Integrating the Planetary Boundaries and Global Catastrophic Risk Paradigms

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Abstract

Planetary boundaries (PBs) and global catastrophic risk (GCR) have emerged in recent years as important paradigms for understanding and addressing global threats to humanity and the environment. This article compares the PBs and GCR paradigms and integrates them into a unified PBs-GCR conceptual framework, which we call Boundary Risk for Humanity and Nature (BRIHN). PBs emphasizes global environmental threats, whereas GCR emphasizes threats to human civilization. Both paradigms rate their global threats as top priorities for humanity but lack precision on key aspects of the impacts of the threats. Our integrated BRIHN framework combines elements from both paradigms' treatments of uncertainty and impacts. The BRIHN framework offers PBs a means of handling human impacts and offers GCR a theoretically precise definition of global catastrophe. The BRIHN framework also offers a concise stage for telling a stylized version of the story of humanity and nature co-evolving from the distant past to the present to multiple possible futures. The BRIHN framework is illustrated using the case of disruptions to the global phosphorus biogeochemical cycle.

Keywords: global catastrophic risk, planetary boundaries, biogeochemical phosphorus cycle, resilience, risk

1. Introduction

Human civilization today faces many threats, as does the global environment. In recent years, two research paradigms have emerged to understand these threats and guide human response to them. Planetary boundaries (PBs) posits global environmental boundaries that, if crossed, could have dangerous effects to both humanity and nature (Rockström et al., 2009a, 2009b). Global catastrophic risk (GCR) analyzes the probabilities and magnitudes of global threats to humanity (Bostrom and Ćirković, 2008). These two paradigms come from different intellectual traditions and likewise offer complementary perspectives and epistemologies for global-scale threats.

The PBs paradigm comes from the intellectual tradition of Earth system science (Steffen et al., 2004). Likewise, PBs also follows in the tradition of research such as limits to growth (Meadows et al., 1972), ecological resilience theory (Holling, 1973), ecological footprints (Wackernagel and Rees, 1996), tolerable windows (Petschel-Held et al., 1999), and Earth system tipping points (Lenton et al., 2008). PBs emphasizes the importance of stable Holocene conditions to the success of human civilization, a theme developed by archeologists and others (Richerson et al., 2001; Gupta, 2004), as well as the related concept of the Anthropocene (Steffen et al., 2007). The PBs perspective highlights certain stressors that could tip the Earth system away from its stable Holocene state and into a new, dangerous state, with "unacceptable" consequences to humanity (Rockström et al., 2009a, 3). PBs also brings a holistic, systemic epistemology that is valuable for characterizing global environmental systems. A shortcoming of

PBs is that it often says little about the impacts to humanity of crossing environmental boundaries.

The GCR paradigm follows from the traditional definition of risk as the product of probability and magnitude. Seminal contributions have come from philosophically oriented scholars looking at big-picture issues for risk analysis and for humanity at large. It is a remarkably interdisciplinary bunch, with contributions from economics (Ng, 1991; Weitzman, 2009), futures studies (Tonn, 1999, 2002), law (Posner, 2004), philosophy (Leslie, 1996; Bostrom, 2002; 2003), physics (Rees, 2003), and risk analysis (Matheny, 2007). This diverse scholarship is unified by the theme of the high stakes associated with global catastrophes and the desire to leverage risk analytic techniques, broadly construed, to understand and address GCR. The GCR perspective highlights the importance of catastrophes causing permanent declines in global human civilization (Bostrom, 2013; Maher, and Baum, 2013). The GCR epistemology is typically more reductionist, with relatively few studies analyzing risks in systemic terms (Baum et al., 2013), but it does offer careful treatment of impacts to humanity.

This article integrates the PBs and GCR paradigms into a unified PBs-GCR conceptual framework, which we call Boundary Risk for Humanity and Nature (BRIHN).[1] The integrated BRIHN framework jointly considers global boundaries to both human and environmental systems. Crossing boundaries for one system does not necessarily imply crossing boundaries for the other, though the two will often be interconnected. The BRIHN framework also considers the probabilities of crossing boundaries—or, more precisely, probabilities of crossing thresholds. The distinction between boundaries and thresholds is explained below. BRIHN thus integrates the system resilience perspective of PBs with the probabilistic risk perspective of GCR, yielding new insights about global-scale threats that cannot be obtained using either paradigm alone.

The integrated BRIHN framework can be applied to system threats at any scale, but it is especially helpful for the global-scale threats considered in PBs and GCR research. The integrated perspective offers the PBs paradigm a straightforward means of evaluating the human impacts of crossing the biogeophysical planetary boundaries, and it offers the GCR paradigm a perspective on the nature of global catastrophe. In addition, the integrated framework offers an elegant stage for telling a stylized version of the story of humanity and nature co-evolving from the distant past through the present and on into multiple possible futures. The net effect is an understanding of how global human and environmental systems reached their present states and how they could be affected by the decisions humanity now faces.

Throughout the paper, we will illustrate PBs, GCR, and BRIHN with the example of the phosphorus biogeochemical cycle, which we introduce in Section 2. Sections 3-4 detail the PBs and GCR concepts. Section 5 presents the integrated PBs-GCR BRIHN framework. Section 6 shows how the BRIHN framework can be used to concisely tell the story of humanity and nature co-evolving across time. Section 7 illustrates the integrated framework using the example of the global phosphorus biogeochemical cycle. Section 8 concludes.

2. The Phosphorus Biogeochemical Cycle

The phosphorus biogeochemical cycle poses local-scale threats and has also been identified as a PB (Rockström et al., 2009a, 2009b),[2] though not (yet) as a GCR. The close fit of phosphorus with only one of the two paradigms makes it an excellent case to illustrate the BRIHN

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[1] By "paradigm", we mean a unified system of thought and its corresponding community of thinkers. By "conceptual framework", we mean the organization of ideas that can underlie a paradigm. In this article we will also speak in terms of "theory" as abstract and overarching ideas and "research" as the work produced to explore and develop the ideas.

framework. The threat comes mainly from the use of phosphorus as an agricultural fertilizer (Cordell et al., 2009; Liu et al., 2008) and from livestock manure (Bouwman et al. 2013). Much of this phosphorus flows into aquatic ecosystems, where it can cause eutrophication, extreme phytoplankton (often harmful algal) and zooplankton blooms, and loss of fisheries productivity and biodiversity. The magnitude of the phosphorous pollution problem is already quite substantial. Eutrophication in the U.S. freshwaters causes an annual economic loss of about $2.2 billion (Dodds et al., 2009). However it is also important to note that in human terms this cost is likely outweighed by the agricultural benefits of phosphorus usage.

The biggest global-scale concern for phosphorus may be the possibility of an oceanic anoxic event (OAE) caused by buildup of phosphorus in oceans (Baroni et al., 2014). Indicated by the deposition of extensive organic-rich shales, OAEs of the geologic past have been linked to intervals of increased organic carbon burial in marine sediments (Jarvis et al., 2011; Jenkyns, 2011), and have been associated with marine biotic extinctions (Wagreich et al., 2011). The modern ocean is already “on the edge of anoxia”, hence current anthropogenic terrestrial phosphorus flows into oceans could trigger enhancement of coastal hypoxia and a new OAE on time scales of centuries and millennia, respectively (Handoh and Lenton, 2003). An OAE would be a dramatic change to ocean ecosystems, resulting in a qualitatively different state than Holocene conditions. Likewise the human impacts of an OAE could be quite large, but to date the human impacts have not been examined. At a minimum, there would be extensive disruption to fisheries. The loss of seafood would be a major disruption to the human food supply if it were to occur today. Aquatic animal food products account for about 16% of animal proteins consumed by humans worldwide, and also have nutritional advantages relative to terrestrial meats (Tacon and Metian, 2013). However, it is difficult to predict the diets of populations centuries or millennia from now. Further research is needed to clarify the human impacts of OAE.

