negative health impacts;[56] and vi) groundwater contamination by nitrate, again with negative impacts on human health.[57]

Environmental consequences of human nitrogen inputs to the environment are not uniformly negative, something that introduces difficult trade-offs for policy and management on all scales. For example, increased nitrogen levels may for example — as in (i) above — boost plant productivity and thereby global net primary production and carbon sequestration in the terrestrial biosphere.[58] This effectively constitutes a negative feedback to climate change by reducing the level of carbon dioxide in the atmosphere. The opposite may also be true, if excess nitrogen reduces the ability of ecosystems to sequester carbon.[59]

SPATIAL COMPLEXITY AND DIRECTION OF CHANGE

Rockström et al.'s focus on a global aggregate limit overlooks the spatial complexity of the nitrogen cycle and its relationship to human welfare. The "fundamental challenge in agricultural nitrogen management," according to Robertson and Vitousek, is to "enhance agricultural productivity to reduce hunger, feed a growing population, and support changing demands for food — while simultaneously reducing the transfer of reactive N to nontarget ecosystems."[60] In terms of enhancing agricultural productivity, the reality is that synthetic fertilizer application is highly uneven on a global scale, ranging from "inputs that are inadequate to maintain soil fertility in parts of many developing countries, particularly those of sub-Saharan Africa, to excessive and environmentally damaging surpluses in many developed and rapidly growing economies."[61] Hence, the appropriate measure in many parts of the world, in terms of human material welfare, would therefore be to *increase* nitrogen input,[62] while in other parts of the world, excessive nitrogen application can be reduced or eliminated while maintaining or enhancing yields.[63] This undermines the capacity of the planetary boundaries framework to inform policy, since the direction of change in aggregate global nitrogen levels is not necessarily the same as the direction of change in human welfare.

GLOBAL FRESHWATER USE

SYSTEM CHARACTERISTICS: Local- to regional-scale; no known global-scale threshold.

CONTROL VARIABLE: Consumptive blue water use (km^3/year).

PROPOSED BOUNDARY: ≤4000 km^3/year

CURRENT STATUS: 2600 km^3/year

MOTIVATION: Global freshwater use "could affect regional climate patterns (e.g., monsoon behavior)." It has a range of other impacts, including on "moisture feedback, biomass production, carbon uptake by terrestrial systems and … biodiversity."[64]

A GLOBAL PERSPECTIVE ON FRESHWATER

Traditionally, the river basin has been seen as the "most appropriate unit for analysis, planning, and institutional arrangements."[65] However, as a result of globalization, water today is an issue that increasingly crosses ecological and national borders. Water is in some cases physically transferred from one basin or country to another, and about one fifth of the global annual water footprint is destined for export, embodied in food and other products.[66] This has led to calls to embrace a global perspective on water governance.[67] However, there are no *ecological* thresholds for freshwater use that are strictly *global*; the evidence that exists for water-induced thresholds is limited to local and regional scales. It may be that, as Rockström et al. claim, continental- and planetary-scale thresholds "may be crossed as a result of aggregate sub-system impacts at local (e.g., river basin) or regional (e.g., monsoon system) scales."[68] This, however, seems to suggest that local and regional — i.e., more geographically specific — boundaries would be more appropriate in order to avoid such potential global effects.

GLOBAL RENEWABLE FRESHWATER RESOURCES AND HUMAN CONSUMPTION

Renewable freshwater resources (RFWR) consist of the water yearly replenished in the process of water turnover on the earth and, on a global level, roughly equal annual runoff from rivers.[69] Global RFWR have been estimated to total around 40,000 km^3/year.[70] Currently, annual total blue water (rivers and groundwater) withdrawals amount to about 4,000 km^3/year.[71] Some of this water is eventually returned to the basin and can be used again. Final consumption of blue water resources — which consists of the water that is lost through evaporation or integration in products — is therefore smaller.[72] Most estimates of consumptive use of blue water fall between 2,000 and 3,000 km^3/year,[73] with the exception of Hoekstra and Mekonnen, who estimate the total annual blue water footprint at about 1,000 km^3/year.[74]

