10. Planetary boundaries: using early warning signals for sustainable global governance[1]

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THE CHALLENGE

Over the past half-century, we have become adept at dealing with environmental problems at the local and regional scales. The worst excesses of the industrial revolution have, in many cases, been ameliorated. Rivers, such as the Thames in London, have been cleaned up and major urban airsheds, such as the Los Angeles basin, are now experiencing vastly improved air quality. DDT has been banned in most developed countries, and lead has been removed from petroleum-based fuels. These impressive successes have been celebrated in many quarters, perhaps most notably in Bjorn Lomborg's book, *The Sceptical Environmentalist* (Lomborg, 2001).

However, to say we have done enough globally would be false on two counts. Firstly, while these problems have been addressed in many European and North American nations, over three-quarters of the world's people do not live in developed countries. For them, many of the local and regional environmental problems still exist and, in many cases, are worsening. Secondly, the environment – our life-support system – is under increasing threat from a wide range of human pressures, many of them emanating from high consumption levels in wealthy countries. The deterioration of the global environment puts even more pressure on the poorest countries to limit growth, even as they struggle to bring their populations out of poverty.

This is an entirely new situation for humanity. In the past, when we fouled our local environment, we could move to someplace else. However, as the human population has grown, this short-term solution has been rendered unviable. Furthermore, the impacts of our presence have rarely been felt beyond our immediate surroundings. This is no longer the case. The global environment has provided an especially accommodating environment over the past 12,000 years for humanity to develop and thrive

(Costanza et al., 2007). But the world population is no longer small, sparsely dispersed, and technologically limited. Humankind's aggregate impact on the natural environment is intensifying.

Does our planet have boundaries regarding the amount of growth in the material economy that it can absorb? We believe it does and that certain preconditions must be set that acknowledge and respect these boundaries.

This situation is captured in the concept of the Anthropocene, a newly defined geological era beginning around the 1800s in the form of the Industrial Revolution. The term was introduced and popularised by Nobel Laureate Paul Crutzen (Crutzen, 2002), who felt the recent influence of human activity on the Earth was significant enough to warrant the naming of a new epoch. The past 12,000 years or so has been a period defined by geologists as the Holocene, an epoch in which global average temperatures have been remarkably stable and during which agriculture and complex societies first emerged and flourished in Africa, Asia, South and Central America, and the Mediterranean region.

Since the Industrial Revolution, the human enterprise has expanded so rapidly that we are now overwhelming the capacity of the Earth system to absorb our wastes and to sustainably provide the ecosystem services we require. In the period since the Second World War, the acceleration of development has become particularly dramatic. Humanity is fundamentally changing the Earth's physical climate (International Panel on Climate Change (IPCC), 2007), overwhelming its capacity to provide ecosystem services, homogenising its biological diversity (Millennium Ecosystem Assessment (MEA), 2005), and substantially modifying the global cycles of critical elements like nitrogen, carbon, and phosphorus (Steffen et al., 2004). We are indeed passing through the exit door of the Holocene and into the unknown world of the Anthropocene.

In this chapter, we present the concept of planetary boundaries for estimating a safe operating space for humanity with respect to the functioning of the Earth system. We make a preliminary effort at identifying key Earth-system processes and attempt to quantify for each process the boundary level that should not be transgressed if we are to avoid unacceptable global environmental change. Unacceptable change is here defined in relation to the risks humanity faces as the planet moves further away from the accommodating environment of the Holocene.

THE CONCEPT OF PLANETARY BOUNDARIES

Although we are building on earlier efforts to limit human impacts on the environment, the concept of planetary boundaries outlined in this chapter takes a rather different approach, more fully described in Rockström et al. (2009a, 2009b) and Steffen et al. (2011). It does not focus directly on the human enterprise but rather emphasises the Earth as a complex system. We identify nine areas that are most in need of set planetary boundaries: (i) climate change; (ii) biodiversity loss; (iii) excess nitrogen and phosphorus production, both of which pollute our soils and waters; (iv) stratospheric ozone depletion; (v) ocean acidification; (vi) global consumption of freshwater; (vii) change in land use for agriculture; (viii) air pollution; and (ix) chemical pollution.

