A Framework for Novel and Adaptive Governance Approaches Based on Planetary Boundaries

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Abstract:

Johan Rockström and colleagues (2009) proposed nine "planetary boundaries" of "safe operating space" for humanity. The authors suggest that these boundaries – based on climate change, extinctions of species, global nutrient cycles, toxic chemical pollution, atmospheric aerosols, stratospheric ozone, freshwater use and land use – might support "novel and adaptive" governance approaches at the global, regional and local levels. How might these forms of governance develop? First, the objectives for framing normative limits on human use of the ecosphere must be considered: what is meant by "safe operating space" and what other principles complement it? Second, policy-oriented metrics must be established for tracking progress toward meeting those objectives. The proposed planetary boundaries and related metrics such as ecological footprint and human appropriation of net primary productivity provide a starting point. Third, an adaptive methodology is needed for transposing those metrics into regulatory and policy regimes. Governance based on "safe operating space" and complementary principles should: 1) treat humans as part of Earth's life systems; 2) give ecological boundaries primacy over socio-economic spheres; 3) integrate ecological boundaries throughout legal and policy regimes; 4) be radically re-focused on reducing throughput of material and energy resources in the economy; 5) be global, but distributed according to the principle of subsidiarity; 6) provide fair shares of the Earth's ecocapacity to present and future generations of life; 7) include binding, supranational rules; 8) be supported by a greatly expanded research and monitoring program; 9) reflect caution about crossing boundaries; and 10) be adaptive.

1. Introduction

The vision of the Stockholm Resilience Centre "is a world where social-ecological systems are understood, governed and managed, to enhance human well-being and the capacity to deal with complexity and change, for the sustainable co-evolution of human civilizations with the biosphere."[1] In September 2009, an international team of twenty-nine scientists and researchers led by Johan Rockström of the Stockholm Resilience Centre, proposed a novel biophysical framework for guiding the human enterprise toward this vision. This framework is built around the concept of "planetary boundaries" of "safe operating space" for humanity: biophysical global limits beyond which humans face "the risk of deleterious or even catastrophic environmental change at continental to global scales." (Rockström et al. 2009). Rockström and his colleagues proposed nine planetary boundaries based on climate change, ocean acidification, stratospheric ozone depletion, atmospheric aerosol loading, land use, freshwater use, chemical pollution, biodiversity loss and nutrient (i.e. nitrogen and phosphorous) cycles, and they provided preliminary estimates for seven of them.

The Rockström team suggested that the planetary boundaries might serve as the basis for "novel and adaptive governance approaches at global, regional, and local scales." (Rockström et al. 2009). This call for novel and adaptive governance emerges from the tension between two opposing narratives of impossibility (Figure 1). On one hand is the narrative that says an economy without growth is impossible. Associated with this narrative is the seeming impossibility of challenging the current global commitment to infinite economic growth and making near-term political, social and economic changes necessary for the emergence of an ecologically bounded governance system. On the other hand is the narrative of ecological limits to the economy. According to this narrative, it impossible to for the human-Earth system to maintain economic growth without suffering long-term catastrophic socio-ecological consequences, and therefore radical political, social and economic changes are necessary.

The deliberate definition of the planetary boundaries as uncompromising against economic objectives and political constraints (Rockström et al. 2009), such that the failure to respect them would raise an intolerable risk of catastrophe, places them within the dynamic tension between these opposing narratives. This dynamic tension creates space for reconsidering conceptions of personhood, well-being, fairness and justice; for developing the emerging primacy of boundaries and limits that apply to the human enterprise; for proposing boundary-based economic indicators that are not dependent on a growth-insistent paradigm; and for paving the

[1] Stockholm Resilience Centre, Vision and Mission, at http://www.stockholmresilience.org/aboutus/visionandmission.4.aeea46911a3127427980003318.html

way to novel and adaptive governance approaches.

As a potential response to this tension, the intriguing suggestion of governance built on planetary boundaries remains undeveloped and in need of a broad range of cross-disciplinary research. In this paper, I propose a framework for using the planetary boundaries and complementary metrics and principles as the foundation for governance of the relationship between the human enterprise and the ecosphere (the human-Earth relationship). Section 2 examines the normative concepts underlying the planetary boundaries and proposes the complementary concept of "right relationship" as a broader normative basis for ecologically bounded governance of the human enterprise. Section 3 suggests how the planetary boundaries and complementary metrics can serve as indicators for determining whether the human enterprise is achieving the normative objectives inherent in concepts like "safe operating space" and "right relationship." Section 4 proposes how these indicators can serve as the basis of novel and adaptive governance approaches at the global, regional and local levels.

2. The normative basis for governance based on planetary boundaries and related concepts

The first step in developing a framework for governance based on planetary boundaries and related concepts is to consider the ecological and ethical principles that should frame normative limits on human use of the ecosphere: What fundamental norms are inherent in "safe operating space" or other framing concepts? Although the Rockström team used "safe operating space" as the central normative concept, the notion of "right relationship" (Brown and Garver 2009), which emphasizes enhancement of the Earth's life systems in a way that transcends the notion of survival and safety inherent in the planetary boundaries framework, provides a complementary and broader normative basis for developing a governance framework. The human enterprise is estimated to be exceeding several planetary boundaries and consuming global bioproductivity faster than it regenerates (Rockström et al. 2009; Ewing et al. 2010). In these circumstances, right relationship implies that the presumed fairness of disparities in wealth and access to biocapacity that result from a growth-driven, capitalist market economy should give way to notions of fairness that ensure a more balanced sharing of the Earth's limited biocapacity among present and future generations of humans and other life.

2.1 The normative concept of boundaries generally

The proposed planetary boundaries may be considered as beacons, projected from the normative rubric of "safe operating space," for guiding fundamental aspects of the human-Earth relationship – i.e, the interactions of the human enterprise, consisting of the global entirety of human endeavors, with the ecosphere, the global entirety of the biotic and abiotic elements and characteristics that make up the Earth and its atmosphere and support life on Earth (Huggett 1999). Other related boundaries are also possible, such as a limit on the human ecological footprint that will adequately allow perpetual provisioning of the human enterprise while also maintaining acceptable levels of biodiversity (Pollard et al. 2010). Recently, an attempt has been made to establish a similar boundary for human appropriation of net primary production (HANPP) (Bishop et al. 2010).

The common features of all of these boundaries are that they are based on systemic, ecological considerations, and they reflect normative notions of acceptable risk of catastrophic environmental consequences for all life on the planet. In addition, the boundaries are related to systemic ecological thresholds in the dynamic human-Earth system. These thresholds are impossible to pinpoint with certainty because of the non-linear dynamics of that system, in which change can occur chaotically, in lurches, and system feedbacks can transcend points of no return long before the consequent impacts become manifest. Boundaries are a human construct with implicit judgments as to the limits beyond which the risk of crossing these systemic thresholds is unacceptable (Rockström et al. 2009). For example, the proposed safe boundary for atmospheric levels of carbon dioxide is set with a margin of safety to avoid a point-of-no-return threshold that is based on solid scientific understanding of the myriad interrelated consequences of increasing temperatures across the planet, such as catastrophic increases in sea level and biodiversity loss. Hansen et al. (2008).

Where, as with the planetary boundaries, several boundaries are used to express the aggregate human ecological impact on Earth, another important feature of the boundaries is their systemic interrelatedness. Noting that "[i]nteractions among planetary boundaries may shift the safe level of one or several boundaries" (Rockström et al. 2009, 24), Rockström and colleagues set each of their proposed boundaries on the assumption that no other boundary was transgressed. If this assumption does not hold, they suggest that the boundaries would most likely have to be adjusted so as to shrink humanity's safe operating space. (Id.).

2.2 Planetary boundaries and the normative features of "safe operating space"

Figure 2 (Foley et al. 2010) shows the proposed planetary boundaries and highlights the three for which the authors concluded the planetary boundary has already been exceeded: climate change, the nitrogen cycle and biodiversity loss. The proposed boundaries, set at the most cautious end of "zones of uncertainty," are:

- For climate change, limiting carbon dioxide in the atmosphere to 350 ppm and net radiative forcing to +1 watt per meter squared (zone of uncertainty: 350-550 ppm and +1 to +1.5 watt per meter squared);
- For ocean acidification, maintaining at least 80% of the pre-industrial level of aragonite in the surface waters of the oceans (zone of uncertainty: 70 to 80%);
- For depletion of stratospheric ozone, limiting the loss to no more than 5% of pre-industrial levels (zone of uncertainty: 5 to 10%);
- For interference with nitrogen and phosphorus cycles, limiting the flow of phosphorus to the oceans to no more than 10 times greater than the flow due to phosphorus from natural weathering (zone of uncertainty: 10 to 100 times greater), and limiting the amount of nitrogen removed from the atmosphere by human means to no more than 35 megatonnes of nitrogen per year (25% of the amount naturally fixed by terrestrial ecosystems) (zone of uncertainty: 25 to 35%);
- For global freshwater use, limiting freshwater withdrawals to no more than 4,000 cubic kilometers per year (zone of uncertainty: 4,000 to 6,000 cubic km per yr);
- For land use change, limiting the percentage of the global ice-free land surface converted to cropland to 15% (zone of uncertainty: 15 to 20%);
- For biodiversity, limiting the rate of extinction of species to no more than 10 extinctions per million species per year (zone of uncertainty: 10 to 100 extinctions).

The authors did not propose global boundaries for atmospheric aerosol (particulate) loading or chemical pollution. The atmospheric concentration of carbon dioxide in 2011 is approximately 390 ppm, net radiative forcing is about 1.6 watts per square meter, the rate of species extinction is estimated to be between 100 and 1000 extinctions per million species, and the amount of nitrogen that humans fix annually is approximately 140 megatonnes (Rockström et al. 2009). Particular emphasis is given to the boundaries for climate change, nutrient cycling and biodiversity in the analysis below.

The notion of "safe operating space" that underlies the planetary boundaries has four inherent normative features that warrant emphasis. The first is the notion of safety, which implies a normative stance in regard to risk and uncertainty that favors precaution. The second is the reference to the Holocene for determining the acceptable ecological conditions for the human enterprise. The third is the notion of the primacy of ecological boundaries, which are uncompromising against social, economic or political considerations. The last is the notion of adaptiveness, which implies an inherent flexibility in any governance framework based on them.

2.2.1 Safety and precaution

Figure 3 illustrates the precautionary approach that Rockström and colleagues (2009) took in estimating the proposed planetary boundaries. The zones of uncertainty in Figure 3 reflect zones that the authors concluded encompass either a threshold representing an abrupt, non-linear systemic change, as with climate change due to atmospheric greenhouse gases, or an accumulation of regional impacts so as to cause a globally dangerous level of impact, as with land use change. These zones of uncertainty reflect incomplete scientific knowledge about the thresholds at which human activities will cause these changes. The authors explain that boundaries, in contrast to thresholds, reflect normative judgments as to the degree of risk that is tolerable in light of the consequences of crossing planetary thresholds, given this uncertainty. Thus, the notion of "safety" in the term safe operating space includes a notion of normative risk aversion, and the authors describe the conceptual framework for planetary boundaries as proposing "a strongly precautionary approach, by setting the discrete boundary value at the lower and more conservative bound of the uncertainty range" (Rockström et al. 2009, Supplementary information, 7). A concern with the precautionary principle is that governments purporting to apply it do not always make clear what to be cautious against (Sunstein 2007). Here, however, the Rockström team make clear that caution about crossing planetary boundaries is of a higher order than concerns regarding economic, social or political consequences.

2.2.2 Reference to the Holocene

Rockström and colleagues (2009) describe the current epoch as the Anthropocene, a term coined in 2000 to describe the era beginning toward the start of the industrial revolution in the 18^{th} century in which large-scale and long-lasting impacts of humans on the Earth's ecology and geology became globally important (Crutzen and Stoermer 2000). The proposed planetary boundaries were developed in large part with reference to the "relatively stable environment of the Holocene, the current interglacial period that began about 10,000 years ago, allow[ing] agriculture and complex societies, including the present, to develop and flourish" (Rockström et al. 2009, 3). Therefore, the conditions of the Holocene, under which "the resilience of the planet has kept … key biogeochemical and atmospheric parameters fluctuating within a relatively narrow range," are key normative characteristics of the boundaries (Id.). In other words, acceptability of risk is determined with reference to the conditions of the Holocene. Basing the planetary boundaries around the Holocene establishes a zone of research for refining existing boundaries or developing new ones.

2.2.3 The primacy of the planetary boundaries

The concept of planetary boundaries contains a powerful message with respect to governance. As conceived, the planetary boundaries of safe operating space are "non-negotiable," (Rockström et al. 2009, 4) and the Rockström team emphasizes that "[t]he thresholds in key Earth System processes exist irrespective of peoples' preferences, values or compromises based on political and socioeconomic feasibility, such as expectations of technological breakthroughs and fluctuations in economic growth." (Id. at 7). Thus, arguing that it is not economically or politically feasible to establish a legal and policy regime that strictly respects the planetary boundaries is tantamount to arguing that ensuring the prospect for humanity's long-term safe operation is not economically or politically feasible—in other words, that ensuring economic and political feasibility is not economically and politically feasible. Instead, the relevant normative inquiry involves establishing the planetary boundaries and how to adjust economic and political policy so as to respect them.