The OAE scenario comes with two important caveats. First, there may not be enough phosphorus available to trigger an OAE. Phosphorus fertilizer comes mainly from nonrenewable phosphate mineral deposits. The depletion of phosphorus reserves may be a more serious problem than OAE (Lewis, 2012), with “peak phosphorus” occurring around 2033 (Cordell et al., 2009; see also Cordell and White, 2011; Van Vuuren et al., 2010), a date much earlier than when OAE would occur. But significant uncertainty remains, including about unconventional (e.g. offshore) phosphorus sources, which could supply phosphorus for millennia (Smil, 2000, 81). A second caveat is that much could change prior to an OAE. Changes in phosphorus usage rates and flows into oceans could affect the probability and timing of an OAE. Such changes may be sought – for example, recycling phosphorus could simultaneously reduce depletion of phosphorus reserves and reduce flows into oceans (Carpenter and Bennett, 2011). Meanwhile, other global human or environmental catastrophes could occur, rendering phosphorus flows unimportant. Indeed, many catastrophes operate faster than the centuries-to-millennia time scales of OAE.

3. Planetary Boundaries

The core idea behind the PBs paradigm is to identify how humanity can maintain Earth system properties in states conducive to a viable human population. PBs theory posits the existence of

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[2] Rockström et al. (2009a, 2009b) discuss the phosphorous biogeochemical cycle together with the nitrogen biogeochemical cycle. While the two cycles interact in important ways, we focus on the phosphorous cycle to keep the discussion more concise.

biogeophysical planetary thresholds that, if crossed, could cause "unacceptable global environmental change", which is in turn "defined in relation to the risks humanity face [sic] in the transition of the planet from the Holocene to the Anthropocene" (Rockström et al., 2009a, 3). The importance of PBs is thus defined in anthropocentric terms—crossing PBs poses "unacceptable" risks to humanity—although most PBs analysis focuses on biogeophysical systems without evaluating impacts to humanity. As we will see, GCR is much more focused on human impacts, both in its theory and its active research.

PBs theory makes an important distinction between boundaries and thresholds. Thresholds are Earth system properties: the points at which resilience is exceeded and the system transitions to a different state. Boundaries are human constructs: self-imposed limits needed to avoid crossing thresholds. Boundaries are defined in terms of a variable under human control, such as the quantity of phosphorous flowing into the ocean (for phosphorous thresholds), the atmospheric greenhouse gas concentration (for climate change thresholds) or the rate of species extinction (for biodiversity loss thresholds). Given the considerable uncertainty about the locations of thresholds, boundaries are placed a safe distance away, in order to keep the risk of crossing a threshold below a normatively defined acceptable level (Figure 1). As with any normative parameter, what qualifies as acceptable is debatable, whereas the nature of thresholds exists independently of human views.

Two types of PBs are identified. First, systemic PBs involve global-scale environmental thresholds, such as ice sheet collapse resulting in global sea level rise or an oceanic anoxic event. PBs here are drawn at a "safe" distance from these thresholds, so that the thresholds will not be crossed (Figure 1a). The phosphorus PB has been tentatively set at 11 million tons of phosphorus entering oceans per year; exceeding this boundary would pose an unacceptable risk of OAE (Rockström et al., 2009a, 2009b). Second, aggregative PBs involve sets of local-scale environmental thresholds found around the world all driven by the same control variable, such that if that variable exceeds some level, then enough of these local thresholds will have been crossed to register a global concern (Figure 1b). Aggregative PBs include extreme weather events driven by climate change or freshwater and coastal eutrophication events driven by nutrient runoff.[3] Both types of PBs are expressed in terms of control and response variables (Figure 1). Uncertainty about threshold location is expressed as a "zone of uncertainty", with the boundary set some safe distance away.

PBs theory emphasizes the importance of the stable Holocene conditions of the last 12,000 years, under the premise that these conditions are important to the emergence and sustainability of human civilization. Humanity thus pushes the global environmental system out of this hospitable state at its own risk. The Holocene is commonly defined in climatic terms, i.e., it is an interglacial period. However, the Holocene also has particular conditions for other environmental variables. Some of these variables were in similar states prior to the Holocene (i.e., the Pleistocene), but human activity nonetheless threatens to push them into new and dangerous states. For example, ocean phosphorus levels were similar during the Pleistocene and Holocene, but human activity threatens to push them to a new state: OAE. Thus the phosphorus biogeochemical cycle qualifies as a PB.

The original PBs study (Rockström et al., 2009a, 2009b) identified nine PBs: climate change; biodiversity loss; biogeochemical flows (interference with the nitrogen and phosphorus cycles); stratospheric ozone depletion; ocean acidification; global fresh-water use; land use change;

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[3] Phosphorus flows into many freshwater and coastal ecosystems have already exceeded boundaries for the thresholds (Carpenter and Bennett, 2011), causing a large number of hypoxic areas worldwide.

chemical pollution; and atmospheric aerosol loading. Of these, three boundaries are estimated to have already been crossed: climate change, the rate of biodiversity loss, and biogeochemical flows (specifically interference with the nitrogen cycle). Also, two boundaries have yet to be quantified in research: atmospheric aerosol loading and chemical pollution. Finally, a tenth boundary has been proposed for primary plant productivity (Running, 2012).

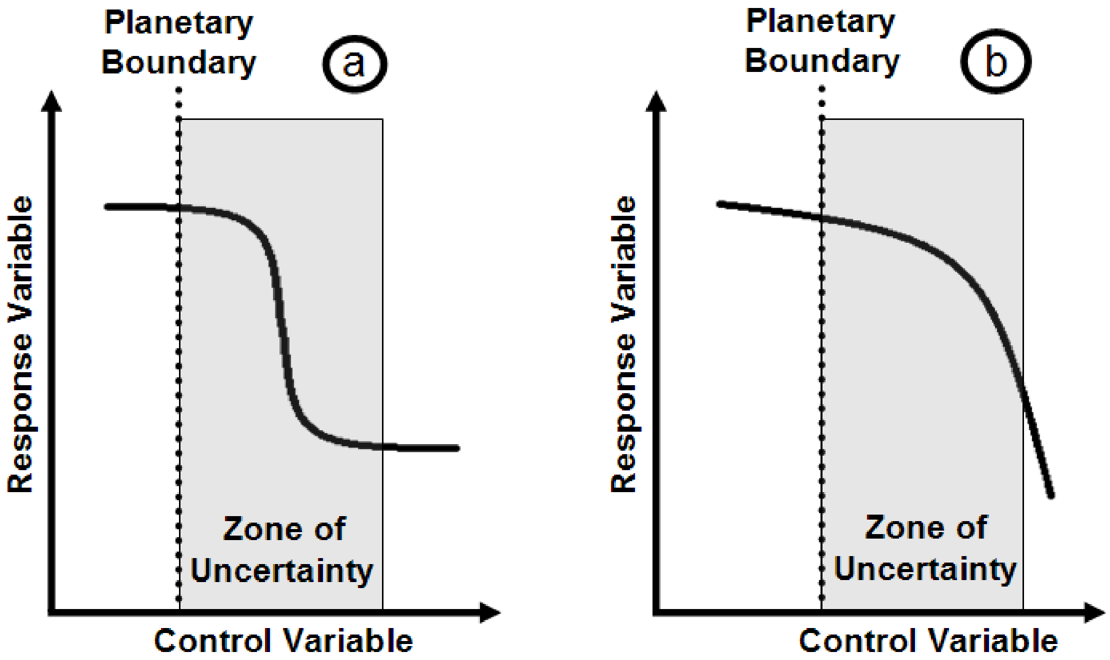

Figure 1. Two types of Planetary Boundaries (PBs): systemic, with a global-scale threshold (1a) and aggregative, with a set of local-scale thresholds (1b). Adapted from Rockström et al. (2009a).