These nine areas are biophysical processes of the Earth system that determine the self-regulating capacity of the planet. Table 10.1 lists all nine identified areas and the proposed boundaries of seven of them (two are still in the process of being determined). Exceeding the thresholds may trigger non-linear changes in the functioning of the Earth system, thereby challenging social-ecological resilience at regional to global scales. Together, the set of boundaries represents the dynamic biophysical 'space' of the Earth system within which humanity has evolved and thrived. The boundaries respect Earth's 'rules of the game' or, as it were, define the 'planetary playing field' for the human enterprise. These boundaries, as thresholds in key Earth-system processes, exist irrespective of people's preferences and values, or, for that matter, perceived compromises based on political and socioeconomic feasibility, such as expectations of technological breakthroughs and fluctuations in economic output (real GDP). As can be seen from Table 10.1, three planetary boundaries have already been transgressed and four boundaries are fast being approached.

The position of these boundaries corresponds to the lower end of the uncertainty zone. This is a conservative, risk-averse approach to quantifying our planetary boundaries that takes account of the large uncertainties that surround the true position of many thresholds.

The planetary boundaries approach rests on three branches of scientific inquiry:

1. The first addresses the scale of human action in relation to the capacity of the Earth to sustain it. This is a significant feature of the ecological economics research agenda (Costanza, 1991), which draws on work on the essential role of the life-support environment for human well-being (Odum, 1989; Vitousek et al., 1997) and on the biophysical constraints that limit the expansion of the economic sub-system (Boulding, 1966; Arrow et al., 1995).
2. The second is the work that has been undertaken to understand essential Earth-system processes (Bretherton, 1988; Schellnhuber, 1999; Steffen et al., 2004), including human actions (Clark and Munn, 1986;

Table 10.1 Proposed planetary boundaries, including current status and pre-industrial value

Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric concentration of carbon dioxide (parts per million, by volume)	350	387	280
	(ii) Change in radiative forcing (watts per square metre)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis		To be determined	
Chemical pollution	For example, the amount emitted to, or concentration of, persistent organic pollutants, plastics, endocrine disrupters, heavy metals, and nuclear waste in the global environment, or the effects on ecosystem and functioning of the Earth system thereof		To be determined	

Source: Steffen et al., 2011.

Turner et al., 1990), that have been brought together as part of the evolution of global change research toward Earth-system science and the development of sustainability science (Clark and Dickson, 2003).

3. The third is the framework of resilience (Holling, 1973; Gunderson and Holling; 2002; Walker et al., 2004; Folke, 2006) with its links to both complex dynamics (Kaufmann, 1993; Holland, 1996) and the self-regulation of living systems (Lovelock, 1979; Levin, 1999). This third framework emphasises multiple basins of attraction and threshold effects (Scheffer et al., 2001; Folke et al., 2004; Biggs et al., 2009).

CRITICAL FEATURES OF THE PLANETARY BOUNDARIES CONCEPT

Earth system science is still in its infancy and much more needs to be known. Nevertheless, we currently understand enough about the functioning of the Earth system to know that we must respect the hard-wired limits of our own life-support system. Moreover, we must find practical ways to respect these limits.

The planetary boundaries approach is one way, but it is still very much a proof-of-concept approach. Much more work is required to refine and operationalise it. The proposed boundaries in Table 10.1 are a preliminary estimate. For some boundaries, the zone of uncertainty is still huge, and for two of them – atmospheric aerosol loading and chemical pollution – we are unable to make even a first, rough guess at where the boundary might lie. In fact, we are not even sure that these nine boundaries are sufficient to define the planetary playing field. More may be needed.

Several features of the planetary boundaries conceptual framework are critical to understanding how the approach works.

Scale

Because of the strong focus on the global scale and the scale of systems immediately below it – such as the Earth's continents and ocean basins – the planetary boundaries approach raises issues of a cross-scale nature. As noted earlier, we are interested in local and regional environmental issues only insofar as their aggregate impact can affect the functioning of the Earth system at the larger scales. However, the Earth's surface, and by this we mean the terrestrial surface and ocean basins, is very heterogeneous in character. Consequently, change in one place is not necessarily equivalent to a similar change in another place. This is particularly important for the interactions among boundaries.