The normative message of safe operating space is that long-term viability of the human enterprise depends on strict observance of ecological boundaries, keeping in mind that the ones Rockström and his fellow researchers propose are open to revision, refinement and complementary measures. Nonetheless, the strictness with which these limits must be respected has some flexibility. First, as noted above, the boundaries that Rockström and his colleagues propose include a notion of how "safe" the operating space for humanity should be, which requires "normative judgments of how societies deal with risk and uncertainty." (Id. at 5). Working through the relevant questions of risk and uncertainty, particularly in a governance context, is complex and will affect how governance is formulated and implemented. Second, although the planetary boundaries imply limits on the aggregate scale of human economic activity, the "operating space" that they envelope allows "humanity . . . the flexibility to choose a myriad of pathways for human well-being and development."[2] Third, the planetary boundaries are interrelated and dynamic, which means that they change over time. Moreover, the processes underlying the boundaries have momentum and will not respond to policy interventions instantaneously, or sometimes even at all within normal policy planning horizons, such that efforts to mitigate human influences on them must be combined with efforts to adapt the human enterprise to changes in them. (Ruhl 2010; Lenton 2008). This explains in part the Rockström group's suggestion that governance based on the boundaries must be adaptive, as discussed further below.[3]

The flexibility as to possible pathways for the human enterprise can be illustrated with the IPAT formula (Ehrlich and Holdren 1971). By this formula, I = f(PAT), aggregate environmental impact (*I*) is a function of the size of the human population (*P*), per capita human affluence (*A*) (or, more accurately, consumption, which tends to correlate closely with affluence, Speth 2008, Krausmann et al. 2004), and technology (*T*) (often expressed as the environmental impact per unit of affluence or consumption, Sachs 2008). Each of the planetary boundaries, or related concepts like an upper limit on the global ecological footprint,[4] can be considered as a fixed value of the I variable, which in turn constrains the *P*, *A* and *T* variables. Thus, if *P* rises, *A* or *T* must fall, but the system is flexible because the combinations of *P*, *A* and *T* for a fixed value of *I* are infinite. Moreover, all of those variables are distributed in complex but interrelated ways from the global to the local level. Thus, for each combination of *P*, *A* and *T*, additional flexibility

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[2] See also Berry (2008) at 40-41: "If the idea of appropriate limitation seems unacceptable to us, that may be because, like Marlowe's Faust and Milton's Satan, we confuse limits with confinement. . . . A small place, as I know from my own experience, can provide opportunities of work and learning, and a fund of beauty, solace and pleasure—in addition to its difficulties—that cannot be exhausted in a lifetime or a generation."

[3] There are two general categories of adaptiveness. One is the need for continual updating of boundaries and the governance mechanisms underlying them. The other is the need to be adaptive in response to far-reaching systemic changes that may occur even if boundaries are respected. For example, climate change that will occur even below a boundary of 350 ppm of carbon dioxide in the atmosphere will require adaptation that will significantly challenge entire regulatory or conservation regimes. For example, climate change may so alter the ecology of protected areas that the purposes for which they were established may need to be changed, or new protected areas to protected the ecosystem values for which they were established may need to be created. In other words, the whole notion of "preserving" an ecosystem may be obsolete in some cases (Ruhl 2001, 394-95) ("The transition [from managing for preservation to managing for change], to put it bluntly, is from the nature we once knew to the nature that we expect to find around us on the other side of climate change.")

[4] Ecological footprint is a measure of human use of the Earth's life support capacity, expressed in terms of normalized "global hectares" of productive land, that was developed in the 1990s by William Rees and Mathis Wackernagel (Ewing *et al*. 2010).

exists in regard to the global distribution of rights, responsibilities and opportunities that exist within the human enterprise and the broader community of life with which humans share the planet. Brown and Garver (2009) propose an additional factor, ethics (*E*)—I = f(PATE)—to reflect explicitly the ethical choices involved in combining the other factors.

2.2.4 Adaptiveness

Ensuring safe operating space for humanity requires an adaptive approach, for two principal reasons. First, in order to exercise caution about crossing planetary and sub-global ecological boundaries, ecological constraints on the human enterprise must be integrated into the global legal and policy structure despite uncertainties, which will persist in some form or another. An adaptive approach allows mechanisms to be put in place to fend off catastrophe and adjusted as research and experience fill gaps in knowledge about Earth systems and about governance of the human-Earth relationship. The adaptiveness called for applies both to the response to evolving scientific understandings and to the mechanisms and institutional arrangements in which to apply them.

Second, adaptation is needed because of the non-equilibrium nature of ecosystems: they are perpetually changing. A key development in the science of ecology in the last few decades has been the switch from an equilibrium view of nature, in which ecosystems were assumed to have an ideal natural state, to a non-equilibrium view, in which ecosystems are now seen as constantly evolving, often in stochastic and non-linear ways (Tarlock 1996, 197-99). "The non-equilibrium paradigm . . . accepts the principal lessons of ecology, that unregulated, humans can damage ecosystems, and that the magnitude of human intervention is often too great." (Id., 202). Much of contemporary environmental law was developed under the equilibrium view of nature. Ecologically bounded governance, by contrast, must incorporate the now well-accepted non-equilibrium view, and in so doing, incorporate an adaptive approach to legal mechanisms that govern the human-Earth interface. "Adaptive management . . . is premised on the assumption that management strategies should change in response to new scientific information: all resource management is an on-going experiment." (Id., 205) Because the Earth's ecology is in constant flux, this new scientific information includes not only improved general understanding of the global ecosystem, its myriad subsystems and social-ecological interactions, but also specific information on the changes taking place within those systems.

That the global ecosystem and its subcomponents are constantly evolving does not mean, as some have suggested, that human influences, however destructive of the Earth's regenerative capacity, are simply one more agent of change and therefore entirely natural and acceptable. Nor does it imply complete management of the Earth's ecology by humans. Rather, understanding how ecology, thermodynamics and other sciences apply to a given situation is not the same as using science to manage the human-Earth relationship with the goal of preserving and enhancing ecological integrity. Ecologically bounded governance calls for legal mechanisms and policy to manage human behavior in an ongoing, adaptive manner, with an emphasis on "the maintenance of processes that produce undisturbed systems [consistent with] the functional, historical and evolutionary limits of nature." (Id., 202).

Law and policy tend to favor finality and certainty, and to resist change,[5] and thus the transition to a system built for adaptation will be difficult. Stable institutions can help solve the tragedy of the commons, but "with a change in circumstances, sensible institutions can morph into tragic institutions." (Daniels 2007, 565). To design institutions that are responsive and adaptive, it is important to promote public participation and transparency, to prepare the users of commons resources to be flexible and adaptive, to integrate management of multiple values rather than single uses of commons resources, to allow trading among commons users within sensible bounds, to build mechanisms for internalizing externalities, to provide incentives for conserving the commons, to give legal rights to those affected by the use of commons to challenge decisions regarding management of the commons, and to buy out entrenched interests if necessary (Id., 566-68).

[5] Daniels (2007) notes that "[w]e see the face of tragic institutions most clearly when incumbent institutions lock out emerging values. Those attempting to protect emerging values can face significant hurdles: collective action, informal norms, established organizations, and institutional remedies." (Id., 562). An example is "rulemaking ruts," a term Blais and Wagner (2008) coined to describe rulemaking that becomes resistant to change in light of new scientific information, such as occurs with technology-based standards when the best information on new technologies is in the hands of the regulated industries with the least interest in wanting to incur costs on new technologies that revised rules might require.

2.3 Right relationship as a broader normative basis for ecologically bounded governance

At least one critique of the planetary boundaries concept warns that overreliance on thresholds in general can support justification of behavior right up to the threshold—the edge of the cliff—when other criteria might provide reasons for staying well back (Schlesinger 2009). One source of additional constraint might be regional or local ecosystem impacts that are more important than the contribution of a local or regional impact to an aggregate limit at the global level. More broadly, social, political or cultural concerns grounded in ethics and justice that transcend the notions of safety and survival inherent in the Rockström group's proposals may provide grounds for additional restraint.

The notion of "right relationship" (Brown and Garver 2009) provides this broader normative basis for developing ecologically bounded governance approaches. Right relationship derives from Aldo Leopold's land ethic (Leopold 1949), updated as follows: "A thing is right when it tends to preserve the integrity, resilience and beauty of the commonwealth of life." (Brown and Garver 2009, 5). It serves as a "guidance system for functioning in harmony with scientific reality and enduring ethical traditions." (Id., 4). Right relationship reflects the scientific reality that the Earth is essentially closed to material inputs but open to energy from the sun, characteristics that define limits on the Earth's life support capacity. But right relationship also has ethical foundations, in that it "include[s] the fair sharing of the earth's life support capacities with all of life's commonwealth." (Id., 17).

A core normative concept inherent in right relationship is that humans are an integral element of, and not separate from, the Earth's life systems. A fundamental critique of the neo-classical economics paradigm relates to its integration of the view that humans stand apart from, and reign over, the environment and non-human species (Berry 1999). Humans are relational beings in a broad complex of interrelated life systems, and ultimately the cosmos. Berry (1999) puts it this way: "We might begin by recognizing that the life community, the community of all living species, including the human, is the greater reality and the greater value. The primary concern of the human community must be the preservation of enhancement of this comprehensive community, even for the sake of its own survival." (Id., 58). Right relationship calls for a revival of the notions of deep ecology and Leopoldian ethics that ceded to the more instrumentalist view of non-human life and life systems of neo-classical economics and dominant contemporary governance systems.

Like the concept of planetary boundaries enclosing safe operating space, right relationship is based on biophysical limits to the Earth's life support capacity. Both are consistent in large part with principles from ecological economics, in particular "biophysical constraints of the economic sub-system" (Rockström et al. 2009, 6). Further, both recognize the uncompromising nature of planetary thresholds of change to life-depleting conditions, such that "ecological and biophysical boundaries should be non-negotiable, and that social and economic develop[ment] (should) occur within the safe operating space provided by planetary boundaries" (Rockström et al. 2009, Supplementary information, 5-6).

Although safe operating space and right relationship are both centered on the notion that the life support capacity on Earth is limited and currently threatened by human activity, they do not overlap entirely. First, right relationship transcends the notion of planetary boundaries because it is framed not only around the outer bounds of the global environmental stresses that pose threats to well being of humans and other forms of life, but also seeks a positive, flourishing human-Earth relationship. The situation that would exist if all of the parameters on which the planetary boundaries are based were at their safe limit is not necessarily one in which the integrity, resilience and beauty of the commonwealth of life is preserved and enhanced. Second, right relationship includes notions of interspecies, inter-human and inter-generational fairness that are not clearly implicit in the notion of safe operating space. The proposed boundaries implicitly safeguard the well-being of ecosystems and non-human species, and not just humans, but criteria for fair distribution of the access to the Earth's life support capacity and for the flourishing of opportunities are less apparent than they are with right relationship.

Despite some differences, right relationship and safe operating space are compatible concepts. Safe operating space is a necessary, but possibly insufficient, condition for the flourishing of life that is inherent in right relationship.

3. Indicators of safe operating space and right relationship

What policy-oriented indicators will accurately and reliably show the extent to which the human enterprise is respecting the planetary boundaries of safe operating space and maintaining right relationship? This question sets the overall framework for developing new economic indicators that can re-orient the human economy toward a respectful relationship with Earth's life systems. These new indicators are intended as alternatives, or at least complements with hierarchical primacy, to existing and emerging metrics and indicators of the economy and well-being, such as GDP, the Genuine Progress Indicator, the Human Development Index, the Happy Planet Index and various sustainable development indicators discussed in Stiglitz et al. (2009) and elsewhere. These other indicators are all either explicitly or intrinsically dependent on a normative framework that insists on economic growth as a necessary or desirable goal for the human enterprise. Alternative indicators based on safe operating space and right relationship challenge this commitment to infinite growth, as well as emerging trends like the monetary valuation of ecosystem services. Here, the concern is that the perceived pragmatic benefits of monetary valuation of ecosystem services (e.g., a Brazilian landowner may avoid using or selling her tropical forestland for soy farming if paid enough for ecosystem services) have prevailed against the more fundamental, longer term concern that commodifying ecosystems dangerously reduces incommensurable values to the single indicator of money (Victor 2008).

Two overarching considerations bear emphasis at the outset. First, the framework for indicators is built around the complex and often non-linear and chaotic systemic behavior of socio-ecological systems at a range of temporal and spatial scales. This systems-based framework poses significant challenges for dealing with uncertainty and measuring parameters suited to boundaries and indicators of the economy. Second, consistent with Herman Daly's conception of ecological economics (Daly 1996), indicators of the performance of he human enterprise against normative criteria based on right relationship and safe operating space can be organized around interrelated questions of aggregate scale, distribution and efficient allocation of human activities (Daly and Farley 2004). Thus, the systems-based framework makes a distinction between indicators of scale, for which the concept of planetary boundaries is well-suited, and indicators of distribution and efficiency, for which the concept of "right relationship" provides criteria that overlap with but go beyond those related to planetary boundaries.

3.1 General features of indicators

The basic question that is relevant for determining the contextual framework of an indicator is, "indicator of *what*?" Here, the focus is on developing novel economic indicators, or more broadly, indicators of the relationship between the human enterprise and the ecosphere. An economic indicator is only meaningful if it conveys information relevant to a stated objective for the economy. Thus, if the paramount objective of the global economy is to ensure continuous growth, then the combined Gross Domestic Product (GDP) of the world's nations presumably would present meaningful and useful information. Framing sustainable development as the objective of the economy would lead to a different set of indicators, although the many different definitions of sustainable development that have been developed, many with clear ties to a growth-insistent economic paradigm, complicates the task of developing sustainable development indicators.

As noted in the previous section, Brown and Garver (2009) contemplate an economy whose purpose is to preserve and enhance the integrity, resilience and beauty of the commonwealth of life. A set of indicators of the extent to which this objective is being attained would be quite different from GDP and indicators of sustainable development that have a strong commitment to economic growth. The notion of "safe operating space" for the human enterprise provides the overall context for indicators in the form of planetary boundaries. That is, the planetary boundaries are indicators of whether the "operating space" for humanity is "safe."

It is also relevant to consider what an indicator will be used for. As noted above, the authors of the planetary boundaries concept clearly had in mind potential applications of the boundaries in systems of governance, which could include their use in developing regulatory limits on human activities. Indicators may also be used for other purposes. For example, they might be used to set agendas for research, including both research aimed at improving the rigor or reducing the uncertainty of the indicators themselves and research on application of the indicators in a specific context. An example of the first type of research is the work of Ranis and colleagues (2006) to analyze the Human Development Index (HDI) against a broad range of human development criteria and to highlight areas of development that are not well captured by the HDI. Examples of the second type of research include the calculation by Quebec's Commissioner of

Sustainable Development of the ecological footprint for Quebec (Lachance 2007), a study comparing the ecological footprints of conventional and organic Italian wines (Niccolucci et al. 2008) and a study of the relationship between HANPP and bird diversity in Austria (Haberl et al. 2005). In addition to supporting research agendas, indicators may be used as means to communicate information, either about the indicators themselves or about the objectives that underlie them (Schiller et al. 2001). A prominent example of the use of an indicator for broad communication purposes is the ubiquitous (and misleading) use of GDP to convey information about the state of the economy at local, national and global levels.