4. Global Catastrophic Risk

The GCR paradigm focuses on risks of events that could significantly harm human civilization or even cause human extinction. Exactly what qualifies as a GCR is a matter of ongoing discussion in the literature. Atkinson (1999; cited in Hempsell, 2004) proposes a definition of global catastrophe as an event in which more than one quarter of the human population dies. Bostrom and Ćirković (2008) suggest that the definition of global catastrophe lies somewhere between events causing at least 10^4 deaths or $\$10^9$ in damages and events causing at least 10^7 deaths or $\$10^{12}$ in damages. Bostrom and Ćirković also present a scheme for classifying risks in two dimensions of event consequence, scope and intensity (Figure 2). GCRs are risks of events that are at least global in scope and at least endurable in intensity. Existential risks (Bostrom, 2002; 2013) are risks of events that are trans-generational in scope and terminal in intensity, in particular risks of events that would result in human extinction (Matheny, 2007).

Maher and Baum (2013) introduce the concepts of global catastrophe adaptation and recovery, focusing on what happens to survivors after a global catastrophe. Figure 3 shows a simplified version of the Maher and Baum scheme, illustrating possible trajectories of human civilization over time measured in terms of total human wellbeing. The total here is specifically instantaneous wellbeing summed across space, which may be at least approximately proportional to instantaneous human population (about seven billion at the moment). Under normal conditions, humanity is at some baseline level of wellbeing (A). Per this scheme, a global catastrophe is anything that causes a large loss in total wellbeing (B). If there are no survivors of a global catastrophe, or if they fail to adapt to post-catastrophe conditions, the result is human extinction (C). If survivors adapt but fail to recover, the result is a persistent low level of wellbeing (D). Finally, if survivors successfully recover, human civilization returns to a normal, baseline level of wellbeing (E).[4] Note that the trajectories specified in Figure 3 are intended as rough sketches and do not necessarily correspond to what would actually occur. Maher and Baum (2013) also connect GCR to the concept of resilience: if a global catastrophe exceeds the resilience of human civilization, then recovery could not occur. Human civilization resilience is in turn linked to the resilience of the environment that sustains civilization.

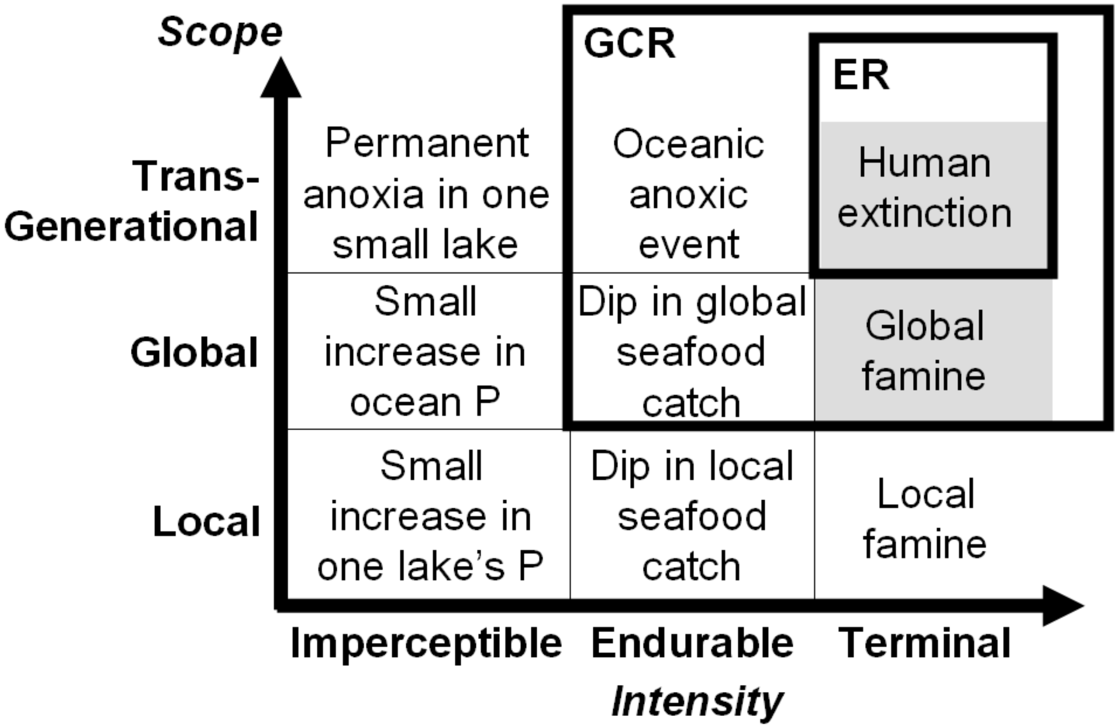

Figure 2. Scheme for classifying risks based on scope and intensity, illustrated with examples from the phosphorous biogeochemical cycle. GCR is global catastrophic risk; ER is existential risk. Adapted from Bostrom and Ćirković (2008); examples from the phosphorus biogeochemical cycle are original to this paper. "Human extinction" and "Global famine" are shaded to indicate that the possibility of phosphorus causing these outcomes has not yet been established in any research and might not be possible. Bostrom and Ćirković also included a "Personal" scope below "Local", though this is less applicable to phosphorus.

A core GCR study (Bostrom and Ćirković, 2008) lists thirteen GCRs, divided into three (admittedly fuzzy) categories: risks from nature, risks from unintended consequences, and risks from hostile acts. The risks from nature covered are supervolcano eruptions, large comet and asteroid impacts, solar radiation fluctuations (found not to be a GCR), supernova explosions, and gamma ray bursts. The risks from unintended consequences covered are climate change,

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[4] Maher and Baum (2013) extend Figure 3 to include the long but finite lifetime of Earth (approximately one to five billion years) and the large total human wellbeing levels that could potentially be achieved through space colonization, two themes often discussed in the GCR literature (Baum, 2009, 2010; Bostrom, 2003; Hempsell, 2004; Matheny, 2007; Tonn, 1999, 2002).

pandemics, artificial intelligence, high energy physics experiments, and social collapse. The risks from hostile acts covered are nuclear war, nuclear terrorism, biotechnology, nanotechnology, and totalitarian governments. While this is not an exhaustive list of GCRs,[5] it is representative of those typically discussed in the GCR literature. Indeed, besides climate change, the GCR literature has seldom evaluated environmental risks.[6] One conclusion from the risks that have been evaluated is that the risks from nature are of much lower probability than most of the other risks involving human activity. However, as with PBs, research on GCR remains tentative, with much uncertainty about many of the specific risks.