FRESHWATER SCARCITY: A RESULT OF SPATIAL AND TEMPORAL UNEVENNESS

In spite of using only a fraction of the global aggregate renewable freshwater resources, as many as 2.7 billion people live in basins with severe water scarcity during at least one month of the year — with countless impacts on human welfare and sustainability.[75] The cause for this apparent paradox is at least twofold. First, freshwater is very unevenly distributed in space, and a large proportion of it occurs in regions with very low population densities whereas some other regions suffer from chronic water scarcity. For example, according to Gleick, current water withdrawals are already "as much as 24% to 30% of total supply in parts of southern and central Europe [while] in the northern part of the continent, there are regions where these values never exceed 3%."[76] Trade — accounting for about one fifth of the global annual water footprint of humanity[77] — can mitigate this inequality to some degree.[78] Second, freshwater is unevenly distributed in time — on average, more than half of global runoff occurs as floodwater, and as such, its capture requires the construction of reservoirs.[79]

DERIVING THE PLANETARY BOUNDARY

The only truly biophysical, non-arbitrary "boundary" for freshwater use is the quantity of renewable freshwater resources, estimated at roughly 40,000 km^3/year. However, consuming a full 100 percent of this is both impractical (for reasons outlined above) and would compromise other uses of freshwater, including ecosystem health and navigation. Setting a boundary for sustainable use accounting for these factors necessarily involves values and trade-offs. According to Hoekstra et al., ecological health is compromised when the ratio of blue water consumption in a basin to the blue water available exceeds 20 percent.[80] Their cutoff for "severe water scarcity" is at 40 percent of natural runoff, which is the same as the definition of water scarcity in a study commissioned by the UN Commission on Sustainable Development.[81] These are measures designed for water basin or national levels. Still, applied heuristically to the global level, they would suggest a sustainable limit of something in the order of 8,000 km^3/year (for 20 percent cut-off) to 16,000 km^3/year (for 40 percent cut-off).

Rockström et al. arrive at the much lower 4,000 km^3/year "planetary boundary" by arbitrarily subtracting freshwater resources that are not currently exploited, but this "boundary," in fact, is not biophysical or ecological at all — it depends on the current capacity of dams and on which rivers are used for human ends. The methodology can be traced back to a 1996 paper by Postel et al. and includes the following steps.[82] Beginning with the global annual RFWR (40,700 km^3/year), Postel et al. i) subtract freshwater occurring in sparsely populated regions such as the Amazon basin (7,733 km^3/year); ii) subtract the 73 percent of remaining RFWR that is floodwater and therefore "much harder to capture" (23,967 km^3/year); and iii) add the amount of runoff regulated by existing reservoirs (3,500 km^3/year). The result is a total of 12,500 km^3/year of "total accessible runoff." (A more recent estimate of total actual water impoundment to date has it at 10,800 km^3.)[83] Rockström et al. then take 40 percent of this figure as the limit for sustainable use, following Hoekstra et al.'s definition of water scarcity above, and subtract from the remaining 5,000 km^3/year another 1,000 km^3/year for good measure, to arrive, finally, at the planetary boundary of 4,000 km^3/year.

HUMAN WELFARE

Given the current spatial and temporal variability in freshwater availability, and the urgent need to increase water consumption in many parts of the developing world, the approach taken by Rockström et al. appears not to be particularly useful: the implied direction of change on a global level does not translate into policies on sub-global levels. Indeed, the boundary's rationale was never a concern for human material welfare *directly*, but rather the maintenance of ecosystem health:

> *A planetary boundary for freshwater resources must thus be set to safely sustain enough green water flows for moisture feedback (to regenerate precipitation), allow for the provisioning of terrestrial ecosystem functioning and services (e.g., carbon sequestration, biomass growth, food production, and biological diversity), and secure the availability of blue water resources for aquatic ecosystems.*[84]

OCEAN ACIDIFICATION

SYSTEM CHARACTERISTICS: Systemic process at planetary scale; global-scale threshold.

CONTROL VARIABLE: Global mean saturation state of aragonite in surface sea water.

PROPOSED BOUNDARY: ≥2.75

CURRENT STATUS: 2.9

MOTIVATION: Ocean acidification may induce "conversion of coral reefs to algal-dominated systems," as well as lead to "regional elimination of some aragonite- and high-magnesium calcite-forming marine biota." It also affects the marine carbon sink.[85]

A PLANETARY-SCALE THRESHOLD SYSTEM

Ocean acidification fulfills the two main criteria for being a planetary-scale threshold system. It is *global*, since its driver — atmospheric carbon dioxide concentrations — is roughly uniform across the surface of the planet. It has *thresholds*, since some waters — chiefly in polar regions — may go from being supersaturated to undersaturated in aragonite calcium carbonate. Ocean acidification has potentially wide-ranging effects on marine life, the most direct being on calcification — the process by which many organisms build their shells and skeletons — but also second-order effects on communities and ecosystems. As with climate change, then, identifying these risk zones is an important scientific undertaking, and management must take these global tipping points into account. Indeed, under a precautionary approach, the suggested boundary may represent what Brewer calls a "reasonable" limit, given the very high level of uncertainty and potentially widespread consequences.[86] A single global limit for ocean acidification, however, suffers from three weaknesses.