Considerations of temporal and spatial scale issues are also important in developing indicators. Temporal scale is important in understanding the timeframes over which the data underlying an indicator were collected, which in turn may be relevant to the timeframes over which the indicator may be applied or relied on prospectively. For example, the calculation of global HANPP for a single year (Haberl et al. 2008) conveys different information than a calculation of decadal averages of HANPP would convey. The temporal scale of an indicator and whether such factors as seasonal variability should be accounted for in measuring or applying the indicator also determine the nature and time scale of the measurements that are needed for the indicator (Beever et al. 2006). Temporal scale is also related to momentum. For example, an indicator at any point in time might be meaningful in relation to objectives for which the indicator is being used only if it is viewed in light of long-term trends and the momentum of causes and effects underlying those trends. For example, a quarter of the carbon dioxide from fossil fuel emissions remains in the atmosphere for several centuries (Hansen et al. 2008). Thus, for the concentration of carbon dioxide in the atmosphere to be meaningful in regard to the objective of ensuring that atmospheric levels of greenhouse gases do not drastically alter the human prospect on Earth, it must be viewed in light of the longevity of carbon dioxide in the atmosphere, long-term trends in the accumulation and removal of greenhouse gases in the atmosphere and the momentum of, or pace of feasible change in, the processes that emit carbon dioxide to the atmosphere.

Spatial scale is also a key characteristic of indicators of the human-Earth relationship. For example, an indicator of biodiversity at the global scale is certain to be quite different from an indicator of biodiversity at the local ecosystem or landscape level, and developing a global indicator of biodiversity is not necessarily a simple matter of adding together local indicators.

For indicators at the global scale, it is important to understand whether the value of the indicator is based on global averages of the measurements on which it is based, or is a composite of more spatially refined measurements. For example, the methodology for measuring HANPP has evolved from using global averages of the harvesting by humans of various forms of biomass and other components of HANPP (Vitousek et al. 1986) to deriving a global estimate of HANPP from a composite of estimates of human appropriation of biomass at a spatial resolution of about 50 kilometers by 50 kilometers (Haberl et al. 2008).

The capacity of indicators to be relevant at, and across, different temporal and spatial scales depends to some extent on the state of scientific understanding of the behavior of the ecosphere at and across different scales, and on the ability to take and organize relevant measurements at different scales. For example, ecological research has focused extensively in the past decade or more on spatial and temporal scale issues related to biodiversity, which has expanded the ability to develop indicators of biodiversity at, and across, different spatial and temporal scales (Beever et al. 2006; Dirnböck et al. 2008; Rossi and van Halder 2010). By contrast, the most significant advances in the methodology for estimating HANPP have involved progress in obtaining and depicting land use, land cover, biomass harvesting and other relevant data at a high spatial resolution using Geographic Information System tools (Haberl et al. 2008).

The contextual considerations outlined above are conceived as dynamic and fluid, so as to allow for an iterative process in which the indicators and the objectives for which they are designed to provide information are refined over time in light of lessons learned through research and applications. Figure 4 depicts this iterative process. The intention is that this iterative approach will lead to continual improvement of indicators and an increase in their value and potential to be applied in a variety of contexts over time.

3.2 Indicators of aggregate scale, distribution and efficiency

Consistent with the primacy of ecological boundaries, the threshold issue to be addressed in developing new economic indicators based on safe operating space and right relationship is limits or boundaries on the aggregate scale of the human enterprise. This may be viewed as developing indicators of the *I* variable in the IPAT or IPATE framework discussed earlier. The Rockström team developed a methodology for fixing planetary boundaries at the cautious end of zones of uncertainty within which systemic "tipping points" may be crossed, causing irreversible deviation from the conditions that have allowed humanity, along with other life, to flourish during the Holocene. While the activities that contribute to the systems to which these boundaries apply are distributed globally in complex ways, the boundaries are global and relate primarily to questions of the aggregate scale of the human enterprise.

Within the envelope of aggregate scale, questions of distribution and efficient allocation arise (Daly and Farley 2004). In reference to the IPAT or IPATE framework, these questions relate to the combinations of the *P*, *A*, *T* and *E* variables. Right relationship provides a normative basis for assessing the fairness of the distribution of the benefits and burdens of the human enterprise and the efficiency with which humans allocate and partake of the Earth's life support capacity. Fairness is achieved when human and natural communities, and the individual living beings in them, have the means to flourish, and is in decline as capabilities and functions decline. The concept of efficiency depends on the underlying idea of the person and related conceptions of the good. In neo-classical economics, people are typically seen as idealized, rational market actors whose goal is to maximize personal well-being measured in terms of wealth accumulation, and the ecosphere has a utilitarian function as a means for achieving this end. The common language, and the main metric of the good, in neo-classical economics is monetary value. The normative goal is the greatest amount of wealth for the greatest number of people. According to the notion of right relationship and at least some conceptions ecological economics, humans are conceived as relational and interdependent ecological actors in the global ecosystem and its subcomponents, embedded in the dynamics and relationships inherent in social-ecological systems. The normative goal emphasizes sufficiency (not unlimited accumulation) for individual people and other living beings within a life-enhancing, flourishing system. Thus, for example, economic indicators based on right relationship would include indicators both of poverty and of excess.

4. A framework for governance based on planetary boundaries and right relationship

Perhaps the most intriguing feature of the proposed planetary boundaries is their potential application in governance arenas, particularly the possibility that governments at various levels could transform them into regulatory limits that would constrain the human enterprise within their boundaries (Rockström et al. 2009, 28). In the supplementary information to the planetary boundaries paper, the authors compare the planetary boundaries approach to other normative frameworks that are primarily concerned with establishing limits on human impacts to the environment. These other approaches include the Tolerable Windows Approach, which was developed in Germany as a means to frame greenhouse gas emissions strategies; the critical loads methodology used in Europe to set air pollution limits based on critical levels at which pollutants have adverse effects on receiving ecosystems; and the safe minimum standards approach, by which limits are set for environmental variables such as species population size, habitat and water quality, taking into account non-linearity and thresholds in the relevant ecosystems (Rockström et al. 2009, Supplementary information). Thus, applications in governance are a key aspect of the contextual framework for the planetary boundaries concept.

The potential for planetary boundaries to be translated into regulatory or normative programs or standards faces significant obstacles. Not only are the proposed planetary boundaries uncompromising in a way that environmental standards that reflect consideration of economic objectives along with environmental considerations are not, they also imply the need for governance at a comprehensive, global-to-local level that has never been achieved before. Moreover, they relate to coupled human and biophysical systems that do not always follow linear, predictable patterns, and that involve tipping points, emergent properties and stochastic events (Kotchen and Young 2007). Yet, the very nature of the boundaries suggests that the failure to apply these boundaries in normative and proscriptive ways would raise an intolerable risk of catastrophe.

Kotchen and Young (2007) propose the need for governance systems that act as filters that "mediat[e] between human actions and biophysical processes" (Kotchen and Young 2007, 150), as shown in Figure 5. In this configuration, the governance filter "consists of the sets of rights, rules, and decision-making procedures that are created by humans to guide actions, including those that may have disruptive impacts on biophysical systems" (id.), as well as mechanisms like insurance programs that address adaptation to impacts. Kotchen and Young contend that whereas natural resource management has traditionally focused on regulating biophysical systems so as to ensure human welfare, the arrival of the Anthropocene heightens the need to apply this governance filter more to human actions so as to reduce their impacts on biophysical systems. Governance based on safe operating space and right relationship falls neatly into this depiction of a governance filter.

Rockström and colleagues (2009) acknowledge that their proposed planetary boundaries are an initial estimate in need of further refinement, and they do not propose boundaries for two of the global variables for which they nonetheless believe the boundary concept should apply. They intend this initial proposal not to be "a roadmap for sustainable development," but rather to identify boundaries "within which humanity has the flexibility to choose a myriad pathways for human well-being and development" (Rockström et al. 2009, 7). In this sense, their proposal is similar to the proposal in Brown and Garver (2009) to frame governance choices using the I=f(PATE) framework, by which, as noted above, a fixed limit on the value for human impacts, I (which could represent the planetary boundaries individually or collectively), allows a range of flexibility for decisions regarding population (*P*), affluence and consumption (*A*), technology (*T*) and ethics (*E*).

Rockström and colleagues also acknowledge the need for further research on the application of risk assessment and the precautionary principle in setting standards, in order to sort out apparent discrepancies that typically exist between the generally low risks deemed acceptable in human health and welfare (particularly from invisible, carcinogenic, low-risk but high-magnitude, inequitable and involuntary risks) and the generally higher risks deemed acceptable in environmental decision-making (Rockström et al. 2009, Supplementary information). Nonetheless, their initial estimates provide a basis for assessing, at least preliminarily, the further development of the governance context for the boundaries individually and collectively.

Here, particular attention is given to the climate change, nitrogen cycle and biodiversity boundaries. Table 1 provides examples of general applications of these three boundaries in the context of governance. Governance with respect to these boundaries must account for both the pressures on the boundaries, which vary geographically to a considerable degree for all the boundaries, and the ecosystem impacts, which are more variable for some boundaries than others. With respect to distribution of human pressures on the boundaries, information should be developed on the contribution of different sectors at the global and sub-global scales. Table 2 summarizes the methodology for developing this sectoral breakdown. Table 3 is an incomplete illustration of how these tables can be combined in a comprehensive manner.

4.1 Climate change

The variables chosen to describe the proposed climate change boundary—concentration of carbon dioxide in the atmosphere and net radiative forcing—are global, indivisible variables that are not directly applicable in a regulatory or other system of governance designed to apportion the right to assert an environmental impact globally, regionally and locally. To fit more comfortably in governance contexts, the climate change boundary can be translated into net emissions of carbon dioxide and other greenhouse gases, taking into account factors such as their relative contributions to climate change, long-term trends in feedbacks and the behavior of terrestrial and marine sources and sinks of carbon, and the time frame in which stabilization at 350 ppm carbon dioxide in the atmosphere and 1 watt per square meter is sought. These boundaries correlate roughly with a limit on average global warming of about 2 degrees Celsius (Rockström et al. 2009).

As the 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which is over 2000 pages long, makes clear, these are complicated matters. Rockström et al. (2009) note that the IPCC's stabilization scenarios, which are built around achieving stabilization at various atmospheric concentrations of carbon dioxide, are similar to boundaries, although the IPCC does not frame those scenarios around thresholds involving abrupt, non-linear and irreversible systemic changes. Nonetheless, the IPCC's stabilization scenarios provide a starting point for translating Rockström and colleagues' climate change boundary into a form that is more readily adapted to the governance context.

In its Fourth Assessment Report, the IPCC (2007b) estimated that stabilizing carbon dioxide equivalent concentrations in the atmosphere at 450 ppm, which is roughly equivalent to 350 ppm carbon dioxide,[6] in the long term would require developed countries to reduce their carbon dioxide emissions by 25 to 40% by 2020, and by 80 to 95% by 2050. The light red shading in Figure 6 shows the total global reductions in carbon dioxide emissions that the IPCC (2007b) estimated would be needed for long-term stabilization at 350 to 400 ppm concentration in the atmosphere. The dipping of those shaded areas below zero accounts for the possible development of technologies that remove carbon dioxide from the atmosphere. Figure 7 shows the path that Hansen and colleagues (2008) proposed for achieving long-term stabilization at atmospheric carbon dioxide concentration of 350 ppm. Because of the longevity in the

[6] Rockström and colleagues' proposed climate change boundary is based on carbon dioxide concentrations, and not carbon dioxide equivalent concentrations, which accounts for the contribution of other greenhouse gases, on the theory that at least for now, the contributions of other greenhouse gases to global warming are roughly compensated by the cooling effect of atmospheric aerosols from human activities (Rockström et al. 2009).

atmosphere of carbon dioxide from fossil fuel emissions, they conclude that even if coal use is phased out by 2030 and oil and gas reserves are priced so as to preclude use of remaining reserves (the actual pricing strategy depending on whose reserve estimates are used), stabilization at 350 ppm will take more than two centuries. Thus, reaching 350 ppm by 2100 will require reforestation, improved agricultural practices and other approaches that will increase carbon storage (Hansen et al. 2008).

The translation of the climate change boundary from stabilization targets for atmospheric concentrations of carbon dioxide to estimated ranges of annual carbon dioxide emissions required to meet those targets over time, as in Figures 6 and 7, is enormously complicated and still wrought with uncertainty. For example, climate-carbon cycle feedbacks have the potential to turn current carbon sinks into carbon sources in coming decades, such that the baseline for estimating those reductions might have to be shifted downward (IPCC 2007a). Because of those feedbacks, the IPCC estimated, for example, that achieving stabilization at 450 ppm "could require that cumulative emissions over the 21st century be reduced from an average of approximately [2460 Gigatonnes of CO2] to approximately [1800 Gigatonnes of CO2]" (IPCC 2007a, SPM-16).

Nonetheless, translating the climate change boundary into targets for reductions of emissions is an essential step for implementing the climate change boundary in proscriptive or other forms of governance. The policy options in various sectors in Table 4 (IPCC 2007b) provide examples of the specific contexts of governance in which the climate change boundary could be applied. Working toward a particular stabilization target allows flexibility, because different kinds of policy options are possible, and because the same stabilization target can be met, on the same schedule, following either a relatively high peak in emissions followed by a sharp decrease or a relatively low peak in emissions followed by a more gradual decrease, where the cumulative emissions are the same (Anderson and Bows 2008). However, choices drawn from this or other menus of options must add up to the reductions needed to meet the climate change boundary. The climate change boundary, unlike the IPCC's six emission scenarios (IPCC 2007a), is not an output scenario based on assumptions about the rate of economic growth, human development and lifestyles, technological change, population and other factors accounted for in the IPCC's scenarios. Rather, inherent in the boundaries concept is the notion that the climate change and other boundaries compel a set of governance options that, while flexible, are bounded.