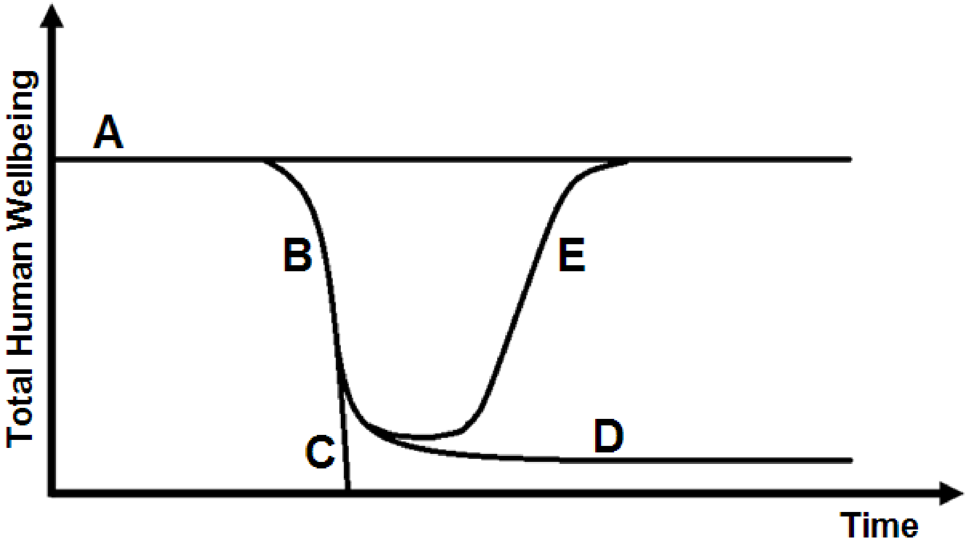

Figure 3. Rough sketches of human civilization trajectories measured in terms of total human wellbeing, including humanity at baseline wellbeing (A), global catastrophe (B), human extinction (C), adaptation (D), and recovery (E). Based on Maher and Baum (2013).

The phosphorus biogeochemical cycle is among the environmental risks that has not been evaluated as a GCR. One possibility is global catastrophe from many local eutrophication events. Such events could cause loss of freshwater and coastal seafood and other disruptions, all long before an OAE could occur. Another possibility is global catastrophe from the vulnerability of national and regional food systems to various stressors of phosphorus scarcity (Cordell and Neset, 2014), because phosphorus, an essential element of life and of the modern food production system, is a finite resource (Scholz et al., 2013). These possibilities highlight a significant shortcoming in GCR theory: it lacks an equivalent to aggregative PBs. Indeed, GCR research tends to focus more exclusively on spatially global processes. More attention to spatially aggregative processes like freshwater and coastal eutrophication could improve GCR research.

But the larger risk probably comes from OAE. Unfortunately, we are not aware of any research on the human impacts of OAE, and so we can only speak in generalities about OAE as a GCR. An OAE would likely cause major loss of seafood. In terms of Figure 3, the ensuing food crisis, plus any additional effects, could cause a global catastrophe (B), though this is highly uncertain. If a global catastrophe occurs, it is likewise uncertain whether humanity would

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[5] The longest list we are aware of contains 34 different GCRs (Tonn and Stiefel, 2013).

[6] Posner (2004) discusses biodiversity loss as a GCR.

recover (E), remain in permanent decline (D), or end up extinct (C). Given that seafood is only one portion of the human food supply, it is plausible that humanity could endure an OAE without global catastrophe. If so, then the phosphorus biogeochemical cycle could be a PB but not a GCR. Or, recalling that PBs by definition pose unacceptable risks to humanity, the phosphorus biogeochemical cycle might not qualify as a GCR. This point speaks to the need for PBs theory to more rigorously engage human impacts, and is one reason why we chose to illustrate BRIHN with the phosphorus case. Meanwhile GCR theory can benefit from PBs theory's use of system resilience. These theoretical constructs are integrated in our BRIHN framework.

5. Integrating the Two Paradigms: The BRIHN Framework

Our integration of the two paradigms focuses on two aspects of PBs and GCR theory: their treatments of uncertainty and impacts. In integrating the paradigms, we combine concepts from both and add in new concepts designed for this purpose. The result is a theoretical framework for probabilistically analyzing the crossing of thresholds in global human and environmental systems. We call this integrated framework Boundary Risk for Humanity and Nature (BRIHN).[7]

5.1. Treatment of Uncertainty: Probabilistic Thresholds

The PBs and GCR paradigms both build in the uncertainty that pervades the complex phenomena that the paradigms study, but they build it in differently, as follows from their differing intellectual basis in resilience and risk. In PBs research, the main uncertain parameter is the locations of the global environmental system thresholds, as depicted in the zones of uncertainty in Figure 1. For example, perhaps an OAE would be caused by annual phosphorous flows into the oceans of 50 million tons, or 20 million tons, or some other amount. The phosphorus boundary is set at a low value, in this case 11 million tons, corresponding to a normatively acceptably low probability of crossing the threshold. In GCR research, the main uncertain parameter is the probability of a global catastrophe occurring, for global catastrophes of various magnitudes. For example, in terms of Figure 3, perhaps an OAE has a 40% chance of causing a global catastrophe that civilization recovers from (E), a 20% chance of causing a permanent collapse (D) and a 10% chance of causing human extinction (C).[8] The two paradigms thus emphasize uncertainty about two different system attributes: the resilience of the system to particular forcings (PBs) and the tendency of the system to result in catastrophe (GCR). These two treatments of uncertainty are mutually compatible.

For the BRIHN framework, we integrate the PBs and GCR treatments of uncertainty into a probabilistic thresholds concept. PBs theory explains that the exact location of thresholds is uncertain. Therefore, for any given forcing, there is a certain probability of crossing the threshold. When boundaries are set at safe distances from possible thresholds, forcings within the boundaries have an acceptably low probability (perhaps zero) of crossing the thresholds.[9] The total probability of crossing a threshold for any forcing can be less than one, indicating the possibility that there is no threshold or that the threshold cannot be exceeded by any possible forcing. Thus we have the probability of catastrophe (i.e. of threshold crossing), as emphasized in GCR theory.

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[7] It would be premature at best to call BRIHN a paradigm, since it is only just now being proposed and is not (yet) accompanied by any sizable community of supporters.

[8] The probabilities listed here are for illustration only and should not be interpreted as actual probability estimates.

[9] Tonn (2009) suggests an acceptable limit of 10^{-20} for the probability of human extinction.

Figure 4 extends Figure 1 to show the probabilistic thresholds concept for PBs. Different control variable levels (e.g. phosphorous flows into oceans) result in different forcings to the global environmental system (e.g. ocean oxygen concentrations). A cumulative distribution function (CDF) for crossing the threshold is contained within the zone of uncertainty for the control variable. A Gaussian CDF is shown, though other CDFs are also possible. The height of the CDF curve represents the probability of having crossed the threshold given a control variable level. Before the control variable crosses the PB, the probability of crossing the threshold is either zero or acceptably low, i.e. the threshold has probably not been crossed. After the PB is crossed, the probability of crossing the threshold increases, as shown by the horizontal line partway up the CDF curve. After the control variable passes the far side of the zone of uncertainty (the right hand side in Figure 4), the probability of crossing the threshold no longer increases significantly, i.e. the threshold has probably been crossed. The total probability of crossing the threshold is the maximum height of the CDF curve. The total probability does not need to be 1; it will be less than one if there is a nonzero probability of the threshold not getting crossed under any amount of the control variable, including if there is no threshold. For example, Figure 4 shows the maximum height around 70%, indicating a 30% chance that the threshold will not be crossed for any amount of the control variable.