KEY VARIABLE IS ATMOSPHERIC CARBON DIOXIDE CONCENTRATIONS

The added value of a boundary for ocean acidification is unclear, as it relates directly to another planetary boundary — that of atmospheric concentrations of carbon dioxide. The proposed limit of 350 ppm carbon dioxide already effectively ensures that ocean pH stays within its Holocene bounds. The linkage goes both ways, as ocean acidification, together with higher temperatures, will gradually diminish the capacity of oceans to offset human carbon dioxide emissions, thus effectively leading to higher net additions of carbon dioxide to the atmosphere and enhanced global warming.[87] Again, however, the real threshold here is the climate system itself. Oceans are one of a large number of factors that determine the level of carbon dioxide in the atmosphere, and their relative contributions have to be weighed against each other and will change dynamically over time.

A SINGLE LIMIT CANNOT CAPTURE ALL IMPACTS ON MARINE LIFE

As Brewer notes, ocean acidification encompasses much more than a simple change in pH, and there is not one single boundary level that captures every aspect.[88] In fact, some of the most important effects of ocean acidification on marine life are gradual rather than non-linear. Tropical waters are limited by calcite rather than aragonite and are therefore *not* at risk of crossing a tipping point and becoming undersaturated.

Instead, the impact of ocean acidification on calcification in tropical waters concerns the *degree* of supersaturation — a linear process. While there is no evidence that ocean acidification is *currently* limiting calcification on coral reefs uniformly at a global scale — changes in ocean temperatures are the primary driver of changes in coral calcification rates to date — calcifying organisms may eventually be affected by declining levels of supersaturation if atmospheric carbon dioxide levels continue rising.[89]

Non-linear, threshold effects whereby waters become undersaturated in calcium carbonate may occur in polar regions, which are limited by aragonite rather than calcite.[90] The implications for marine organisms of crossing this threshold are uncertain. It is, according to Doney et al., "likely [to] limit aragonitic organisms and change food web dynamics."[91] However, Brewer points out that, in fact, "many animals form calcareous shells in waters that are well undersaturated with aragonite."[92]

In addition to the direct effect on calcification rates, which primarily threaten corals and some other shell-forming organisms, ocean acidification may lead to a range of second-order effects on marine organisms and ecosystems. This may, according to Doney et al. "have far-reaching consequences for the oceans of the future and the millions of people that depend on its food and other resources for their livelihoods."[93] The exact consequences, however, are not known.[94] Indeed, Doney et al. suggest that "an emerging body of evidence suggests that the impact of rising CO_2 on marine biota will be more varied than previously thought, with both ecological winners and losers."[95] There is, for example, no evidence of any potential impacts on fish stocks,[96] or on the growth of the majority of the micro-organisms that form the basis of marine food chains — even at the levels of carbon dioxide projected for the end of the century.[97] But system-wide impacts are inherently hard to predict, and also depend on the ability of organisms to adapt to changing conditions.[98] A comprehensive study of ocean acidification by the British Royal Society concludes that:

> *Organisms will continue to live in the oceans wherever nutrients and light are available, even under conditions arising from ocean acidification. However, from the data available, it is not known if organisms at the various levels in the food web will be able to adapt or if one species will replace another. It is also not possible to predict what impacts this will have on the community structure and ultimately if it will affect the services that the ecosystems provide.*[99]

HUMAN CHOICE

Crossing the planetary boundary for ocean acidification — set so as to avoid undersaturation in aragonite calcium carbonate — cannot be called “non-negotiable,” as it is unlikely to have catastrophic consequences for human well-being. It may, however, result in the loss of important values — both economic and aesthetic —along the way. This is ultimately a human choice — involving political, economic, cultural, and moral trade-offs — that cannot be determined by science alone.

CLIMATE CHANGE

SYSTEM CHARACTERISTICS: Systemic process at planetary scale; global-scale thresholds.

CONTROL VARIABLE: (i) Atmospheric CO_2 concentration (ppm); (ii) Energy imbalance at Earth’s surface ($W\ m^{-2}$).