Another governance challenge in allowing flexibility within strict boundaries for climate change is in distributing the right to contribute to the boundary among regions and sectors. To illustrate through a somewhat unrealistic example, Figure 8 shows one conceptual approach, in which the main principle to be applied in distributing the right to contribute to climate change (or, as in the figure, to exert an ecological footprint, much of which comes from the carbon footprint) is that every person is entitled to an equal carbon or ecological footprint. Under an "equal sharing" scenario, each country would have to commit to a trajectory for ecological or carbon footprint toward the global average per capita footprint resulting in attainment of a given boundary (in the figure, elimination of the global ecological deficit in 2050 and establishment of a ten percent biocapacity reserve by 2060). In this scenario, the trajectory for countries with current per capita footprints below the target per capita average could (depending on population growth) allow for increased per capita consumption over this four-decade period. By contrast, countries with current per capita ecological footprints above the target per capita average would need to decrease per capita consumption over this period.

This transition period can be illustrated with ten countries with different current ecological footprint profiles: Brazil, Canada, China, Germany, India, Mexico, Namibia, Spain, the United States and Viet Nam. Table 5 shows the population and per capita ecological footprint for those countries and the world total in 2005 (World Wildlife Fund 2008), along with projected population in 2060 (United Nations 2009).[7] In Figure 8, the ecological footprint trajectories (total footprint and per capita footprint) are shown for those countries to reach the global per capita ecological footprint that would an equal footprint for all people. The United Nation's medium variant projection for a world population of 9.15 billion people in 2050 is used for the world population in 2060. Assuming biocapacity is the same in 2060 as in 2010,[8] 13.6

[7] The United Nation's medium variant projected populations for 2050 are used for the year 2060. (United Nations 2009). For simplicity, 2005 values for population and ecological footprint are used for 2010, using figures from the 2008 Living Planet Report. (WWF 2008).
[8] The actual biocapacity in 2060 will depend on a number of complex factors, such as climate change and CO_2 fertilization effects due to human-generated greenhouse emissions, some of which will likely increase biocapacity and some of which will decrease it.

billion global hectares (gha),[9] per capita ecological footprint that would allow a ten percent biocapacity reserve by 2060 is approximately 1.3 gha.

A possible, if not likely, objection to the equal sharing scenario is that it assumes equal sharing of biocapacity across the globe, without accounting for initial endowments of biocapacity. In climate change negotiations, developing countries have favored per capita accounting and equal sharing of the atmosphere, but wealthy countries have objected. (Kumar 2009; Posner and Sunstein 2008). However, as Rockström and his colleagues, myriad pathways are possible.

The promise of the planetary boundaries concept is that it frames the options in terms of biophysical realities, allowing a margin of safety to account for risk and uncertainty but with no softening of ecological thresholds to accommodate socio-economic or political concerns. The dark side of this promise—the opposing narrative of impossibility noted earlier—is the international community's collective inability to date to respond to a concept like planetary boundaries. Anderson and Bows (2008) conclude, in light of the most recent information on carbon cycle feedbacks and emissions trends, along with the lack of resilience of "the current global economic orthodoxy," that it "is increasingly unlikely that an early and explicit global climate change agreement or collective ad hoc national mitigation policies will deliver the urgent and dramatic reversal in emission trends necessary for stabilization at 450 ppmv CO_2e [i.e., around 350 ppm CO_2]" (Anderson and Bows 2008, 18). In their view, even stabilization at 650 ppm CO_2e (a level that by their estimation is over the 550 ppm CO_2 upper limit of Rockström and colleague's zone of uncertainty for climate change)[10] is challenging and improbable, but they end up recommending that climate policy aim for stabilization at around that level given the political realities (Anderson and Bows 2008)—an approach that abandons the precaution of the planetary boundaries approach. The most recent policies of the United States, whose target is to reduce its carbon dioxide emissions in 2020 by only about 4% compared to its emissions in 1990, and of Canada, whose target is to *increase* its carbon dioxide emissions in 2020 by about 2% compared to its emissions in 1990, lend credence to their conclusion. Yet, those policies represent not simply a compromise of economic and environmental concerns, but a dangerous departure from

[9] A global hectare is a normalized unit of land area used in ecological footprint calculations. It represents the average productivity of the different land and near-shore sea that are included in ecological footprint calculations. It is a fictional land unit, rather than an actual one. (WWF 2008).
[10] Anderson and Bows (2008) estimate that 550 ppm CO_2 is roughly the same as 615 ppmv CO_2e.

the emissions reductions required to avoid the risk of catastrophic systemic changes in the climate system.

4.2 Nitrogen cycle

According to Rockström and colleagues (2009), humans now add nearly four times the amount of nitrogen to global ecosystems than the level of the proposed planetary boundary for nitrogen. Through conversion of atmospheric nitrogen to ammonia using the Haber-Bosch process (about 80 megatonnes of nitrogen per year), agricultural fixation of nitrogen from leguminous crops (about 40 megatonnes of nitrogen per year), combustion of fossil fuel (about 20 megatonnes of nitrogen per year) and burning of biomass (about 10 megatonnes of nitrogen per year), humans now incorporate into global ecosystems about the same amount of nitrogen as is fixed by non-anthropogenic processes (Rockström et al. 2009). Prior to the industrial revolution, human fixation of atmospheric nitrogen was negligible (Id.). Figures 9 and 10 show a modeled time series of the human-induced changes in the partitioning of the nitrogen released and stored in global land (Figure 9) and coastal margin (Figure 10) systems, with projections out to the year 2030 assuming a business-as-usual scenario (MacKenzie et al. 2002). Positive values on those figures represent storage mechanisms, and negative values represent release mechanisms.

This rapid expansion in the addition of nitrogen to biogeochemical systems contributes, along with human-caused additions of phosphorus and sulfur, to climate change, increases in smog and ground-level ozone levels, eutrophication of aquatic systems, and acid deposition (MacKenzie et al. 2002). At the same time, the accumulation of nitrogen and phosphorus in the environment can enhance the ability of terrestrial ecosystems to capture atmospheric carbon dioxide (Id.). These various impacts are significant both locally or regionally, where they contribute to urban and other locally significant air pollution and to eutrophication of aquatic systems, and globally, where nitrogen acts as a "slow variable, eroding the resilience of important sub-systems of the Earth System" (Rockström et al. 2009, 15), as with contributions of nitrous oxide to climate change. Thus, the planetary boundary for nitrogen is relevant to governance at both the local and global levels.

The units for the nitrogen boundary—megatonnes of nitrogen per year—could simplify its direct application in governance contexts, for example by setting a limit on the amount of nitrogen fixed through the Haber-Bosch process as ammonia. However, the end use of this ammonia as fertilizer used in food production greatly complicates such a simple application of the boundary, even if Rockström and colleagues (2009) see the nitrogen boundary as a potential impetus for reducing synthetic fertilizer production. Further, Rockström and colleagues (2009) acknowledge that the nitrogen boundary is a "first guess" and in need of further development, and others have found it to be somewhat arbitrary as well (Schlesinger 2009).

In the short term, attempts to limit smog and to protect local or regional aquatic systems, as in Quebec, where excessive nutrients have caused outbreaks of cyanobacteria, are likely to be the most active areas of governance. These local and regional efforts are likely to vary considerably, depending on the pressures from various sectors that contribute to nitrogen pollution and on the sensitivity of local and regional ecosystems. Figure 11 (Bouwman et al. 2002) shows one estimate of the global distribution of critical loads of nitrogen eutrophication (i.e., the estimated maximum ecosystem tolerance of added nitrogen) and of the extent to which those critical loads have been exceeded. Matched with information on sectoral contributions, this distribution can support the development of priorities for regional and local controls on nitrogen pollution. This is essentially the approach taken in Europe using the critical loads and levels methodology, where "critical load" is defined as a "quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Umweltbundesamt 2004, V-1). However, at the global level, further research on the biogeochemistry of nitrogen and on the impact of local and regional controls is needed to determine the most effective way to implement the nitrogen boundary in global governance contexts.

4.3 Biodiversity

Of the seven boundaries that Rockström and colleagues (2009) proposed, the proposed boundary for biodiversity perhaps best illustrates the challenge of translating planetary boundaries into a form suitable for governance. Although climate change is already exacerbating pressures on biodiversity globally and is expected to continue to do so (Ehrlich and Pringle 2008; Butchart et al. 2010), the most pressing threats to biodiversity are at the local level, through direct takings of species, habitat destruction or degradation, toxic pollution and invasive species (Ehrlich and Pringle 2008; Wilson 2002). Yet, even in jurisdictions with apparent policies of zero-tolerance for species extinctions, in which endangered and threatened species are protected either strictly, as in the United States, or less so, as in Quebec, threats to biodiversity persist. Further, recent studies indicate not only that global goals for reducing biodiversity losses are not being met, but also that declines are worsening (Ehrlich and Pringle 2008; Butchart et al. 2010). In Quebec, threatened and endangered species are protected under the Act Respecting Threatened or Vulnerable Species (1999), but the government resources for conducting comprehensive inventories and for ensuring protection of species and their habitat on private property are limited. Thus, the Western chorus frog, listed as threatened in Quebec, faces ongoing and incremental fragmentation of its habitat from suburban and urban development in the Montérégie region—each increment a small diminution of the species chance of long-term survival in Quebec, but the cumulative effect together a significant threat (Équipe de rétablissement de la rainette faux-grillon de l'ouest 2000; Government of Quebec 2010; Coté 2010).

A planetary boundary based on the rate of extinction does not easily translate into effective regulations and policies at the local level. Extinction is the end point of a generally long process of decline, and preservation of biodiversity therefore requires mechanisms of governance that apply at earlier points in the process. These mechanisms must be fashioned so as to be applicable at every scale of importance—in the case of the Western chorus frog and many other species, down to the landowner level. Further, a complete set of complementary, mutually reinforcing mechanisms is necessary. A restriction on land uses to protect species of concern so as to maintain biodiversity will be effective only if the responsible government authorities also have the capacity to conduct comprehensive inventories of the occurrence of species and to obtain comprehensive information on the ecological requirements for the species' long-term survival. Further, they must have the ability to apply a precautionary approach that does not place the burden of uncertainty regarding factors that affect species' survival on the species. It is safe to say that jurisdictions in which all of these conditions are satisfied are few and far between.

The planetary boundary for biodiversity based on extinction rates requires some form of translation to make it useful in regulatory applications. However, as with the nitrogen boundary, Rockström and colleagues (2009) acknowledge that "it remains very difficult to define a boundary level of biodiversity loss that, if transgressed for long periods of time, could result in undesired, non-linear Earth System change at regional to global scales" (Rockström et al. 2009, 18). Thus, a boundary based on extinction rates is proposed as an interim indicator. At least one commentator agrees with the search for a different boundary measure, given that data on the abundance and distribution of species is limited and unequal among species, the relationship between extinction and global environmental change is complex and not well understood, and rates of speciation and extinction vary widely among groups of organisms and habitats (Samper 2009).

Accordingly, while enforcement of laws and implementation of programs that protect species and habitats at the local and regional level should clearly continue and be strengthened, in the context of global governance, the primary agenda with respect to the biodiversity agenda should be a research agenda. A key area of research is to develop better knowledge of species around the globe that are facing extinction, which can be used to identify hotspots for priorities for governance related to preservation of biodiversity. Even at the global level, an effective system of governance tools to address the extreme transgression of the biodiversity boundary that has already occurred will likely depend on local and regional measures tailored to local and regional circumstances and specific species and ecosystems. Figure 12 shows the current distribution of species in major taxonomic groups that are included on the International Union of Conservation and Nature's (IUCN) Red List of Threatened Species. Table 6 is a summary of a recent proposal to expand the Red List so it can serve as a better barometer, across all major taxonomic groups, of the most pressing threats to biodiversity globally and regionally (Stuart et al. 2010). Among other things, this research would help identify bioindicator species that can be monitored, and can serve as the focal points of governance action aimed at preserving biodiversity (Bestelmeyer and Wiens 2001; Stuart et al. 2010; Rossi and van Halder 2010)

Another promising area is research on the relationship between species extinctions and human use of ecosystems on which they depend. For example, Wright (1990) used HANPP in conjunction with species-energy curves, which relate the number of species to the total production of available energy in a region. By examining the effect of HANPP on the total energy available, Wright derived estimates of the percentage of species expected to be extinct or endangered that were generally consistent with observations. More recent work has expanded the research on the relationship between HANPP, or of activities that contribute to it, and species diversity in various contexts (Haberl et al. 2008). Specific examples include the relationship of livestock grazing (Bestelmeyer and Wiens 2001), agricultural production more generally (Haberl et al. 2004) and land-use decision-making (Bestelmeyer et al. 2003) to biodiversity, using

HANPP and other measures of human impact. Further refinement of these methodologies, especially in a spatially explicit manner, would be useful for better identifying or forecasting, and then to controlling, threats to biodiversity.

4.4 Other boundaries and interactions of boundaries

The adaptability of the other boundaries for which Rockström and colleagues (2009) propose initial estimates to novel governance approaches can be analyzed along the lines presented above for climate change, nitrogen and biodiversity. The boundaries for freshwater use and phosphorus loading are both quantitative annual measures, which provides at least a superficial advantage for applying them normatively. The boundary for stratospheric ozone is expressed in terms of percentage of depletion from pre-industrial levels, which requires some translation back to the rate of emissions of ozone-depleting substances, but this boundary is perhaps the best understood and is already generally accepted and globally enforced (Rockström et al. 2009). The boundary for land use change, expressed in terms of the percentage of ice-free land converted to cropland, can be readily translated into an areal limit, so that the challenge in the governance context is to determine how to distribute that global limit regionally and locally. The boundary for ocean acidification, expressed in terms of the retention of a minimum level of the pre-industrial saturation state of aragonite in surface water of the oceans, would require translation to other parameters, primarily emissions of greenhouse gases, to be readily subject to application of mechanisms of governance.