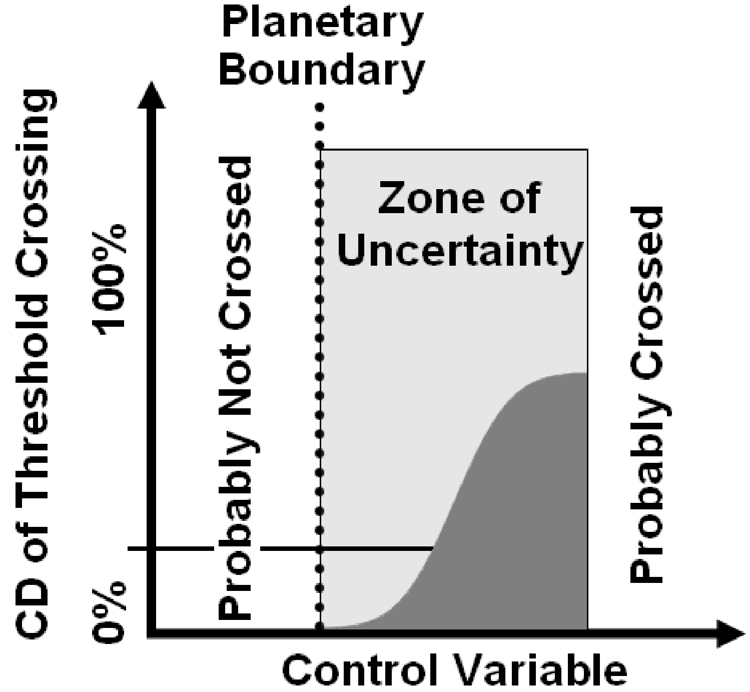

Figure 4. Cumulative distribution function of crossing a planetary threshold as a function of control variable. The use of a Gaussian CDF is illustrative; other CDFs are also possible.

There is one other important aspect of how PBs and GCR treat uncertainty to discuss. Both paradigms are similar to each other in that for both, greater uncertainty implies that greater precautionary action should be taken. For PBs, greater uncertainty about threshold location necessitates more stringent boundaries, shifting the PBs to the left in Figure 1. For GCR, greater uncertainty means higher upper bounds on possible damages and in turn higher expected value of GCR reduction (Weitzman, 2009). For both paradigms, additional research can reduce the uncertainty, thereby permitting less precautionary action, if and only if threats are found to be less severe upon closer inspection. This result is in contrast with the common practice to treat uncertainty as a reason to avoid acting, under the premise that society should delay action until it better understands what will happen (Bradshaw and Borchers, 2000).

5.2. Treatment of Impacts: Human and Environmental System Boundaries

The PBs and GCR paradigms are both, in different ways, vague on the impacts of crossing a threshold or experiencing a global catastrophe, a significant theoretical shortcoming for both paradigms. Crossing thresholds would pose "unacceptable" consequences for humanity, but it is unclear what these consequences would be. This is seen, for example, in the ambiguity regarding the human impacts of OAE for the phosphorus PB. After all, the thresholds themselves are biogeophysical; crossing them would be harmful to environmental systems but not necessarily to humanity (Nordhaus et al., 2012). Indeed, environmental degradation can even be correlated with *improvements* in human condition, at least temporarily (Raudsepp-Hearne et al., 2010). If crossing a global biogeophysical threshold does not significantly harm humanity, does that threshold still merit a PB? It is unclear how PBs theory would answer this question. Cornell (2012) makes the helpful suggestion of a systems approach encompassing the distinction between ecosystem structure, process, function, and service, with services having direct impact for humanity. But it remains to be established, both in theory and empirically for specific PBs, exactly what the human impacts of crossing thresholds would be.

GCR focuses more explicitly on the magnitude of human impacts. However, GCR theory is vague in defining the magnitude of global catastrophe. Atkinson's (1999) 'death of one quarter of the human population' definition is the most precise, but it is based on arbitrary demographic statistics, as is Bostrom and Ćirković's (2008) range of 10^4 to 10^7 deaths or $\$10^9$ to $\$10^{12}$. Bostrom and Ćirković's definition is explicitly vague; they write "The stipulation of a precise cut-off does not appear needful at this stage" (p.3). But a precise cut-off would focus valuable attention. Maher and Baum (2013) suggest an important distinction between global catastrophes from which humanity recovers vs. those resulting in permanent collapse or extinction (E vs. C and D in Figure 3). While this distinction leaves open which global catastrophes will yield which outcomes, it is helpful for suggesting a meaningful point to draw the line. We will extend this reasoning for the BRIHN framework, noting that when humanity fails to recover from a global catastrophe, the catastrophe has exceeded the resilience of the global human system.

The starting point for the BRIHN treatment of impacts is a joint consideration of global boundaries to both human and environmental systems. Since PBs are environmental in nature, a PB is a global environmental system boundary. Crossing a PB can result in a large and damaging threshold effect for the environmental system. We likewise postulate that crossing a global human system boundary can result in a large and damaging threshold effect for the human system. For both the environmental and human systems, thresholds can either be systemic, involving a single global threshold (as in Figure 1a), or aggregative, involving a set of local-scale thresholds (as in Figure 1b). The idea of aggregative human system boundaries suggests a means of incorporating spatially local effects into GCR theory, which as noted above has otherwise been a limitation of GCR theory.

Extending the global thresholds concept to the global human system offers a new definition of GCR: the risk of crossing a large and damaging human system threshold. Crossing such a threshold could involve abrupt and/or irreversible harms to the human system, possibly sending the human system into a completely different state. The new state could involve significantly diminished populations and levels of development, or even outright extinction. In terms of

Figure 3, crossing a global human system threshold would mean that recovery (E) could not occur – either humanity would adapt and persist in a diminished state (D) or it would go extinct (C). Likewise Figure 3 can be interpreted as an upside-down "ball-in-cup" resilience diagram, with (B) being the side of the cup. If the disturbance – the global catastrophe – is too large, then it exceeds humanity's resilience and humanity either goes extinct or remains in a persistent diminished state. This theoretical insight about resilience further links GCR theory and the concept of global human system thresholds to PBs theory. This resilience-based GCR definition offers a precise definition of global catastrophe in system theoretic terms, as opposed to previous definitions based on arbitrary demographics.

Figure 5 extends Figure 4 to show the BRIHN framework, with probabilistic thresholds for global human and environmental systems. To enable joint display of both systems, the axes show variables for system wellbeing instead of control and response variables.[10] The wellbeing variable is oriented such that zero is bad, and larger positive numbers are better, as in Figure 3. The thresholds and boundaries for each system are specific wellbeing levels. Wellbeing for each system is multidimensional, with one dimension for each threshold, i.e. for each threat: climate change, biodiversity loss, nuclear war, etc. In Figure 5, the dotted vertical line is the planetary boundary, i.e. the global environmental system boundary. The dotted horizontal line is the global human system boundary. Both boundaries have zones of uncertainty such that if the boundaries are crossed, there is a risk of crossing the corresponding thresholds. The risk is shown as cumulative distribution functions with the zones of uncertainty, as in Figure 4. Crossing the global human system threshold results in a global catastrophe.