PROPOSED BOUNDARY: (i): $\leq$350 ppm; (ii): $\leq$+1 $W\ m^{-2}$

CURRENT STATUS: (i): 387 ppm; (ii): 1.5 $W\ m^{-2}$

MOTIVATION: Climate change may lead to “loss of polar ice sheets,” “regional climate disruptions,” and “loss of glacial freshwater supplies.” It also weakens carbon sinks.”[100]

SCIENTIFIC BASIS FOR THE BOUNDARY

The boundary level for climate change is supported by three observations.[101] First, the equilibrium sensitivity of climate to greenhouse gas forcing, including slow feedbacks (operating on longer timescales), is taken into account. Second, Antarctic glaciation is chosen as the key, long-term tipping element in the climate system. The threshold for Antarctic glaciation is estimated at carbon dioxide levels in the range of 350-500 ppm. If these levels are exceeded, fast and slow feedbacks could in the long run lead to the disappearance of these large ice sheets, with huge consequences especially in terms of rising sea levels. Staying below 350ppm is thought to avoid this risk. The third line of evidence is that, at the current carbon dioxide concentration of about 390ppm and +1.5 $W\ m^{-2}$ net radiative forcing, “the climate is moving out of the envelope of natural variability characteristic of the Holocene.” This includes melting sea ice and glaciers, altered species distributions and so on. These observations would thus indicate that 390ppm is already beyond the tipping point, since feedback effects have started to occur.

TIPPING POINTS AND THE CHOICE OF BOUNDARY

There is ample evidence that the climate exhibits tipping points,[102] the crossing of which carries very significant risks to human welfare, making the identification of this risk zone an important scientific undertaking. The 350ppm and 1 W m^{-2} suggested by Rockström et al. represent a strongly precautionary approach, involving an overtly normative choice of *complete risk aversion on all timescales.* This is evidenced by i) their decision to include slow feedbacks — which operate over timescales beyond the usual policy horizon of decades up to a century — and ii) their choice of a tipping element. Indeed, Antarctic glaciation is only one of many threshold mechanisms in the climate system that could have been chosen, each of which has its own potential consequences for human welfare and its own threshold.[103] Nonetheless, the 350ppm boundary could be usefully regarded not as a fixed boundary, but as one of many possible conditional policy targets: *if* we want to entirely avoid harmful climate change on any timescale, *then* the atmospheric concentration of carbon dioxide should be kept under 350ppm. As such, the boundary contributes to clarifying the choices and options that society is confronted with in the face of climate change.

POLICY RELEVANCE

The usefulness of a zero-risk, long-term boundary for policy over the next few decades might nevertheless be limited. By most measures, we are already in a risk zone and are — in terms of greenhouse gas emissions — heading momentously in the wrong direction. As Allen remarks:

> *There is no need to speculate about the behaviour of the climate system into the next millennium to make the case that emission reductions are urgently needed to avoid dangerous climate change.*[104]

The level of greenhouse gases in the atmosphere that is ultimately aimed for may become a more relevant concern if or when the current trend of rising concentrations is reversed and humanity gains greater control of net emissions. Until then, a pragmatic approach to mitigation and adaptation need not rely on an exact end target. Allen continues:

The problem is not that 350 p.p.m. is too high or too low a threshold, but that it misses the point. The actions required over the next couple of decades to avoid dangerous climate change are the same regardless of the long-term concentration we decide to aim for.[105]

STRATOSPHERIC OZONE DEPLETION

SYSTEM CHARACTERISTICS: Systemic process at planetary scale; regional thresholds.

CONTROL VARIABLE: Stratospheric O_3 concentration (Dobson Units).

PROPOSED BOUNDARY: ≥276 DU

CURRENT STATUS: 283 DU

MOTIVATION: Stratospheric ozone depletion may lead to "severe and irreversible UV-B radiation effects on human health and ecosystems."[10]

This system has tipping points, but they are mostly regional (polar), and Rockström et al. note that, for extra-polar stratospheric ozone, "there is no clear threshold around which to construct a boundary."[107] Molina deems the boundary "reasonable, but a bit arbitrary."[108] Following the global phasing out of ozone-depleting substances, Rockström et al. conclude, "we appear to be on a path that avoids transgression of this boundary."[109]

GLOBAL PHOSPHOROUS CYCLE

SYSTEM CHARACTERISTICS: Local- to regional-scale; no known global-scale threshold.

CONTROL VARIABLE: Quantity of phosphorous flowing into the oceans (Mt P/year).