With the exception of the boundary for stratospheric ozone depletion, all of these boundaries warrant further development and refinement before they can be readily in systems of governance at the global level. However, this does not mean that inaction is appropriate. Rockström and colleagues (2009) anticipate the use of the boundaries in adaptive governance mechanisms. This is partly because they were each established on the assumption that other boundaries were not transgressed for long periods of time, they interact with each other to various degrees and they are subject to complex, non-linear behavior that precludes easy forecasting. However, adaptive governance also allows governance measures to get started at all levels, with improvements on the basis of increased knowledge and experience. The precautionary approach of the planetary boundaries concept warrants aggressive local and regional action to reduce the pressures on all of the boundaries, with global coordination increasing over time.

4.5 Institutional implications of planetary boundaries

The potential for planetary boundaries to support mechanisms of governance at the global, regional and local levels implies the need for institutional frameworks for those mechanisms of governance. The proposal of Brown and Garver (2009) to establish new or fortified global institutions to manage the human-Earth relationship according to the principle of right relationship provides a helpful start, in particular the proposal for an Earth Reserve to oversee the global distribution, allocation and stabilization of the Earth's life support capacity. Further developing and refining the planetary boundaries, including how related indicators or methodologies such as HANPP, ecological footprint and material and energy flow accounting might be used in conjunction with them, would fall squarely within the mandate that Brown and Garver (2009) proposed for that institution.

It is perhaps not surprising that most of the authors of the planetary boundaries proposal are European, given Europe's evolution in the past fifty years to the increasingly integrated European Union, which has broad supranational authority with respect to pollution control, conservation of biodiversity, certain matters related to mitigation of climate change and other areas that are relevant to the boundaries. Although the European Union does not yet have all the answers in regard to how to govern in a comprehensive manner the complex set of interactions involved in the human-Earth relationship, it is the best example to date. A key feature of the European Union and its institutional arrangements is the mandates in the European Union treaties of subsidiarity and proportionality, which require the European Union to act only to the extent necessary to meet objectives and only if lower levels of government cannot effectively act to meet those objectives.

Where the European Union and all other national governments and international institutions consistently fall short, however, is in funding and implementing comprehensive systems for monitoring the impacts of human activities on the domains described by the planetary boundaries. And more critically, individually and collectively they have so far failed to muster the political will to respect the Earth's biophysical limits before the failure to do so brings on catastrophe. The European critical loads and levels approach is a good example: although the approach is generally sound as a limits-based, ecosystem-driven program, many of the critical loads are expected to be exceeded indefinitely because of economic and technological considerations (Pelletier 2010; Spranger 2008). Adequate institutional arrangements for implementing planetary boundaries at the global level, using principals of subsidiarity and proportionality, will require that those shortcomings be overcome.

4.6 Issues of scale related to planetary boundaries

Figure 13 (Rockström et al. 2009) shows the scales of the processes and of the known thresholds that are associated with the nine proposed categories of planetary boundaries. Clearly, the proposed planetary boundaries are subject to myriad processes operating at a wide range of spatial and temporal scales. In the context of governance, a key challenge in dealing with scale issues is to figure out how to scale boundaries, and any associated norms or policies, that involve processes of global scale, such as climate change, down to the regional and local level, and how to scale boundaries that primarily involve locally variable processes, such as biodiversity loss, up to the global level. Expanded use of models of carbon-climate cycles, coupled dynamic global vegetation models, global biogeochemical models and the like, and of spatially explicit data sets (Haberl et al. 2008), will help manage the daunting scale issues inherent in the planetary boundaries concept.

4.7 Issues commensurability and transversality related to planetary boundaries

Commensurability in ecological economics refers to whether different dimensions of value, such as historical, spiritual or ecological values as compared with direct economic valuation used in economic exchanges, are amenable to common measures of valuation (Martinez-Allier et al. 1999). Where monetary valuation is used across different dimensions of value, commensurability of value is assumed (Id.). If commensurability of value is assumed, then money or another common measure serves as the basis for making decisions that resolve choices among competing options. Where incommensurability of value exists, rational decision-making may be possible, but it entails a pluralistic evaluation of multiple criteria and the rationality involved is more procedural than substantive (Id.). In other words, decisions can be reached, but not simply by making comparisons based on a single unit of value such as money. Commensurability is also relevant to whether an indicator has uniformity of meaning in different contexts or at different scales, such that rational decisions can be made according to a direct comparison using the indicator as the common measure of value. For example, ecological footprint has been criticized for assuming that a hectare's worth of ecological footprint means the same everywhere on Earth, regardless of the heterogeneity of ecosystems and of processes that contribute to ecological footprint (Van Kooten and Bulte 1999; Van den Bergh 1999).

Transversality refers to the relationship between the different components that make up an indicator, or, more commonly, an index. For example, the Sustainable Society Index (SSI) is a problematic broad index of sustainability, where a sustainable society is defined, consistent with the Brundtland Commission's definition (Brundtland 1987), as one "that meets the needs of the present generation, that does not compromise the ability of future generations to meet their own needs, in which each individual has the opportunity to develop himself in freedom, within a well-balanced society and in harmony with its surroundings" (Sustainable Society Foundation 2010). The SSI consists of 22 different variables, each of which is evaluated on a scale of 1 to 10, where a value of 10 indicates 100% sustainability. Figure 14 shows the SSI for the world in 2008, as calculated using this methodology. Transversality refers to the interrelationship between the 22 different sub-components of the index. By contrast, commensurability in relation to the SSI would refer to the extent to which the SSI provides a meaningful common measure, such that calculations of SSI for different countries or regions can be compared meaningfully with each other, or can or should be used as the basis of decisions that would affect those different countries or regions.

Table 7 summarizes issues of commensurability and transversality related to Rockström and colleagues' (2009) proposed planetary boundaries for climate change, nitrogen and biodiversity. The commensurability of the climate change boundary is rated as high, in that the concentration of carbon dioxide in the atmosphere and the net radiative forcing are essentially uniform around the globe, and a ton of carbon dioxide has the same impact no matter where on Earth it is emitted. By contrast, the commensurability of the biodiversity boundary, stated in terms of rates of extinction of species, is rated as low, in that not all species have equivalent roles across the Earth or even in particular ecosystems, and rates of speciation and extinction vary among different organism groups (Rockström et al. 2009; Samper 2009). The commensurability of the nitrogen boundary is rated somewhere in between, in that the meaning of some aspects of the boundary, such as the contribution of nitrous oxide to climate change and the conversion of atmospheric nitrogen to fertilizer components, is not spatially dependent, while other aspects, such as the role of nitrogen in specific ecosystems, is subject to wide variability.

Generally speaking, transversal relationships among the individual boundaries are strong and quite important. Rockström and colleagues (2009) note the strong interactions among the boundaries, and in particular that individual boundaries, which were set on the assumption that other boundaries were not exceeded, may shift depending on what happens with other boundaries. This is because of strong feedback loops among the boundaries, as when climate change increases loss of biodiversity, nitrogen cycles influence the behavior of carbon sources and sinks, or aerosol loading reduces the global warming effect of greenhouse gas emissions. This strong degree of transversality is not a deficiency of the planetary boundaries approach, but rather an implication of its highly dynamic nature.

5. Conclusion

The notion of safe operating space in the planetary boundaries concept can readily align with more holistic paradigms for the human-Earth relationship, such as the proposal in Brown and Garver (2009) of a "whole earth economy" built on a principle of right relationship. In particular, the focus in Rockström and colleagues (2009) on ensuring biophysical conditions suitable for long-term human welfare is consistent with the notion of preserving the integrity, resilience and beauty of the commonwealth of life, even if not co-extensive with it. Thus, planetary boundaries are a promising set of indicators for assessing whether the human enterprise is in right relationship with the Earth. However, they should not be viewed as an invitation for humanity to live life on the edge, by burdening Earth systems right up to the boundaries. Instead, the goal should be a flourishing commonwealth of life.

Implementation of the planetary boundaries framework that Rockström and colleagues (2009) propose to ensure that humanity stays within safe operating space will require research to reduce uncertainties in the boundaries and the use of a broad and regionally variable set of subsidiary measures for most if not all of them. The intention that the planetary boundaries support mechanisms of governance at the global, regional and local level implies the need to translate them into regulatory limits or other policy prescriptions that will regulate human behavior, preferably using principles of subsidiarity and proportionality. That the proposed boundary for depletion of stratospheric ozone has already been accepted internationally, and the international community is at least attempting to address climate change collectively, offers some hope that planetary boundaries might at some point translate into effective mechanisms of governance. New or fortified institutional mechanisms, such as the Earth Reserve and other supranational institutions and functions proposed in Brown and Garver (2009), would help move the development of the planetary boundary concept in that direction. An Earth Reserve or similar institution would be well suited to refine the planetary boundaries, and to develop them in conjunction with related indicators, such as HANPP and ecological footprint, and with the I=f(PATE) framework.

Any system of global governance that is based on principles of safe operating space and right relationship should include the ten following mutually reinforcing features:

1. It should recognize that humans are part of the Earth's life systems, not separate from it.

2. Legal and policy regimes must be constrained by ecological considerations necessary to avoid catastrophic outcomes and promote the flourishing of life, with the socio-economic sphere fully contained within these ecological constraints and ecosystems restored where necessary.

3. Boundaries-based laws and policies must permeate legal and policy regimes in a systemic, integrated way, and not be seen as a specialty area of law or policy.

4. Because the human enterprise has already surpassed global ecological limits, legal and policy regimes should be radically re-focused on reduction of the throughput of material and energy in the economy.

5. Boundaries-based governance must be global, but distributed fairly using principles of proportionality and subsidiarity, with protection of the global commons and public goods paramount and constraints on property rights and individual choice implemented as needed to keep the economy within ecological limits.

6. Legal and policy regimes must ensure fair sharing of resources among present and future generations of humans and other life.

7. Boundaries-based laws and policies must be binding and supranational, with supremacy over sub-global legal regimes as necessary, and with rights of enforcement for non-state actors.

8. A greatly expanded program of research and monitoring for improved understanding and continual adjustment of ecological boundaries and means for respecting them is needed to support boundaries-based governance approaches from the global to the local level.

9. Boundaries-based governance approaches requires precaution about crossing planetary boundaries, with margins of safety to ensure both that the boundaries are respected from the global to the local level and that the Earth's life systems have the capacity to flourish.

10. Boundaries-based governance must be adaptive, because ecosystems evolve constantly and because we need to get started on a comprehensive effort to constrain the economy within ecological limits despite uncertainty.

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Tables

Table 1. General policy options for three critical planetary boundaries

Boundary	Policy options (examples)
Climate change	• Reduce GHG emissions • Increase carbon sinks • Geo-engineering
Nutrient cycles	• Control point & non-point source water pollution • Reduce N and P fertilization • Reduce industrial fixation of atmospheric N • Control fossil fuel emissions
Biodiversity	• Protect species of concern • Protect habitat • Improve species inventories • Address global warming

Table 2: Global and sub-global distribution of pressures on boundaries

Global and regional distribution of pressures on boundaries			
Boundary	**Sector**	**Percentage contribution**	**Nature of impact**
Climate change	Agriculture	?	E.g., reduction in carbon uptake capacity, direct GHG emissions, indirect GHG emissions
	Forestry	?	
	Fisheries	?	
	Freshwater	?	
	Manufacturing	?	
	Buildings	?	
	Transport	?	
	Tourism	?	
	Waste	?	
	Energy	?	
Nitrogen flux	Same approach		E.g., fertilizer use, fossil fuel combustion,
Biodiversity	Same approach		E.g., habitat harm or loss, direct take (harvest), invasive species, pollution

Table 3. Global to local distribution of governance options

Planetary boundary	Geographic scale	What to measure	Key policy arenas and/or options	Target sectors	Existing models or frameworks
Climate Change 350 ppm CO_2 in atmosphere, 1 W/m^2 net solar radiation	Global	Total net emissions and net radiation – Gt CO_2/yr, W/m^2	Post-Kyoto GHG and climate change agreement	National governments	Kyoto, UNFCCC
	Regional/national	National accounts – net GHG emissions in Gt CO_2/yr	Regional or national GHG emissions control	Sub-national or sub-regional governments	European carbon market
	Local	Source-specific emissions limits – Gt CO_2/yr	Regulatory limits on GHGs for specific sources; credits for creation or protection of GHG sinks; fuel switching; carbon capture and storage; forest protection; low-carbon agriculture; building and energy codes; vehicle efficiency requirements; renewable energy support; etc.	All economic sectors (building, power generation, transportation, agriculture, forestry, etc.)	California, NE states in the US
Nitrogen flux	Global				
	Regional/national				
	Local		- Control point and non-point pollution sources - Reduce fertilizer use - Reduce industrial fixation of atmospheric N - Reduce fossil fuel emissions		
Biodiversity 10 extinctions per million species per year	Global	- Extinction rates - Status of and changes in species abundance and diversity - Status of and changes in habitat - Status of and changes in drivers of biodiversity loss, e.g. relationship of ecological footprint or HANPP to biodiversity metrics	- habitat change - overexploitation - pollution - invasive alien species - climate change		
	Regional/national	-	- habitat change - overexploitation - pollution - invasive alien species - climate change		
	Local	-	- habitat change - overexploitation - pollution - invasive alien species - climate change		

Table 4. IPCC (2007b) list of potential policies for mitigating climate change

Sector	Policies[47], measures and instruments shown to be environmentally effective	Key constraints or opportunities
Energy supply [4.5]	Reduction of fossil fuel subsidies	Resistance by vested interests may make them difficult to implement
	Taxes or carbon charges on fossil fuels	
	Feed-in tariffs for renewable energy technologies	May be appropriate to create markets for low emissions technologies
	Renewable energy obligations	
	Producer subsidies	
Transport [5.5]	Mandatory fuel economy, biofuel blending and CO_2 standards for road transport	Partial coverage of vehicle fleet may limit effectiveness
	Taxes on vehicle purchase, registration, use and motor fuels, road and parking pricing	Effectiveness may drop with higher incomes
	Influence mobility needs through land use regulations, and infrastructure planning	Particularly appropriate for countries that are building up their transportation systems
	Investment in attractive public transport facilities and non-motorised forms of transport	
Buildings [6.8]	Appliance standards and labelling	Periodic revision of standards needed
	Building codes and certification	Attractive for new buildings. Enforcement can be difficult
	Demand-side management programmes	Need for regulations so that utilities may profit
	Public sector leadership programmes, including procurement	Government purchasing can expand demand for energy-efficient products
	Incentives for energy service companies (ESCOs)	Success factor: Access to third party financing
Industry [7.9]	Provision of benchmark information	May be appropriate to stimulate technology uptake. Stability of national policy important in view of international competitiveness
	Performance standards	
	Subsidies, tax credits	
	Tradable permits	Predictable allocation mechanisms and stable price signals important for investments
	Voluntary agreements	Success factors include: clear targets, a baseline scenario, third party involvement in design and review and formal provisions of monitoring, close cooperation between government and industry.