The global hot-spots of biodiversity comprise a well-known example of the implications of this heterogeneity. Conversion of a tropical rainforest to cropland, which directly influences the land-use change boundary, can have a much greater effect on the biodiversity boundary than the conversion of the same area of temperate grassland to a cropland. Similarly, the same amount of freshwater used for human consumption can have quite different effects on land-use change and biodiversity depending on the source of the water and the nature of the irrigation system used. Even more subtly, different patterns of the same type and overall area of land-use change – say, from forest to cropland – can affect biodiversity very differently depending on the nature of the fragmentation pattern created.

The list of such heterogeneities could go on. The point is that the nature of the changes at the fine scales occurring well below the larger scales of interest can become important for the planetary boundaries approach, particularly when these smaller-scale processes are aggregated back up to continental, ocean basin, or global scales. From the examples cited above, dealing with these cross-scale interactions may appear hopelessly complicated. However, new approaches, such as the fine-grained land architecture concept (Turner, 2009), may offer an efficient way to deal with the interactions between the land-use change boundary and other boundaries at a variety of scales.

There is ample evidence from local to regional-scale ecosystems, such as lakes, forests, and coral reefs, that gradual changes in certain key control variables (e.g., biodiversity, harvesting, soil quality, freshwater flows, and nutrient cycles) can trigger an abrupt system state change when critical thresholds have been crossed (Carpenter et al., 2001; Folke et al., 2004; Hughes et al., 2007; Scheffer, 2009). More research is urgently needed on the dynamics of thresholds and feedbacks that operate at continental and global scales, especially for slow-changing control variables, such as land use and land cover, water resource use, rates of biodiversity loss, and nutrient flows. Here, we distinguish between: (i) identifiable planetary thresholds driven by systemic global-scale processes which have a 'top-down' impact on sub-systems; (ii) thresholds that may arise at the local and regional scales, which become a global concern at the aggregate level if occurring in multiple locations simultaneously; and (iii) situations where gradual aggregate impacts may increase the likelihood of crossing planetary thresholds in other Earth-system processes, thus having a 'bottom-up' effect on the Earth system.

Interactions Among the Boundaries

Interactions among planetary boundaries may shift the safe level of one or several boundaries, which we have provisionally set under the (strong) assumption that no other boundaries are transgressed. There are cascading impacts in which transgressing one boundary can have implications for other boundaries. Even small changes can have a synergistic effect when linked to other small changes. For example, conversion of forest to cropland, increased use of nitrogen and phosphorus fertilisers, and a larger extraction of freshwater for irrigation can collectively act to reduce biodiversity much more than if each of these variables is acting independently. This is because many changes feed back into each other. The processes involving ocean acidity and atmospheric carbon dioxide (CO_2) concentration are an example of a reinforcing feedback loop. An increase in ocean acidity reduces the strength of the 'biological pump' that removes carbon from the atmosphere, which increases the atmospheric concentration of CO_2. This magnifies the physical uptake of CO_2 by the ocean, which further increases ocean acidity, and so on.

Tropical forests are a key component of both regional and global energy balances and hydrological cycles. In the Amazon basin, a significant amount of water in the atmosphere is recycled through the vegetation. In addition, the forest produces aerosol particles that can form cloud droplets. Changing particle concentration influences how likely the clouds are to produce rain and the strength of the convective circulation. Deforestation and biomass burning associated with dominant land-use practices have changed convection and precipitation over the Amazon basin (Andreae et al., 2004). These changes in precipitation complete a feedback loop because the availability of water influences the amount and kind of aerosol particles that the vegetation emits (Kesselmeier et al., 2000). Such interacting processes driven by change in land use and climate could reach a tipping point where the Amazon forest is replaced by savanna-like vegetation by the end of the 21st century (Nepstad et al., 2008).

This feedback loop is not limited to regional effects – it can also influence surface temperatures as far away as Tibet. Model simulations predict that large-scale deforestation in the northern Amazon could drastically change the surface energy balance, leading to a weakening of deep convection (Snyder et al., 2004a; Snyder et al., 2004b). This, in turn, would drive a weakening and northward shift in the Inter-Tropical Convergence Zone, which causes changes in the jet stream that directs the trajectory of mid-latitude weather systems. This would ultimately influence surface temperature and precipitation in Tibet.