PROPOSED BOUNDARY: ≤11 Mt P/year

CURRENT STATUS: 8.5–9.5 Mt P/year

MOTIVATION: The planetary boundary for phosphorous is set so as to "avoid a major oceanic anoxic event (including regional), with impacts on marine ecosystems."[11]

GLOBAL TIPPING POINT FAR OFF

A planetary tipping point is unlikely to occur. Rockström et al. acknowledge:

> *It remains highly uncertain whether and, if so, when anthropogenic P [phosphorous] inflow could reach a point where a human-induced [ocean anoxic event] would be triggered… for humans to trigger an [ocean anoxic event] should be still over 1000 years away.*[111]

OTHER PHOSPHOROUS BOUNDARIES

As Townsend and Porder point out, "human alteration of the P [phosphorous] cycle has multiple potential boundaries" other than Rockström et al.'s riverine phosphorous export.[112] For example, Carpenter and Bennett note that surface freshwaters and some coastal waters are highly sensitive to eutrophication by excess phosphorous.[113] They computed planetary boundaries for the input of phosphorous to freshwaters, the input of phosphorous to terrestrial soil, and the mass of phosphorous in soil. By their definitions, current conditions exceed all planetary boundaries for phosphorous. This is a useful and valid point, but it still refers to the state of the ecosystems per se, and not in relation to human welfare. Communities and societies may still decide to let phosphorous levels cross these tipping points on a local to regional level, as it does not necessarily endanger welfare on a net basis. As such, it does not constitute a "non-negotiable" biophysical boundary. As with nitrogen, large imbalances in phosphorous fertilizer use exist across the world, and while nearly a third of global cropland area suffers from phosphorous deficit, some areas have intense surpluses, the latter often associated with low phosphorous-use efficiency.[114] Notably, phosphorous exists in limited mineral supplies, providing further incentive to improve phosphorous use efficiency in global agriculture.[115]

AEROSOL LOADING

SYSTEM CHARACTERISTICS: Local- to regional-scale; no known global-scale threshold.

CONTROL VARIABLE: Overall particulate concentration in the atmosphere, on a regional basis.

BOUNDARY: To be determined.

CURRENT STATUS: To be determined.

MOTIVATION: Aerosol loading may cause "disruption of monsoon systems" and "human-health effects." It also "interacts with climate change and freshwater boundaries."[116]

The effects of aerosol loading on the global climate does not justify a separate boundary — it is the climate system that has thresholds, the crossing of which involves significant risk for human welfare. Aerosols are one of many factors influencing the state of the climate system, and could in theory be traded off against other variables depending on their cost-effectiveness and other criteria. In cases where aerosol loading affects local and regional climate patterns, limits are more appropriately set at these scales.

Impacts on human health are a serious concern but not one that is necessarily amenable to global boundary-setting. Lacking a tangible threshold, the choice of boundary level will always be arbitrary, and the spatial heterogeneity of aerosol loading warrants more geographically specific management.

CHEMICAL POLLUTION

SYSTEM CHARACTERISTICS: Local- to regional-scale; no known global-scale threshold.

CONTROL VARIABLE: For example, emissions concentrations, or effects on ecosystem and Earth system functioning of persistent organic pollutants, plastics, endocrine disruptors, heavy metals, and nuclear wastes.

BOUNDARY: To be determined.

CURRENT STATUS: To be determined.

MOTIVATION: Chemical pollution may cause “unacceptable impacts on human health and ecosystem functioning” and may “undermin[e] resilience and increase risk of crossing other thresholds.”[117]

As with aerosol loading, chemical pollution has very significant impacts on human welfare, but appears poorly suited for a single, aggregate global limit, which would be prone to obscuring geographical and other complexities.

DISCUSSION

NON-THRESHOLD SYSTEMS DO NOT HAVE BOUNDARIES

Climate change, ocean acidification, and stratospheric ozone being exceptions, the proposed planetary boundaries have no evidence of planetary-scale threshold behavior. Instead, their inclusion is based on their providing the "underlying resilience of the Earth System." But while the resilience argument is valid — at least in terms of interlinkages with climate — setting a boundary level for these processes can be only arbitrary, since it does not correspond to any biophysical threshold. Rather, it represents an inherently subjective judgment about the preferred state of these systems. The very selection of non-threshold systems is arbitrary, as the six identified by Rockström et al. are among a large number of processes that could fit the vaguely specified description of providing "resilience."[118] There is no reason not to include grazing, fire, or any other ecosystem variable that may cause a system to shift into a qualitatively different stable state on a local level.