Agriculture [8.6, 8.7, 8.8]	Financial incentives and regulations for improved land management, maintaining soil carbon content, efficient use of fertilizers and irrigation	May encourage synergy with sustainable development and with reducing vulnerability to climate change, thereby overcoming barriers to implementation
Forestry/Forests [9.6]	Financial incentives (national and international) to increase forest area, to reduce deforestation, and to maintain and manage forests	Constraints include lack of investment capital and land tenure issues. Can help poverty alleviation.
	Land use regulation and enforcement	
Waste management [10.5]	Financial incentives for improved waste and wastewater management	May stimulate technology diffusion
	Renewable energy incentives or obligations	Local availability of low-cost fuel
	Waste management regulations	Most effectively applied at national level with enforcement strategies

Table 5. Current and target country-specific populations and ecological footprints: Equal sharing scenario

Country	2005 population (millions)	2005 per capita ecological footprint (gha)	2005 total ecological footprint (million gha)	2060 projected population (millions)	2060 target total ecological footprint (million gha)
Brazil	186.4	2.4	447.4	218.5	327.8
Canada	32.2	7.1	229.3	44.4	66.6
China	1323.3	2.1	2778.9	1417.0	2125.5
Germany	82.7	4.2	347.3	70.5	105.8
India	1103.4	0.9	993.1	1613.8	2420.7
Mexico	107.0	3.4	363.8	129.0	193.5
Namibia	2.0	3.7	7.4	3.6	5.4
Spain	43.1	5.7	245.7	51.3	77.0
United States	298.2	9.4	2803.1	403.9	605.9
Viet Nam	84.2	1.3	109.5	111.7	167.6
World	6476	2.7	17485	9150	12240

Table 6. Proposed "barometer of life" research needs

SPECIES AND PROJECTED COSTS FOR A BAROMETER OF LIFE

			FOR THE BAROMETER	
Major taxonomic grouping	Described species*	Species assessed on IUCN Red List by 2009†	Provisional target number of species	Estimated cost to complete (US$)
Chordates	64,788	27,882	61,635	16,000,000
Invertebrates	1,359,365	7,615	45,344	20,000,000
Plants	310,129	12,151	38,521	17,000,000
Fungi and others	165,305	18	14,500	7,000,000
	1,899,587	**47,666**	**160,000**	**60,000,000**

*Data on the number of described species taken from (1). †Data on the number of assessed species from www.iucnredlist.org.

Source: Stuart et al. (2010).

Table 7. Commensurability and transversality of three key planetary boundaries

Boundary	Commensurability	Highly transversal with:
Climate change	High	All other boundaries
Nutrient cycles	Medium	Climate, freshwater use, land use change, biodiversity
Biodiversity	Low	All other boundaries

Figures

Figure 1. Opposing narratives of impossibility

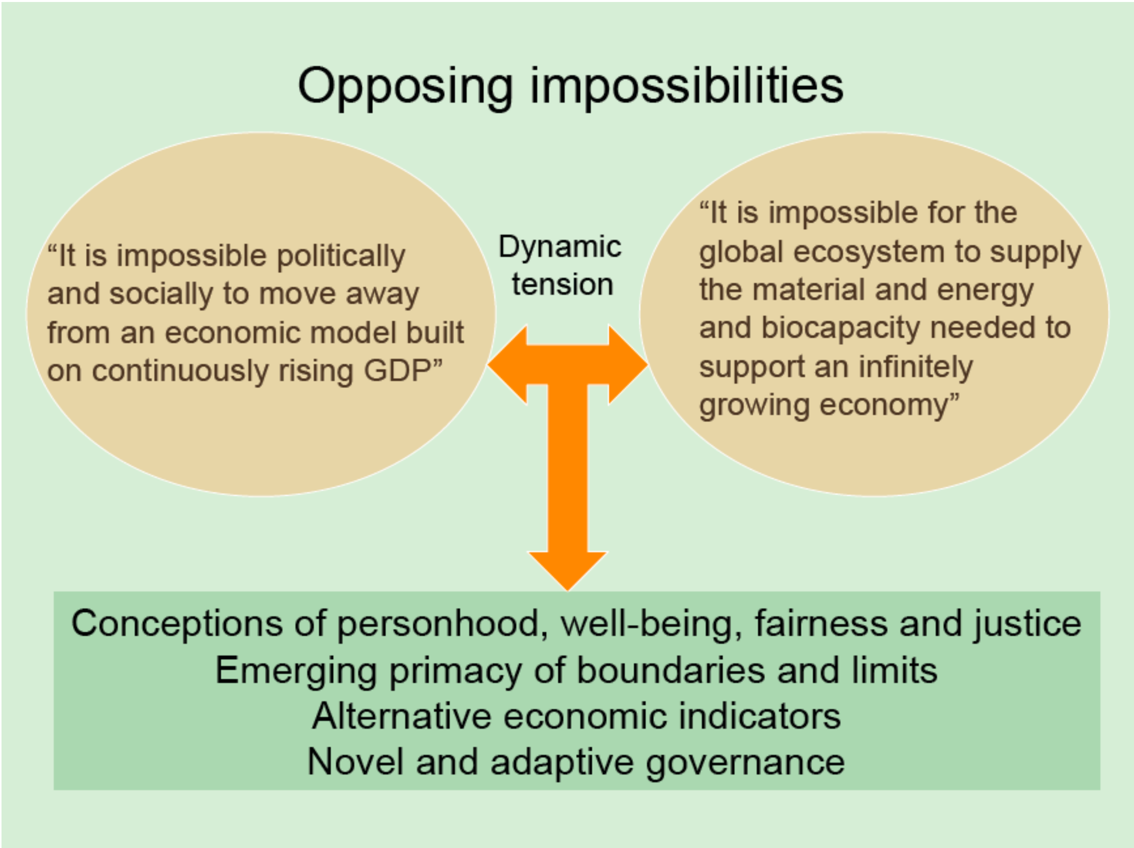
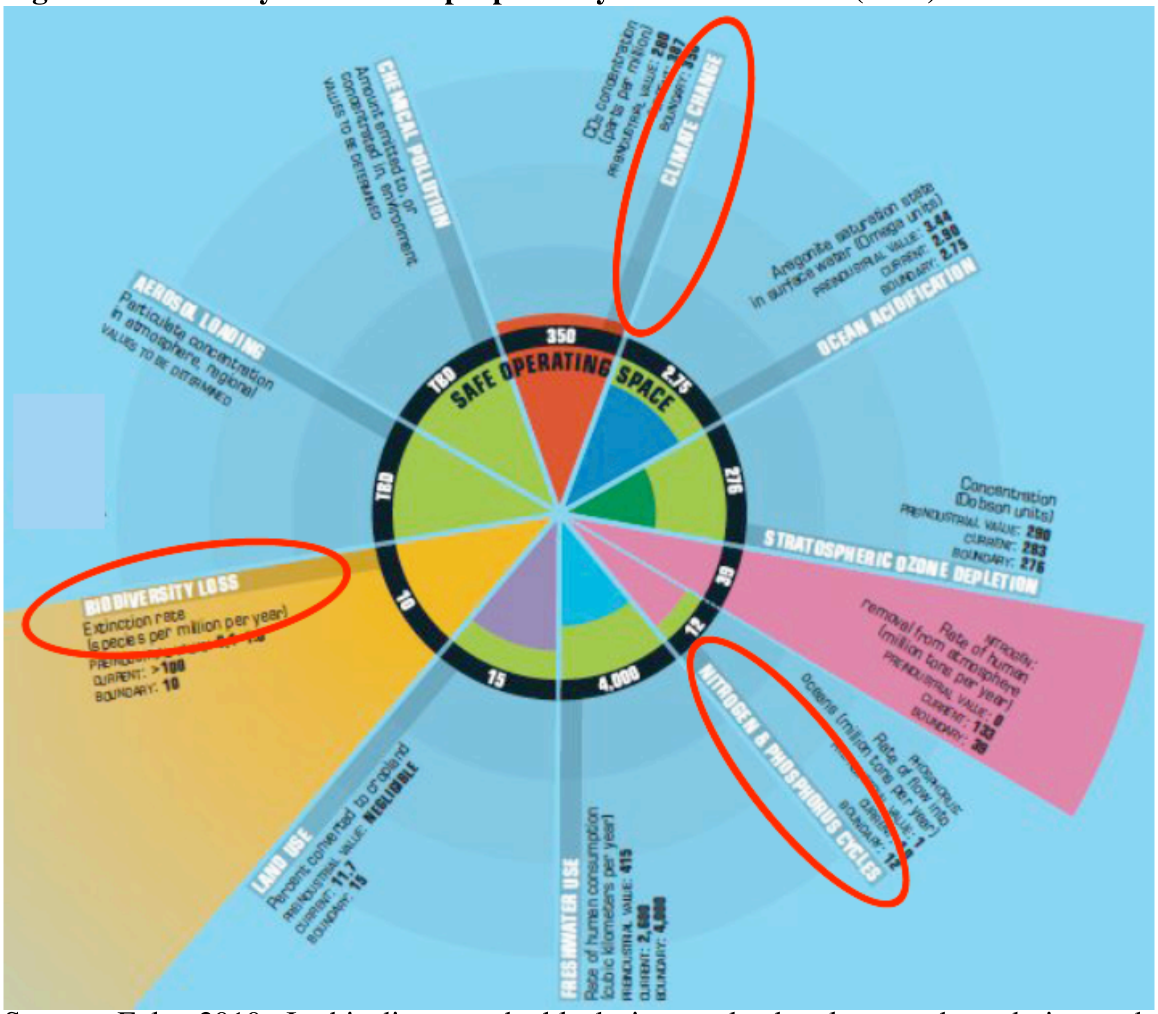
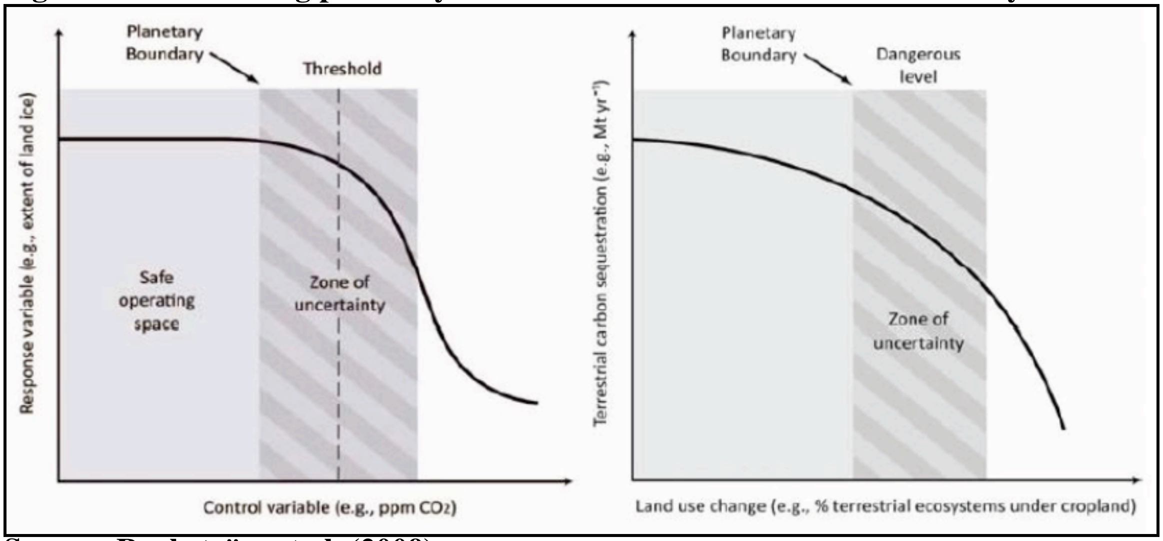


Figure 2. Planetary boundaries proposed by Rockström et al. (2009)



Source: Foley 2010. In this diagram, the black ring marks the planetary boundaries, and the green interior denotes "safe operating space." The colored shading for each of the boundaries indicates the extent to which the boundary has been reached. Particular attention is paid in this paper to the red-circled boundaries, which are those that Rockström and colleagues indicate humans have already transgressed.