Changes in climatic conditions in Tibet directly affect much of Asia's water resources. The 15,000 glaciers in the Himalaya-Hindu Kush region store an estimated 12,000 km^3 of freshwater, which is a main source of freshwater for roughly 500 million people in the region, plus an additional

250 million people in China (Cruz et al., 2007). Glacier melting, initially causing short-term increases in runoff, leads to increased flood risks, seasonal shifts in water supply, and increasing variability in precipitation. Although the calculated land-cover changes discussed here are extreme, the results illustrate that changes in the global climate system driven by land-use change in one region can affect water resources in other parts of the planet.

Although we have not systematically analysed the interactions among planetary boundaries, the examples we present suggest that many of these interactions will reduce rather than expand the boundary levels we propose, thereby shrinking the safe operating space for humanity. This suggests the need for extreme caution in approaching or transgressing any individual planetary boundaries.

Resource Use, Affluence, and Human Population Size

Many other approaches to managing global change more explicitly deal with the human enterprise itself, especially in terms of resource use. The planetary boundaries approach leaves the thorny issues of population size, affluence, equity within and between countries, technologies, resource use, and pollution management as variables that can be traded off in infinite combinations depending on the socio-economic systems, cultures, and worldviews of groups of humans. The only requirement is that the aggregate outcomes of the human enterprise as a whole must be such that the critical control variables stay within the set of planetary boundaries.

The $I = PAT$ identity (Ehrlich and Holdren, 1971) can provide a simple conceptual tool for analysing trade-offs within the human enterprise. Here I denotes Impact, and can be defined as the globally aggregated impact on an Earth-system process in terms of its control variable. The value of I should not exceed the value of the planetary boundary. Beyond that, however, there is a very wide range of combinations of P (Population), A (Affluence), and T (Technology) that can keep the human enterprise within the boundary for I. A low human population would, for example, allow for higher affluence per capita and perhaps more flexibility in the technologies employed to generate that affluence. On the other hand, a much higher human population coupled with high and rising affluence per capita would place enormous demands on technology to maintain a global impact within the boundary value. This is, in fact, the situation that humanity finds itself in now.

A further point concerning the IPAT framework is that the planetary boundaries approach is only concerned with ensuring that the impact remains within the boundary. It says nothing about the distribution of affluence and technologies among the human population. For example, it is possible that a 'fortress world', in which there are huge differences in the distribution of affluence, and a much more egalitarian world, where socio-economic systems are designed to share wealth more equitably, could equally satisfy the planetary boundary conditions. They would, however, deliver vastly different outcomes for human well-being.

THE IMPLICATIONS FOR GOVERNANCE

As a practical solution for living sustainably in the modern era, the planetary boundaries approach raises important questions and opportunities for governance and institutions, even to the point of challenging the concept of national sovereignty. We have identified four specific challenges for governance (Young and Steffen, 2009).

Early-Warning Systems

The nature of Earth-system dynamics – nonlinearities, tipping elements, and thresholds/abrupt changes – strongly suggests that humanity needs a system to warn us when we are approaching potentially catastrophic threshold points. Indeed, the planetary boundaries approach is based directly on this feature of the Earth system. An early-warning system is a prerequisite for being able to recognise and steer away from such thresholds.

Some recent research using a complex systems framework offers hope of finding a reliable biophysical basis on which to build an early-warning system (Scheffer et al., 2012). Such analyses are pointing to empirical indicators of the proximity of complex systems to critical thresholds that could serve as a means of anticipating abrupt system change. It is well known that as a system approaches a key threshold, its capacity to recover from a small perturbation begins to decline, since it becomes less resilient. Hence, the rate of recovery slows down. This is sometimes referred to as 'critical slowing down' (Scheffer et al., 2012). Indicators that reveal the rate of system recovery therefore offer a potential foundation upon which to create early-warning systems.

Dealing With Uncertainties

Each of the planetary boundaries is placed within a zone of uncertainty, some much larger than others. Although further scientific research will reduce these uncertainties in many cases, they will never be completely eliminated. In an adversarial political environment, uncertainties can be exploited as reasons for inaction. Hence, scientists must be able to address uncertainty without being attacked or scapegoated.