CLIMATE CHANGE MITIGATION

Most, if not all, of the non-threshold systems, as Rockström et al. note, feed into climate change in one way or another. Reactive nitrogen can increase growth rates in plants and thereby stimulate faster uptake of carbon from the atmosphere, as well as escape to the atmosphere in the form of nitrogen oxide. Land-use change is the source of a large proportion of global greenhouse gas emissions. Freshwater influences the ability of the terrestrial biosphere to act as a carbon sink. All of these processes affect the level of greenhouse gases — chiefly carbon dioxide and nitrous oxide — in the atmosphere, which, in the case of carbon dioxide, in turn also determines the rate and magnitude of ocean acidification. Therefore, at the nexus of all the boundaries, except for stratospheric ozone, is climate change.

No climate strategy is complete without accounting for nitrogen, land-use change, freshwater, and other factors influencing the global carbon cycle and other greenhouse gases: these all require rigorous monitoring and management on local, regional and global scales. [119] Non-threshold processes do not, however, merit the designation as "planetary boundaries" as such. In a sense, Rockström et al. appear to confuse means (factors that influence the level of greenhouse gases in the atmosphere) with ends (climate stability). A very large number of factors influence the level of greenhouse gases in the atmosphere and thereby the scale and speed of climate change. Some of them are environmental — such as carbon sequestration in forests and oceans — but of equal or greater importance are the social, economic, and technological factors that determine human emissions of greenhouse gases in the first place, as well as individuals' and societies' resilience in the face of climate change impacts. From a strict climate perspective, a carbon dioxide molecule is a carbon dioxide molecule — be it anthropogenic or natural.

All these different means of mitigation and adaptation will have to be weighed against each other in the pursuit of climate stability, based on their social, political, economic, and technical feasibility and desirability. Hypothetically, deploying low-carbon energy technologies may have a lower net cost, for example, than halting land-use change. Some negative side effects of excess nitrogen may be tolerated if they are judged to be outweighed by the increased rates of plant growth that are induced. The fact that these processes can affect the level of greenhouse gases in the atmosphere and therefore constitute *means* to climate change mitigation does not mean that there is an absolute *boundary* for them. Assigning them fictional boundaries may hamper efforts to deal with trade-offs and judgments in a democratic, rational, and holistic way.

MANAGING NON-CLIMATE SYSTEMS

Assigning global, aggregate boundaries to non-threshold systems may also impede effective decision-making about the non-climate systems themselves, with respect to their own values and functions. A global perspective is certainly justified to understand and monitor the dynamics of these systems, not least to determine their influence on the climate system.[120] However, in many cases, the most important trade-offs — and thus implications for human welfare — occur on a local to regional level. In these cases, global regulation may be inappropriate. For example, nitrogen and freshwater are best dealt with on a broad drainage basin level, including the coastal ocean into which it discharges. Here, the different uses of water can be weighed against each other, and the trade-off between agricultural productivity and the health of coastal oceans (as a result of nitrogen runoff) can be understood and acted upon. Just like there are basins where water extraction and nitrogen additions should be curtailed, there exist many where the appropriate direction of change from a human welfare perspective is the *opposite*. The same also applies to land-use change. Only accounting for the negative consequences makes for a very partial perspective. For systems or processes whose desirable direction of change is different at the global and local levels, and where a global threshold does not exist, a global boundary cannot inform any management decisions.[121]

HUMAN WELFARE AND THE HOLOCENE BASELINE

The planetary boundaries framework is explicitly framed around human welfare: the crossing of boundaries, it is claimed, can be "deleterious or even catastrophic for human well-being" and the set of boundaries represents the "dynamic biophysical 'space' of the Earth System within which humanity has evolved and thrived."[122] However, beyond these cursory claims, there is almost no description of or evidence for the linkages between the state of the environment and human welfare. Instead, the planetary boundaries framework rests upon two assumptions that are largely unproven or even contradicted.

The first assumption is that environmental variables — commonly referred to as ecosystem services — are closely linked to human welfare, and that, consequently, loss of ecosystem services or natural capital implies declining human welfare. Stated differently, it conflates *ecological* resilience and *social* resilience.[123] This broad assumption does not stand up well to evidence. As Raudsepp-Hearne et al. point out, human welfare has improved significantly on a global level over the last few decades, even as a majority of ecosystem services have declined.[124] This "environmentalist's paradox" strongly warrants against generalizing assumptions about the relationship between environmental variables and human welfare. For a policy-oriented framework like planetary boundaries to be useful, it must offer a stronger account of the mechanisms and relative importance of the interlinkages between environmental quality and human welfare.