Figure 3. Establishing planetary boundaries based on zones of uncertainty



Source: Rockström et al. (2009)

Figure 4. An iterative process for establishing and refining indicators

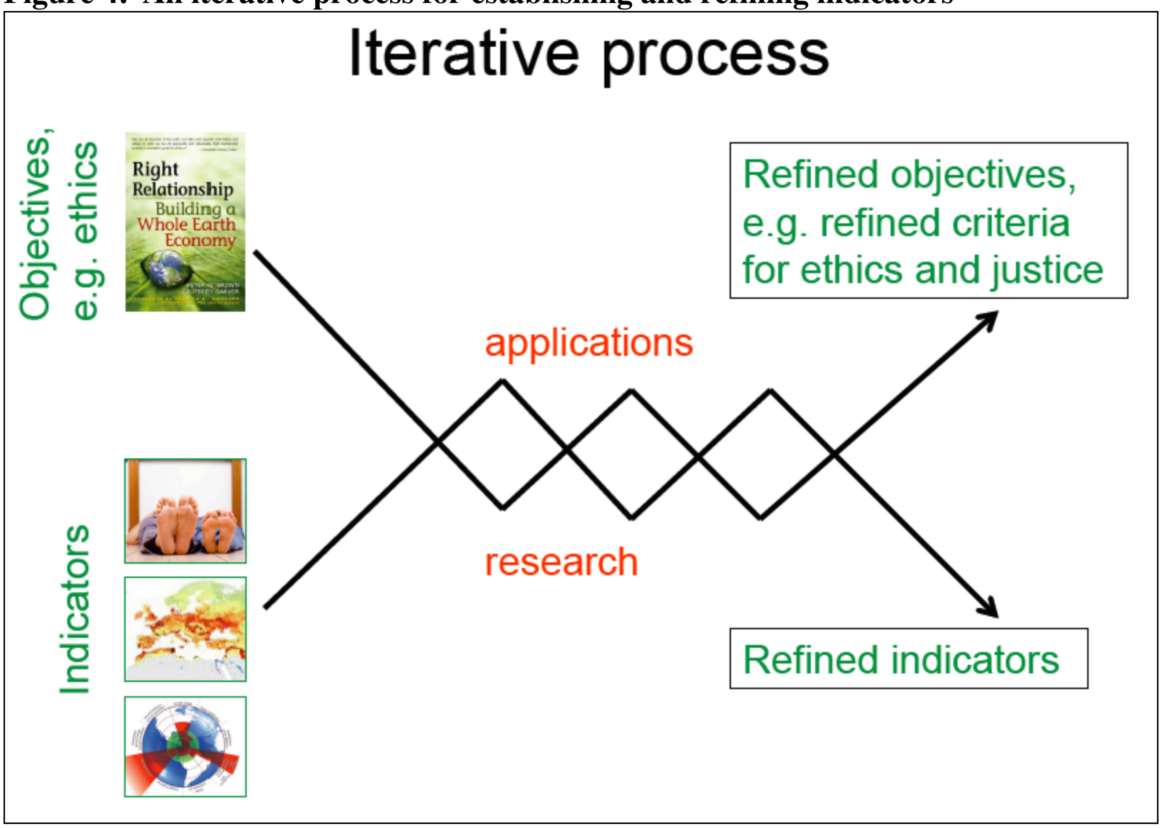
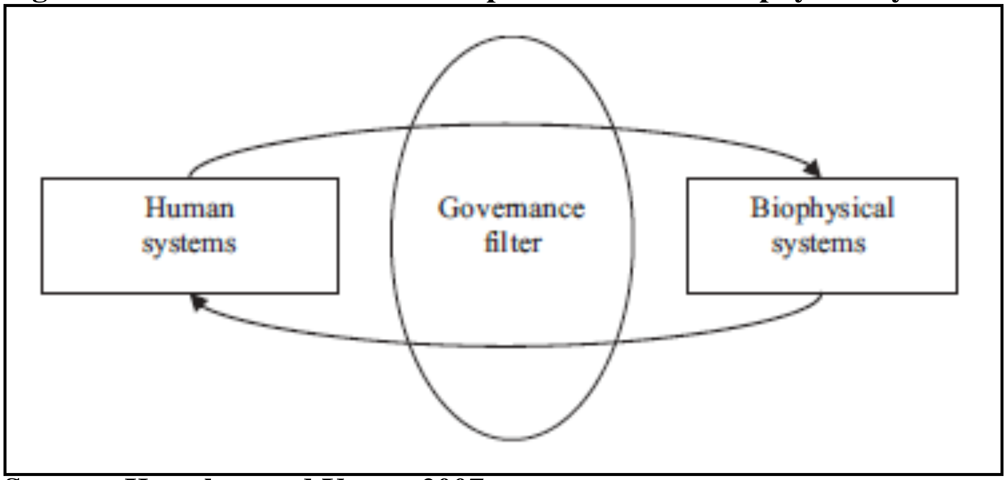
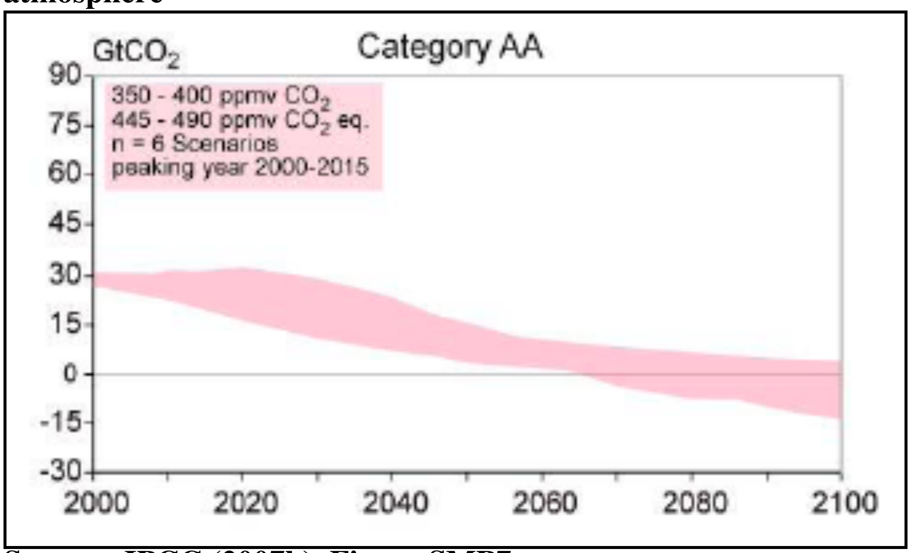


Figure 5. Governance filters in coupled human and biophysical systems



Source: Krotchen and Young 2007.

Figure 6. Global emissions pathways to stabilization at 350- 400 ppm CO_2 in the atmosphere



Source: IPCC (2007b), Figure SMP7

Figure 7. Emissions reductions proposed by Hansen et al. (2008) for achieving atmospheric carbon dioxide concentration of 350 ppm by 2100

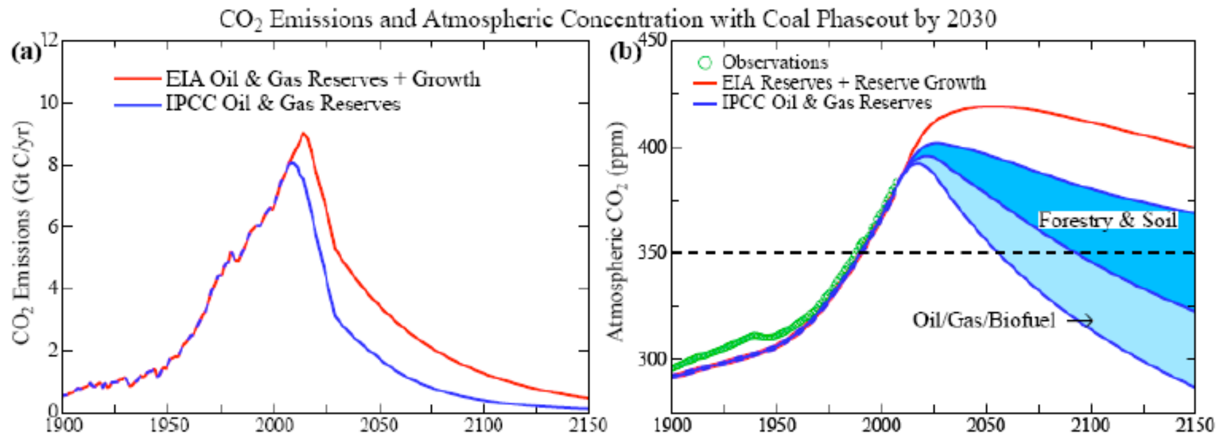


Fig. (6). **(a)** Fossil fuel CO_2 emissions with coal phase-out by 2030 based on IPCC [2] and EIA [80] estimated fossil fuel reserves. **(b)** Resulting atmospheric CO_2 based on use of a dynamic-sink pulse response function representation of the Bern carbon cycle model [78, 79].

Figure 8. Distribution of footprint regionally on the basis of equal per capita footprint

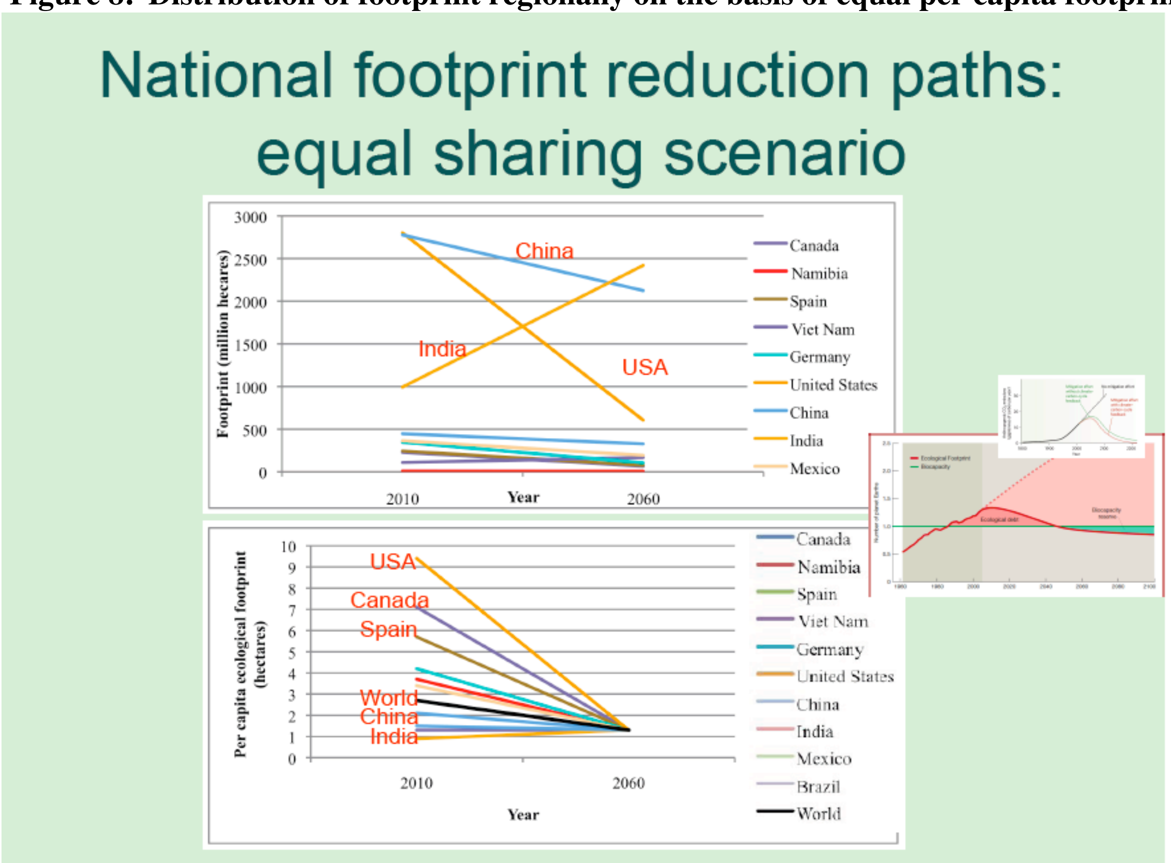
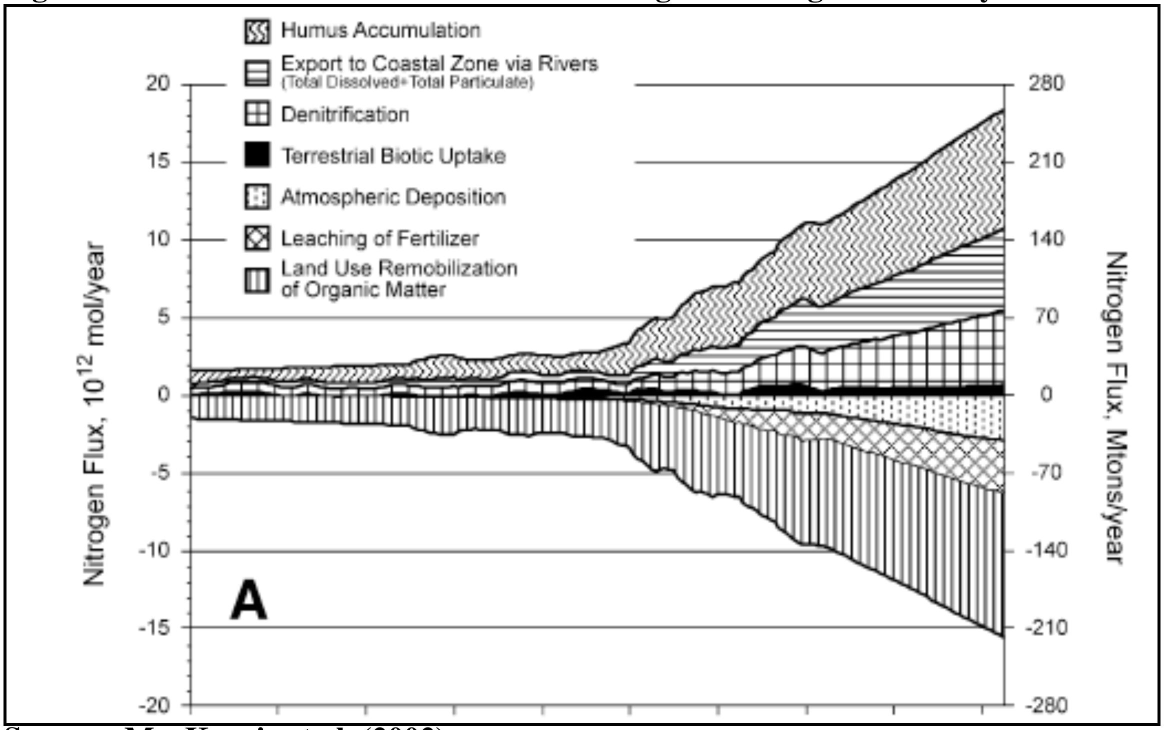
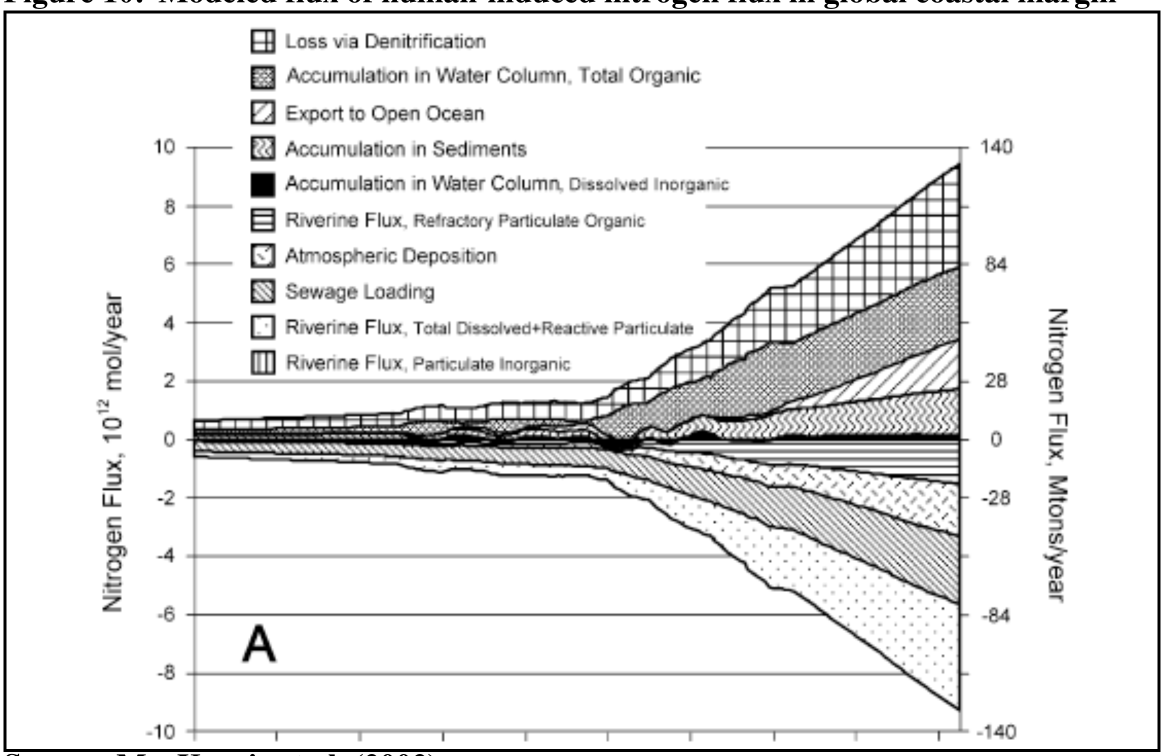