Because the environmental problems that society is currently dealing with are highly complex and feature nonlinear and often abrupt changes, a successful governance system (i.e., one capable of offering viable solutions to these problems) must be able to concurrently make decisions involving extreme uncertainty and respond in an adaptive manner as new information becomes available. Given the need to recognise and coexist with a certain level of uncertainty, global governance systems will need to emphasise and adopt a precautionary approach when determining where humanity should operate with respect to each of the planetary boundaries.

Multi-Level Governance

As the human impact on the environment extends to the global level, the creation of institutions with the capacity to implement viable solutions on the same scale is key. However, interaction with the more traditional institutions that currently exist at national, sub-national, and local levels will be critical, and will require a complex network of cross-level interaction.

Often global environmental developments, such as climate change, can impact on social welfare at local levels. Similarly, local developments can have significant effects on the global scale, such as the contribution of deforestation to global concentrations of CO_2. Such varying interactions will require various forms of multi-level governance. Furthermore, it will require distinct arrangements operating at different levels of social organisation that interact in a mutually reinforcing manner to provide effective Earth-system governance. Creating such multi-level governance systems will be especially important for those planetary boundaries that are based on aggregates of many local and regional actions.

Governance can address specific problems, such as climate change and biodiversity loss, through two approaches that can turn general objectives like sustainable development into well-defined and operation goals in specific cases.

1. The first approach involves turning general goals and problems into specific measures and boundaries at an operational level. For example, it is possible to define a climate change boundary of no more than 450 parts per million (ppm) of CO_2 in the atmosphere or to define a goal in the form of halving the number of people without safe drinking water by 2015 as spelled out by the UN Millennium Development Goals. Scientific knowledge and the ability to pursue these goals actively and

effectively must be a critical aspect of setting such specific and defined goals.

2. The second approach involves creating safeguards to prevent or control runaway processes like abrupt disintegration of ice sheets or financial panic. This will require a strengthening of adaptive capacity with regard to issues like climate change and the creation of counter-cycling mechanisms to prevent positive feedback loops. These types of approaches are adopted regularly at national levels through, for example, the creation of mechanisms to prevent an escalating financial crisis, which is achieved by emphasising prevention and preparedness as well as emergency response preparedness to extreme events like hurricanes or tsunamis. Global society now needs to develop similar preparedness mechanisms at the global level.

Capacity to Assimilate New Information

In addition to reducing the zone of uncertainty for some boundaries, scientific research will continue to uncover more insights into the dynamics of the Earth system itself. This could lead to the need for additional planetary boundaries or the reformulation of existing ones. The increasing flow of new scientific information will undoubtedly put pressure on any institutional framework to keep up with the pace of new knowledge. A case in point is the debate over what quantity of greenhouse gases can be released without disastrous effects. After a long time trying to convince the international community that the climate change boundary should be an atmospheric concentration of 450 ppm of CO_2, a growing number of scientists are suggesting that a 350 ppm boundary would be more appropriate.

Acknowledging the End Goal

Staying within the planetary boundaries is not a goal in itself, but is a necessary condition for achieving the ultimate goal – the improvement of sustainable human well-being. Well-being is created through the satisfaction of fundamental human needs, including such basics as shelter, food, and water, but also good health, time with friends and family, education, fairness, a sense of security, freedom, and a healthy natural environment capable of providing a range of ecosystem services (Costanza et al., 2007). Exceeding planetary boundaries will ultimately have consequences for society by reducing the overall quality of life.

For example, as the climate change boundary is exceeded, more severe weather events are likely to occur. Such variability and uncertainty will

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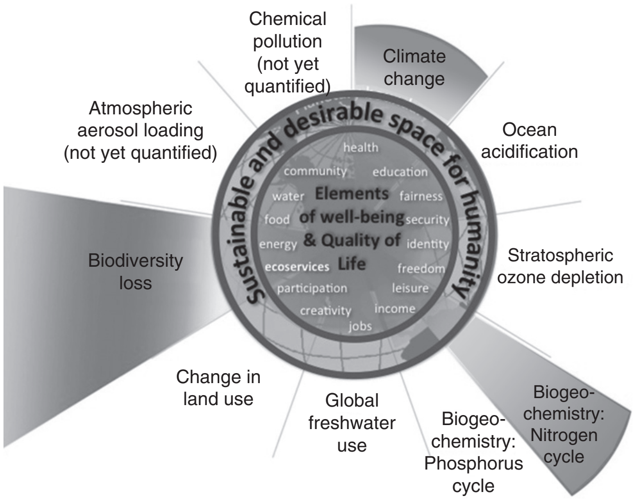

Sources: Planetary boundaries: Steffen et al., 2011; well-being: as developed by Oxfam (Raworth, 2012).