The second, and related, assumption is that the Holocene represents the most desirable state of the environment for human welfare. Rockström et al. write:

> *We must take the range within which Earth System processes varied in the Holocene as a scientific reference point for a desirable planetary state.*[125]

The justification for making the Holocene the baseline toward which global change management should be targeted is that the Holocene environment is thought to have been a central factor behind human civilization and development in the last 10,000 years or so. The authors state:

> *The relatively stable environment of the Holocene… allowed agriculture and complex societies, including the present, to develop and flourish. That stability induced humans, for the first time, to invest in a major way in their natural environment rather than merely exploit it.*[126]

The claim that the Holocene environment "allowed" or even "induced" human development is unsupported by the single reference offered.[127] The sole remaining piece of evidence for the assumed advantageousness of the Holocene environment for human welfare is a graph indicating *correlation* between the beginning of agriculture and subsequent emergence of human civilization, on the one hand, and global temperatures, on the other.[128] No evidence for a causal relationship is offered. In reality, an extensive body of scholarship points to a complex mix of social, demographic, technological, environmental and other factors that enabled the Neolithic revolution and subsequent developments such as urbanization and population growth.[129] The relative importance of environmental quality and stability here is far from certain.

There are of course very good reasons to prefer the *climate* of the Holocene, which was relatively warm and stable. However, there is little evidence that land cover, nitrogen levels, biodiversity, or any of the other non-climate systems had, *in themselves*, a stability or level that were particularly beneficial for human development. Arguably, the human population and the level of material welfare that exist today depend very much on the fact that some of the non-climate systems do not remain at Holocene levels. Synthetic fertilizer — the main source of human nitrogen additions to the environment — was an essential factor behind the enormous increase in food production over the past century, together with increased freshwater withdrawals for irrigation. Land-use change has been fundamental to establishing agriculture and thus feeding the world. And there is little doubt that *until now*, the net benefit in terms of human welfare of using fossil fuels and thus emitting carbon dioxide to the atmosphere has been immense. It is not the environmental conditions of the *Holocene* that have enabled human development in the past two hundred years, but the environmental conditions of the *Anthropocene*. This is by no means to deny the negative local, regional, and global impacts of excessive nitrogen use, biodiversity loss, and the other elements of the Earth System — and the very real risks associated with global climate change — but rather to say that a one-sided perspective accounting only for the negative effects of these changes is wholly inadequate.

The stated "desirability" of the Holocene in terms of non-climate factors simply does not match the evidence, making it clear that the planetary boundaries framework is designed not to optimize environmental conditions for human material welfare, but to maintain an environmental status quo — the Holocene — per se. In other words, the Holocene is deemed desirable for *intrinsic* reasons, and not directly as a means to human welfare — even while planetary boundaries are proposed as objective limits to human development. This is partially admitted in the Supplementary Information, where Rockström et al. say that the idea of "'preservation of the Creation' … comes very close to the normative planetary boundary assumption of sustaining a desired Holocene state of the Earth System."[130]

CONCLUSIONS

The Earth has entered the Anthropocene, a time in which humans are the dominant force shaping all Earth systems. All of the nine systems and processes identified by Rockström et al. are important determinants, albeit in complex ways, of human welfare — indeed, they enable life on this planet to exist. They all need to be managed wisely and consciously. The planetary boundaries concept was suggested as a framework for doing so, and it makes several important contributions worth highlighting. It brings resilience thinking and complex systems theory to the center of the debate, and draws attention to the many interrelated elements and processes of the Earth system. However, our review of the framework has identified some serious flaws, which together make planetary boundaries a poor, even misleading, answer to the challenge of planetary stewardship. The implications of this review apply not only to the planetary boundaries concept in itself, but to Earth Science as a whole, especially as regards the way it interfaces with policy making.

The arbitrary nature of identifying non-threshold planetary boundaries and assigning them quantitative limits seriously challenges Rockström et al.'s claims that planetary boundaries are "non-negotiable" or that they "exist irrespective of peoples' preferences, values, or compromises based on political and socioeconomic feasibility."[131] In fact, this is exactly what these "boundaries" are about.[132] For example, the amount of nitrogen added to the environment as synthetic fertilizer confers enormous benefits to people in terms of the food production it enables, but it also has negative side-effects such as groundwater pollution, "dead zones" in coastal oceans, and emissions of greenhouse gases.[133] Conversion of natural habitats to agriculture can increase food production and improve livelihoods, but may also harm biodiversity and lead to emissions of greenhouse gases.[134] Extracting more freshwater from rivers and groundwater can allow for irrigation or other human uses, but also compromises the resilience and functioning of associated ecosystems.[135] And so forth.