6. Storytelling with BRIHN

The illustrative storytelling power of the BRIHN framework is considerable. Indeed, it can be used to tell a stylized version of the story of humanity and nature co-evolving, from the very beginning through now and into multiple possible futures.[11] Figure 6 tells this story as it appears in the PBs literature (and thus omits the global catastrophe boundary). For simplicity, it omits the zone of uncertainty. Point A marks humanity's tenure in the late Pleistocene, characterized by difficult environmental conditions and little human success. The long duration of this era–about 95% of humanity's temporal existence–is indicated by darkened black circles. Point B is about 12,000 years ago; it marks the environment shifting to the more favorable conditions of the Holocene, which in turn may have enabled the success of human civilization (Richerson et al., 2001; Gupta, 2004).[12] Point C is about 10,000-8,000 years ago and marks the agricultural revolution (Handoh and Hidaka, 2010). Point D marks the industrial revolution (ca. 1800 AD) and the beginning of the Anthropocene. Point E is today. Points F, G, and H are all possible futures. Point F shows humanity changing its course to lessen its environmental impact. This change could involve humanity transforming from a state of sustainable parasitism, in which

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[10] Our use of the term 'wellbeing' is intended in a general sense to refer to the overall quality of the state of the global human or environmental system. We expect and hope that this usage is at least approximately consistent with more precise definitions of the term.

[11] We believe this storytelling to be in the spirit of the long-term, transdisciplinary dynamic modeling recently called for by the IHOPE project (Costanza et al., 2007; Van der Leeuw et al., 2011). The storytelling can also be treated as an exercise in scenario analysis, looking at multiple possible future stories/scenarios.

[12] We acknowledge that the curve from Point A to Point C may show an anthropocentric interpretation of environmental system wellbeing. Some environmental indicators were unchanged during this period, as seen in Figure 8 for phosphorus biogeochemical cycles. The predominantly climatic conditions that did change were of particular benefit to humans, though the changes may have benefited other species as well. We thank Dave Denkenberger for drawing this issue to our attention.

humanity parasitically extracts as much as it sustainably can from the environment, to a state of futurable mutualism, in which humanity treats nature as a mutual, symbiotic partner towards a mutually beneficial future (Handoh and Hidaka, 2010). Point G shows the idea (as in Nordhaus, et al. 2012) that crossing PBs would not be harmful to humanity despite the concomitant environmental degradation; here humanity maintains a state of sustainable parasitism. Finally, Point H shows the idea (as in Rockström et al., 2009a, 2009b) that crossing PBs would harm humanity.

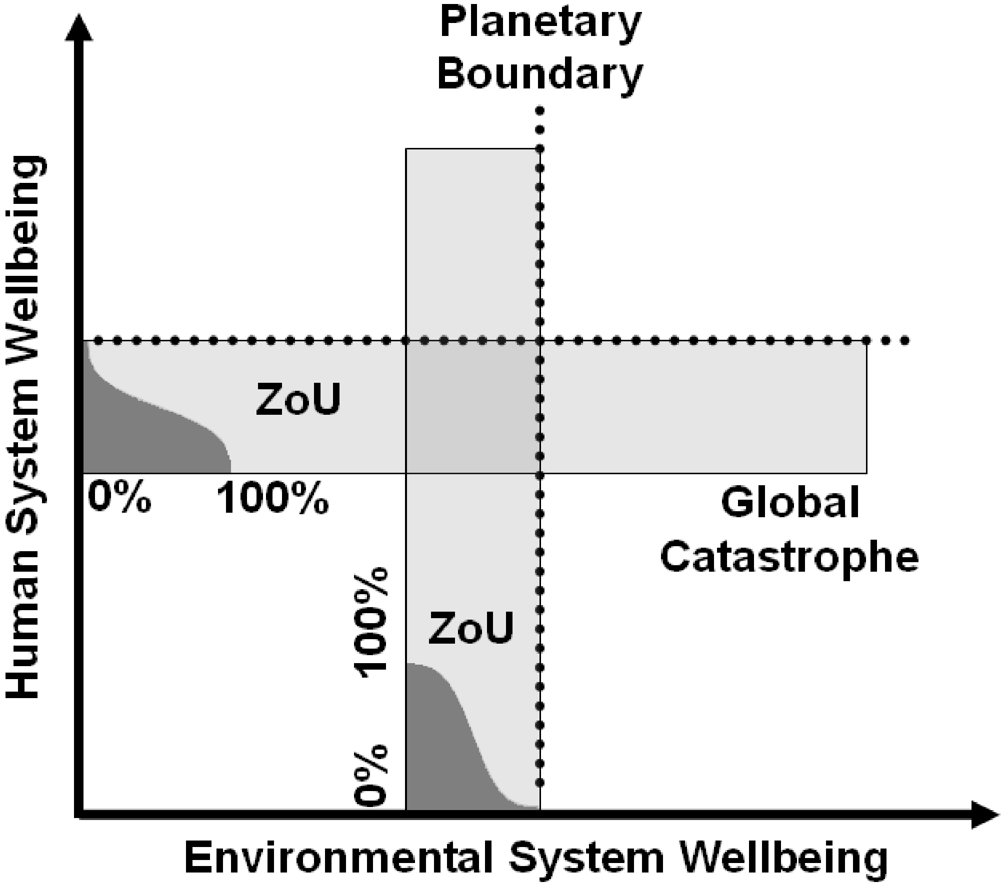

Figure 5. The BRIHN framework, showing one dimension for each of the global human and global environmental systems. ZoU is zone of uncertainty. The dotted lines are boundaries. The curves are cumulative distribution functions for the probability of crossing thresholds.

The story depicted in Figure 6 is compelling but incomplete. First, there is no precision as to how harmful Point H is, and no indication of what happens next. Second, there is no consideration of the various non-environmental threats that humanity faces, as discussed in the GCR literature. Figure 7. thus extends Figure 6 to show the story as told by an integration of the PBs and GCR literatures. The global catastrophe boundary is added back in, and Points A through H are the same as in Figure 6. Points A, B, and C are below the global catastrophe boundary because they show humanity prior to advanced civilization. Point I shows humanity experiencing a global catastrophe in the aftermath of crossing a planetary boundary. The catastrophe is irreversible: Humanity never rebuilds.[13] Point J shows humanity avoiding the global catastrophe boundary, adapting to the new environmental conditions and eventually recovering, an outcome comparable to E in Figure 3. Meanwhile, Point K shows a non-environmental catastrophe. Point L shows the catastrophe crossing the global catastrophe boundary; humanity never recovers, but the environment gradually does as it benefits from diminished human interference.[14] Finally, Point M shows humanity avoiding the global catastrophe boundary and recovering from the catastrophe, returning back to its previous trajectory.