Figure 9. Modeled flux of human-induced nitrogen flux in global land systems



Source: MacKenzie et al. (2002).

Figure 10. Modeled flux of human-induced nitrogen flux in global coastal margin



Source: MacKenzie et al. (2002).

Figure 11. Global distirbution of exceedances of critical loads of eutrophication

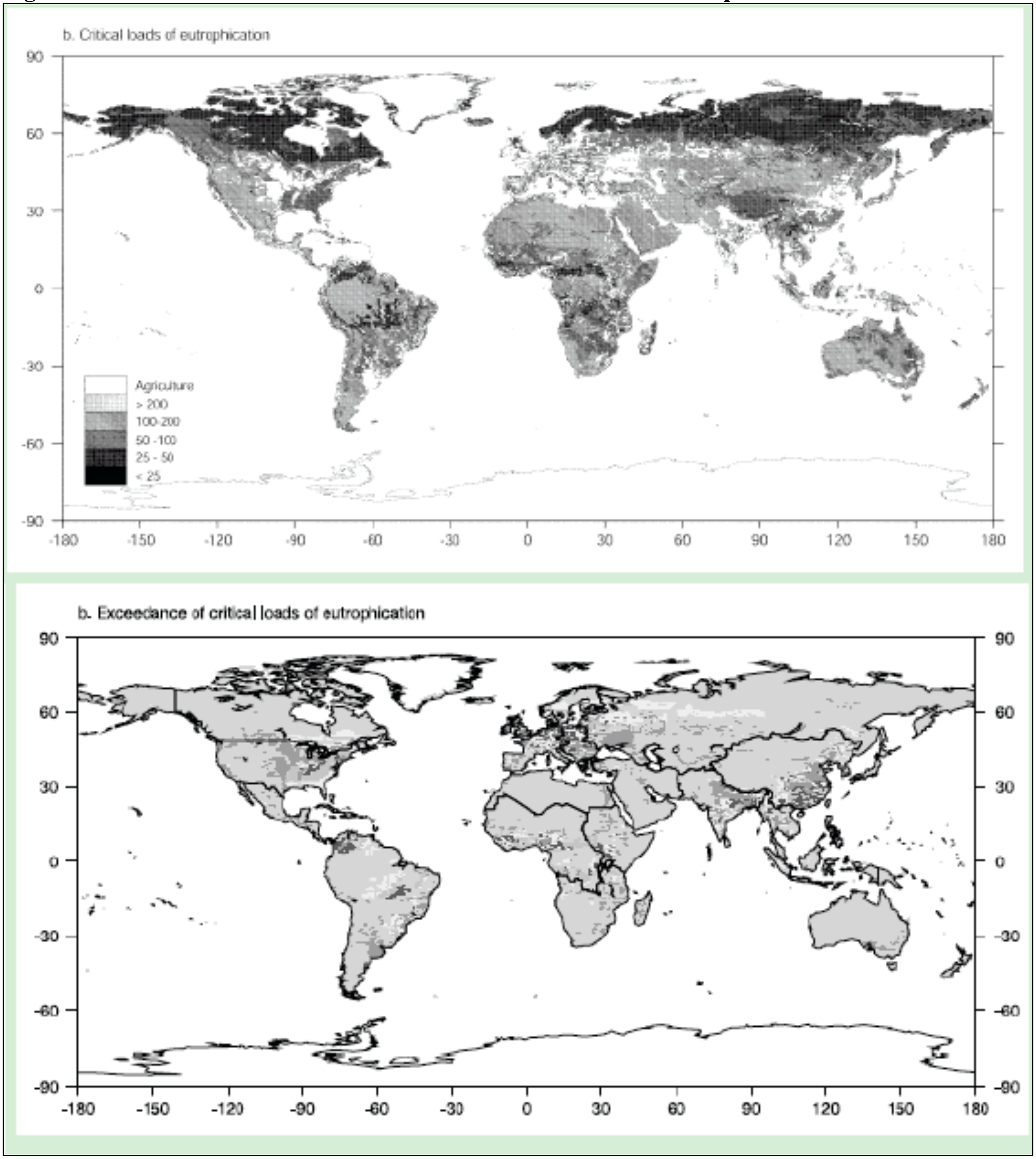
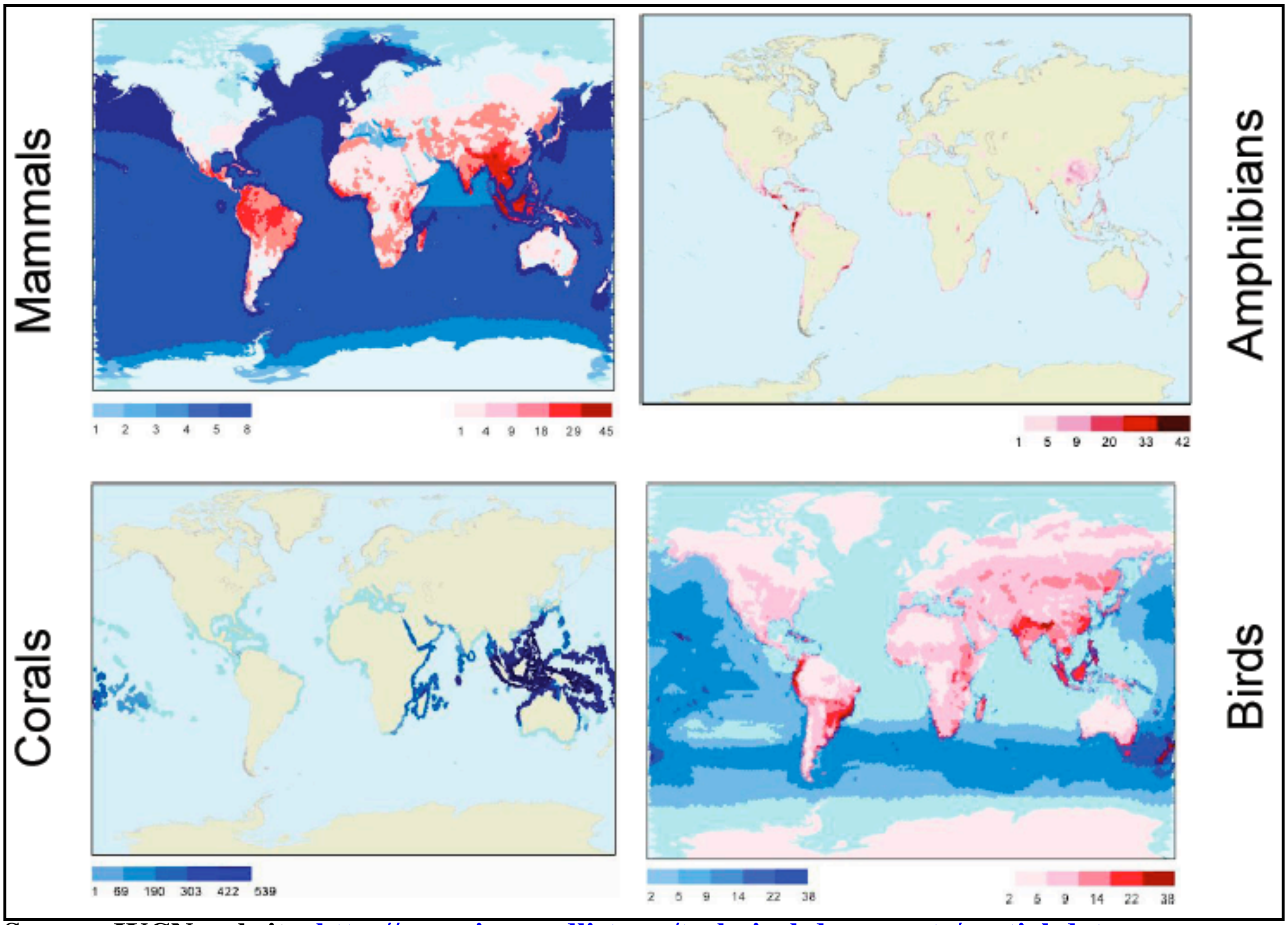
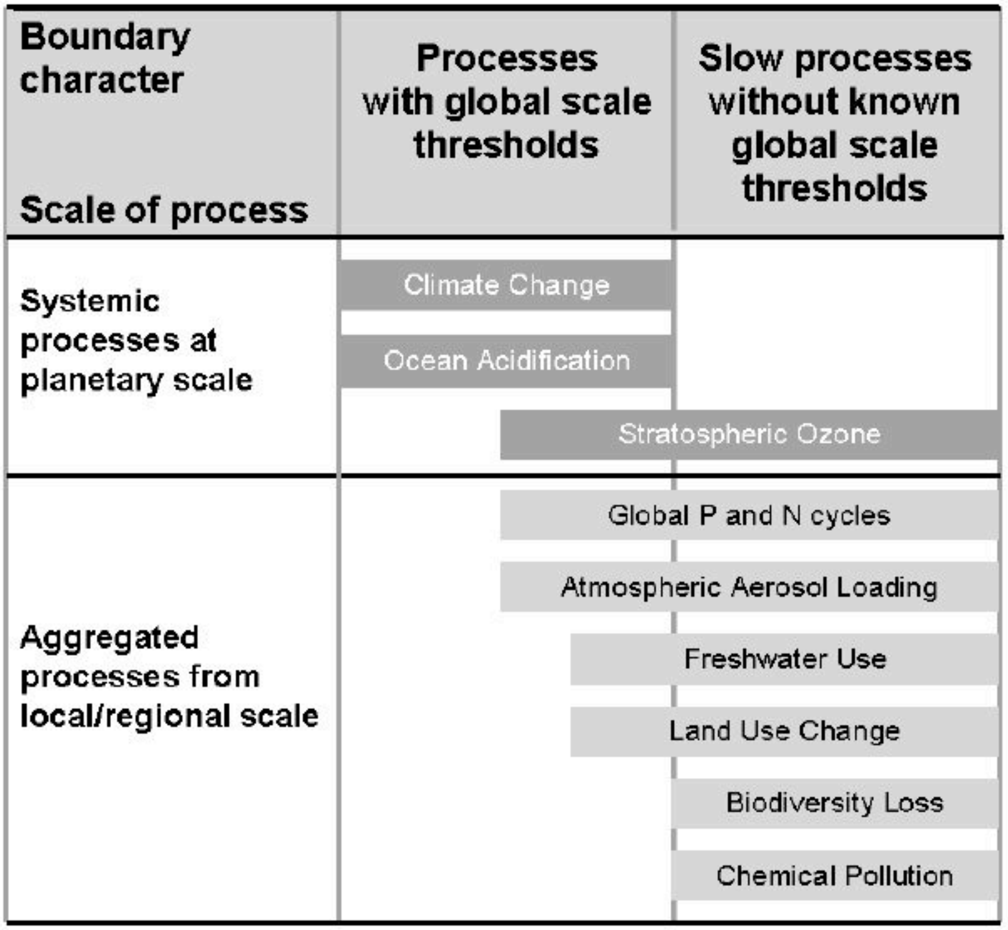


Figure 12. IUCN Red List of Threatened Species



Source: IUCN website, http://www.iucnredlist.org/technical-documents/spatial-data.

Figure 13. The scale of the proposed planetary boundaries



Source: Rockström et al. (2009)

Figure 14. The Sustainable Society Index (SSI) for the world in 2008