These costs and benefits are unevenly distributed temporally, spatially, and socially — there are both winners and losers. Balancing these trade-offs is an inherently political question, and attempts to depoliticize it with reference to scientific authority is dangerous, as it precludes democratic resolution of these debates, and limits, rather than expands, the range of available choices and opportunities.[136] As Norton remarks, "In a democratic society, the question of what to do must be a public question. It cannot be resolved by science alone."[137] A more constructive function of global change science would therefore be, as DeFries et al. argue, to identify and explicate these trade-offs, in order to usefully inform the public, decision makers, and interest groups about possible courses of action and their implications and thereby facilitate deliberative decision making.[138]

ENDNOTES

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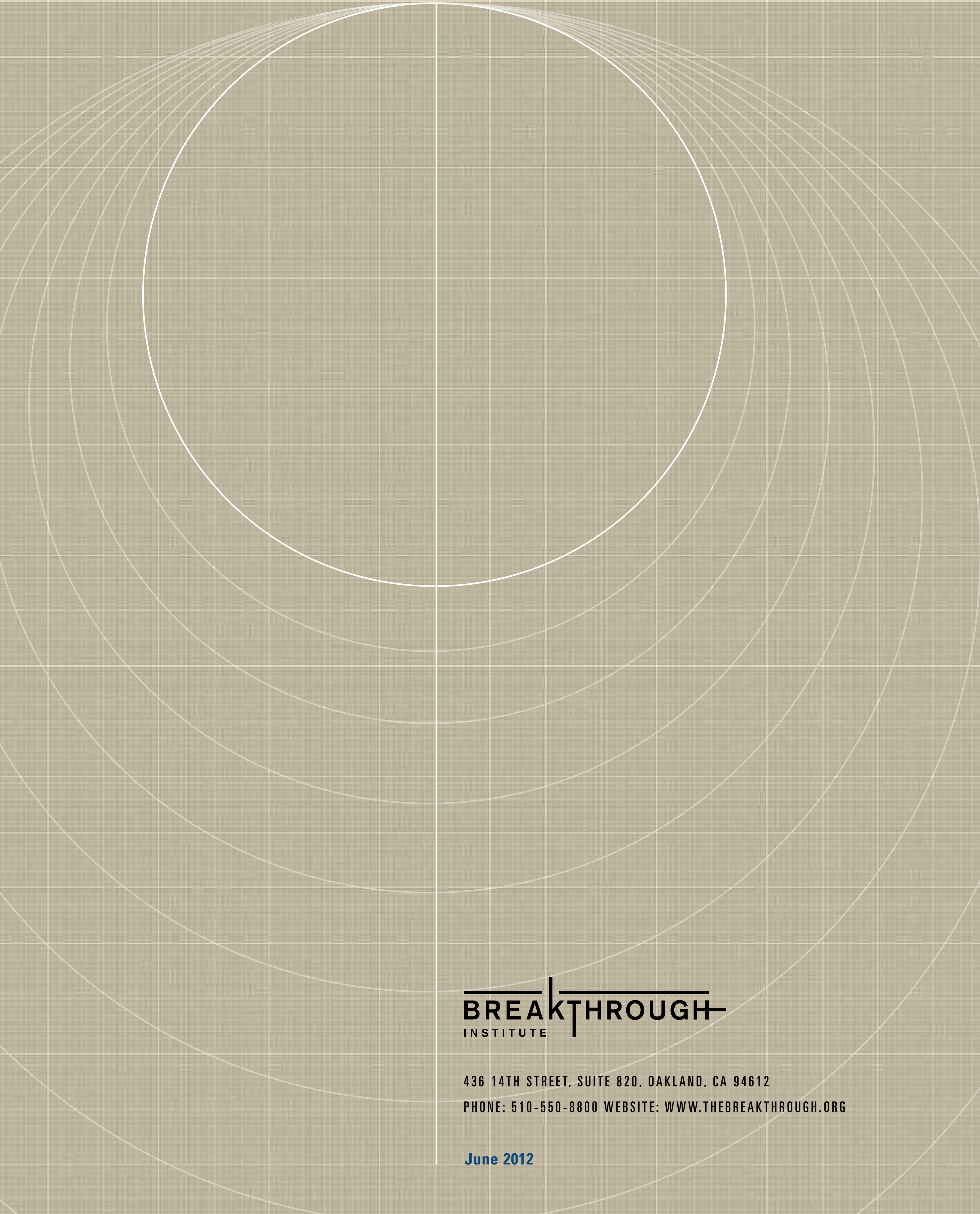

BREAKTHROUGH
INSTITUTE

436 14TH STREET, SUITE 820, OAKLAND, CA 94612
PHONE: 510-550-8800 WEBSITE: WWW.THEBREAKTHROUGH.ORG

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