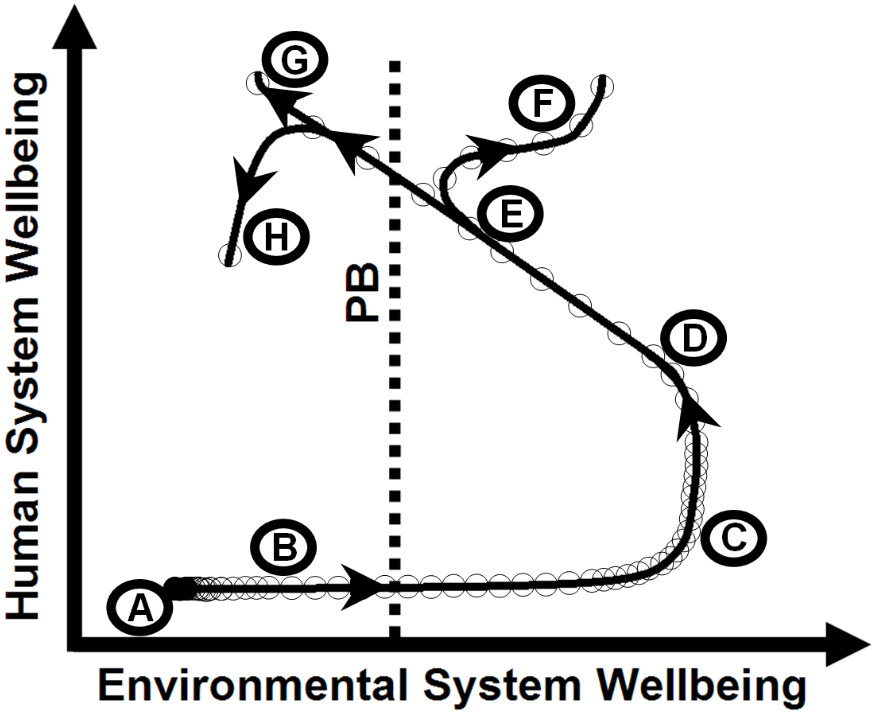

Figure 6. A stylized story of humanity and nature co-evolving as told by the PBs literature. The letters A through G mark significant points in the story and are explained in the main text. The circles indicate points in time; they are spaced farther apart when events change more quickly.

It should be emphasized that Figure 7 offers but a rough, stylized sketch of possible humanity-nature stories, and shows only broad contours, not detailed specifics. Other stories are possible too. Trajectories of those humanity-nature co-evolution stories could be identical to a phase portrait of the dynamical system that describes interactions between humanity and nature. For example, when Points I and A meet and make a closed trajectory, humanity and nature may form a prey-predator relationship that was exemplified by Henrich (2002). This looping trajectory suggests the possibility of humanity recovering from global catastrophe. Just as humanity was once in a pre-civilization form, perhaps humanity could re-form civilization after a

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[13] One might notice that Point I has higher human system wellbeing and lower environmental system wellbeing than Point A, suggesting a global catastrophe that leaves humanity better off and the environment worse off than it was during the earliest era of human existence. We intend no particular significance to this configuration. Points A and I could reasonably be placed in any relative position. Similarly, we also place no significance to the location of Point L on the vertical (human system wellbeing) axis.

[14] Weisman (2007) offers a colorful depiction of environmental regrowth following human extinction.

global catastrophe. Detailed empirical analysis is needed to characterize the human and environmental system boundaries and their properties.

It is a testament to the great uncertainty surrounding the global human and environmental systems that so many different futures are possible. Raudsepp-Hearne et al. (2010) found several plausible explanations for why human wellbeing has recently increased while environmental wellbeing has decreased, suggesting several plausible future directions for both. Similarly, Points F through M in Figure 7 show stylized versions of many possible futures, and indeed other futures are possible as well. Basic features of the future are not currently known: Will there be any global catastrophes? When will they occur? What type of catastrophes will they be? How will the catastrophes affect humanity and nature? Will humanity and nature recover from the catastrophes or will there be permanent collapse? Figure 7 provides a visualization of many possible futures in terms of their timing and their consequences for humanity and nature, and these are not the only possibilities. But the bottom line question is, given all these possible futures, and given the uncertainty about them, what should humanity do? This is an ethical question, and its answers will depend on humanity's ethical views. Assuming that human and environmental system wellbeing is desirable, the key question is, What steps can humanity take to prevent permanent global collapses of humanity and nature, i.e. to keep it in the top-right quadrant of Figure 7? Answering this question requires looking at the details of specific threats.

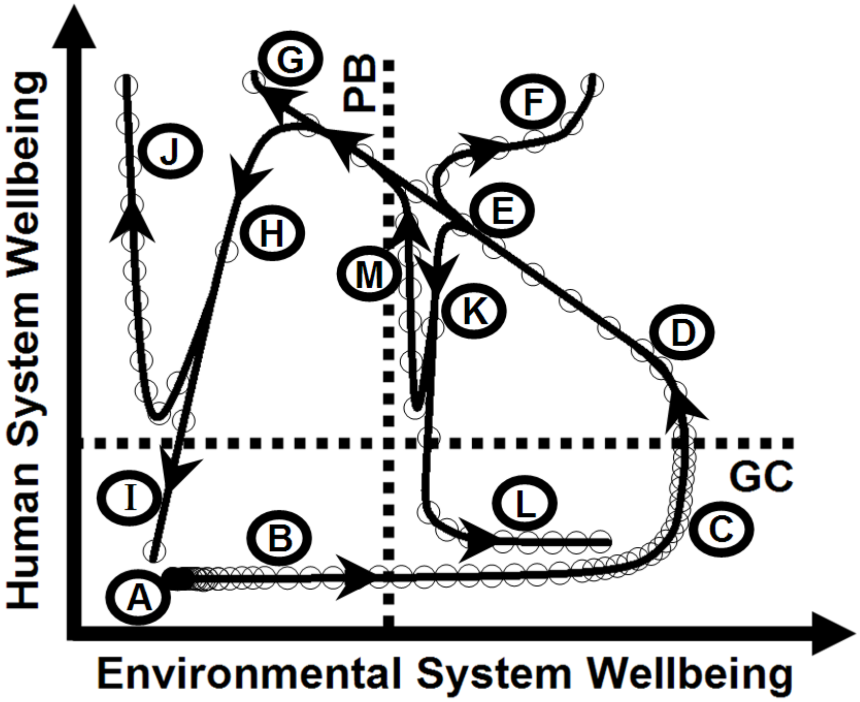

Figure 7. A stylized story of humanity and nature co-evolving as told by the PBs and GCR literatures. The letters A through L mark significant points in the story and are explained in the main text. The circles indicate points in time; they are spaced farther apart when events change more quickly.

7. The BRIHN Phosphorus Story

We now tell the story of humanity and nature co-evolving with the phosphorus biogeochemical cycle, in the same stylized terms as above. Figure 8 illustrates the story; as with Figures 6-7 it omits the zone of uncertainty to keep the diagram relatively simple. Prior to the Quaternary Period (about 2.6 million years ago), the formation of mineral phosphorus deposits reached its peak during the Miocene (23 to 5.3 million years ago), with no significant human or environmental system impacts (Point a in Figure 8). These deposits remained largely intact through the rise of human civilization (b) until mined for fertilizer production in the 1900's (c). Points a and c are below the global catastrophe boundary because they show humanity prior to advanced civilization, analogous to Points A, B, and C in Figure 7. Since the 1900's, phosphorus flows have already exceeded some freshwater environmental system thresholds, though with limited net impact on human system wellbeing (d). Ocean environmental system thresholds have not been exceeded (e), but this potentially could occur in the future, resulting in an OAE (f). If an OAE occurs, humanity could successfully avoid harm and continue developing (g). Or, the OAE could cause major harm to humanity (h), resulting in either global catastrophe (i) or eventual recovery (j). If an OAE does not occur, it could be because humanity transitions to sustainable agriculture based on recycled or reduced phosphorus input, resulting in improved human and environmental system wellbeing (k). Or, humanity could deplete phosphorus reserves, in which case humanity could either successfully adapt to the depletion and eventually recover (m) or the depletion could result in global catastrophe for humanity, with some environmental recovery (n). We emphasize that Figure 8, like Figures 6-7, is a rough, stylized sketch of possible past and future trajectories; it is not intended as precise or as depicting the only possible future trajectories.