Figure 10.1 Planetary boundaries diagram overlaid with an inner boundary of elements of sustainable human well-being

decrease our overall sense of security and, in certain cases, will also impact on our physical security by endangering our shelter, food, and water.

Figure 10.1 is the planetary boundaries diagram (Steffen et al., 2011) overlaid with an inner boundary of elements of sustainable human well-being as developed by Oxfam (Raworth, 2012). This creates a sustainable 'doughnut' which brings together the biophysical boundaries with the social boundaries to create a safe and sustainable space in which humans can thrive.

Ultimately, there will need to be institutions operating, with authority, above the level of individual countries to ensure that the planetary boundaries are respected. In effect, such institutions, acting on behalf of humanity as a whole, would be the arbiter of the myriad trade-offs that need to be managed as nations and groups of people jockey for economic and social advantage. It would, in essence, become the global referee on the planetary playing field. While humanity is still a long way from meeting this challenge, some creative thinking about new institutions is showing some promise. For example, one proposed institution that moves in this direction is the concept of an Earth Atmospheric Trust (Barnes et al., 2008), which would treat the atmosphere as a global common property asset managed as a trust for the benefit of current and future generations.

SUMMARY AND CONCLUSIONS

Earth system science is still in its infancy and much more needs to be known to create robust solutions to humanity's global dilemmas. Nevertheless, we know enough now about the functioning of the Earth system to recognise that we must learn to respect the hardwired limits of our life-support system. We must also find practical ways to respect those limits. Much more work is required to refine the concept of planetary boundaries and make it operational. The nine proposed boundaries outlined here are a preliminary estimate. For some of the boundaries, the zone of uncertainty is still huge, and for two of them – atmospheric aerosol loading and chemical pollution – we are unable to make even a first, rough guess at where the boundary might lie. In fact, we are not even sure that these nine boundaries are sufficient to define the planetary playing field. More may be needed.

Just when we are developing some solutions for environmental problems at the local and regional scales – at least in developed countries – we are confronted with the challenge of environmental problems of a more complex nature at the global scale. Climate change is just the tip of the proverbial iceberg, with many more linked environmental, socioeconomic, and cultural changes sweeping rapidly across the planet.

Effective solutions for living sustainably in the post-industrial age require innovative frameworks and implementation strategies. Rather than tackling these global-scale problems one by one, as we are attempting to do with respect to climate change, we need a far more holistic and integrated approach. The planetary boundaries framework provides such an approach.

Within the boundaries of the planetary playing field, there are an infinite number of strategies, tactics, and trade-offs that humanity can deploy as it continues to strive to improve human well-being. The rules of the game are familiar – economics, trade, laws and regulation, ethics, local and regional environmental protection, and so on, are recognisable to us all. What is new is that the playing field for this game is not infinite. It has boundaries and the players must respect these boundaries.

Implementing the concept of planetary boundaries presents huge challenges for global governance and institutions. Science is well on the way to defining the planetary playing field, but we have yet to define the roles of the global referees and grant them the authority to keep the players on the field. Respecting the boundaries means respecting the global commons – the atmosphere, oceans, and ecosystem functioning and the services derived from that functioning. The solution, as Peter Barnes has suggested (Barnes et al., 2008), is to greatly expand the 'commons sector' of the global economy by establishing institutions with the capacity to keep humanity within a safe operating space. These new kinds of commons institutions need to be developed at multiple scales, from local to global, with full participation of the affected stakeholders.

NOTE

1. This chapter is based on the following papers: 'How defining planetary boundaries can transform our approach to growth' (Steffen et al., 2011); 'Planetary boundaries: exploring the safe operating space for humanity' (Rockström et al., 2009a); and 'A safe operating space for humanity' (Rockström et al., 2009b). See these papers for a complete description of the planetary boundaries.

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