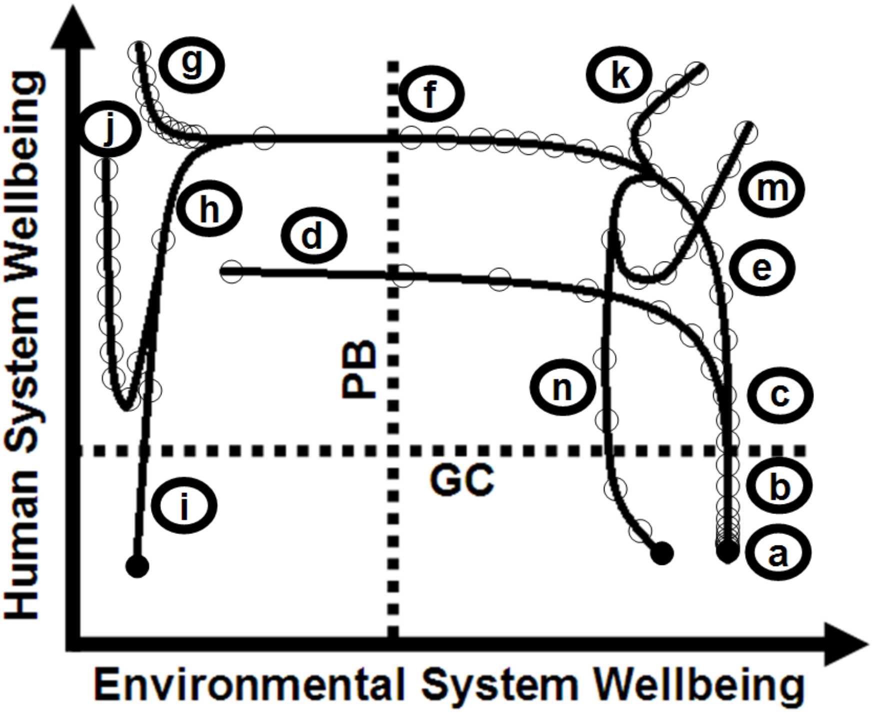

Figure 8. A stylized story of humanity and nature co-evolving for phosphorus biogeochemical cycles. Two environmental systems are shown: freshwater ecosystems (a-d) and ocean ecosystems (a-c, e-j).

Once again, significant uncertainty pervades the exercise, which also only shows only broad contours, not detailed specifics. All of the many futures described in Figure 8 (Points f through

n) are possible given current knowledge. To be sure, some existing evidence points towards some futures as being more likely than others. For example, evidence suggesting imminent "peak phosphorous" (Cordell et al., 2009) suggests that Points m and n are most likely, whereas evidence suggesting an abundance of unconventional phosphorous (Smil, 2000) suggests that Points f through j are more likely. A major gap in existing knowledge concerns how effectively humans will adapt to either the decline of phosphorous reserves (i.e., is m or n more likely) or an oceanic anoxic event (i.e., is g, i, or j more likely). Addressing this knowledge gap, and similar gaps for other global human and environmental risks, is an important challenge for future research.

8. Conclusion

Global human and environmental systems face many threats. PBs and GCR are two paradigms that emerged from two intellectual traditions to help understand and address these threats. The PBs paradigm comes mainly from the ecological resilience tradition and emphasizes threats to the global environmental system. The GCR paradigm comes mainly from the risk analysis tradition and emphasizes threats to the global human system. Integrating these two paradigms into one "Boundary Risk for Humanity and Nature (BRIHN)" conceptual framework offers theoretical advances in the treatment of uncertainty and of impacts. These advances are of practical significance, as illustrated by the case of the phosphorus cycle.

Two core lessons can be learned from this exercise, both suggesting broad directions for future research. First, the human consequences of even major global environmental changes are often poorly understood. This uncertainty can be seen in the widely divergent possible impacts of a phosphorus-induced OAE (Points g, i, and j in Figure 8), and the accompanying lack of research on this topic. Similar uncertainty can be found for other PBs, with PBs research focusing mainly on biogeophysical processes. Comparable human impacts research is not found in the GCR literature, since most PBs have not been identified as GCRs. The main exception is climate change, which has received much research attention regarding its human impacts, both in GCR research and in other lines of research. Other PBs would benefit from more analysis of human impacts, especially at the global scale. Raudsepp-Hearne et al. (2010, 587) put it well: "although we have a good understanding of the negative impacts of much of human action on biodiversity, natural capital, and the biosphere, we have only a weak understanding of the consequences of changes in the Earth system for human well-being".

The second lesson is that threats to humanity are poorly understood at a systemic level. Discussion of global catastrophe tends to focus on somewhat arbitrary statistical measures such as lives or dollars lost. These measures mask the resilience of the human population. Some demographic and economic declines can be restored through increased fertility and development. Other declines cannot be restored. These are the catastrophes that exceed humanity's resilience, the catastrophes from which recovery is not possible. These catastrophes send the global human system into a completely different state, just as crossing PBs can send the global environmental system into a completely different state. These resilience-exceeding catastrophes are of particular concern. Indeed, the GCR concept can be defined as the risk of catastrophes that would exceed humanity's resilience. This system theoretic definition of global catastrophe has a conceptual precision absent from the definitions based on arbitrary statistical measures.

The importance of understanding threats at a systemic level highlights a remaining shortcoming in each of PBs, GCR, and BRIHN: They do not effectively handle interactions between different threats. For example, perhaps phosphorous could not cause a global catastrophe to humanity on its own, whether through OAE or depletion of phosphorus reserves, but perhaps either of these events could contribute to a global catastrophe alongside other stressors such as climate change, disease outbreaks, and war. The shortcoming exists at the theoretical level and also as an absence of empirical studies. The BRIHN framework presented here acknowledges that human and environmental system wellbeing is multidimensional, with one dimension for each threat, but the analysis presented here only considers one threat at a time. Dedicated attention to the interactions is especially important because the interactions are not necessarily linear; interaction effects can either amplify or attenuate the total harm to human and environmental systems. Interactions between threats is an important topic for future research for each of PBs, GCR, and BRIHN.

While the integrated BRIHN framework has been developed for the global-scale threats of PBs and GCR, it can be adapted for other contexts as well. Most generally, the integrated framework can be used for analyzing the risk and resilience of any two interacting systems. The simplest adaptation of the framework would be for local-scale threats to human and environmental systems. The framework could, for example, be used to tell the story of the collapse of ancient civilizations, or of current populations threatened by local environmental stressors. Other types of systems could also be used, such as technological or cultural systems. The integrated framework thus helps merge risk and resilience theory more generally than in just the case of global human and environmental system threats.

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