Jonathan Boston

Biophysical Limits and Green Growth

For a world of seemingly unlimited resources, mankind is gradually accustoming itself to the Earth as a limited, crowded and finite space, with limited resources for extraction and a narrowing capacity for waste disposal of pollution.

Jean-Claude Trichet (quoted in Jackson, 2009, p.67)

In mid-June 2011 the Institute of Policy Studies and Landcare Research co-hosted a symposium in Wellington on 'Biophysical Limits and their Policy Implications'.[1] The symposium addressed two interrelated sets of questions. The first are *empirical* in nature: what are the earth's biological and physical (or biophysical) limits and what are the practical implications of these limits for humanity? For instance, is exponential global economic growth, as measured by GDP, technically possible on a planet with limited natural resources and waste absorption constraints, and, if so, under what conditions? Does 'green' growth, as proposed by the OECD (2011), offer a feasible way to circumvent or negate these limits, and, if so, what policy changes will be required to enable such growth? Second, there are various *normative* issues: given the earth's biophysical properties, how should we choose to live? In other words, how should the empirical reality of absolute constraints shape the nature of humanity's goals and the means chosen to pursue them? Further, what ethical criteria and other considerations should inform the setting of global limits or thresholds – or what Rockström et al. (2009a, 2009b) call 'planetary boundaries' – within which humanity should endeavour to operate?

Drawing on the contributions to the symposium on biophysical limits, this article focuses on four main issues: the nature of the earth's biophysical limits; the setting of 'safe' planetary boundaries; the implications of biophysical limits for economic growth; and the political economy issues involved in moving the global economy onto a 'green' growth path. But first, let me provide some context.

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Background

Debates about environmental limits and economic growth are not new. Nor are concerns over the capacity of this planet to sustain an ever-increasing human population. More than two centuries ago, in 1798, Thomas Malthus published his important study *An Essay on the Principle of Population*, in which he argued that the number of human beings would ultimately be limited by scarce resources, and especially by constrained food supplies. As he put it: 'The power of population is indefinitely greater than the power in the earth to produce subsistence for man' (Malthus, 1798, p.13). Thus far, Malthus has been wrong. The human population has continued to grow and the production of food has expanded even more rapidly (although significant distributional issues remain). But whether, and for how long, it will be possible to feed an ever-rising population is uncertain. After all, much global food production currently relies upon finite non-renewable and/or conditionally renewable resources, as will be discussed shortly.

Almost two centuries after Malthus, Meadows et al. (1972), of MIT, argued in *The Limits to Growth* (and various subsequent publications eg, 1992, 2004) that long-term exponential economic growth is impossible, given the earth's limited resources and constrained absorptive capacity. Indeed, the MIT team claimed that even under the most optimistic assumptions concerning technological innovation, continuing economic and population growth would eventually lead to overshoot and collapse. The thesis advanced by Meadows et al. proved to be highly controversial and was the subject of many sustained and detailed rebuttals (e.g. Cole et al., 1973). Such critiques – which covered a range of methodological, empirical and normative issues – led many policy makers to dismiss the core arguments in *The Limits to Growth* as utterly flawed and misguided.

But in recent years opinions within the international policy community have begun to change as concerns over the planet's biophysical limits have intensified (e.g. see OECD, 2011; Reynolds, 2011; UNEP, 2007; Whitehead, 2008). In part, this revisionism has been prompted by growing anxiety over anthropogenic climate change and its likely negative ecological, economic, social and political impacts (see Garnaut, 2008; Hansen, 2009; IPCC, 2007; Stern, 2007, 2009, 2011). But there has also been mounting evidence that humanity is harming many other vital biophysical systems, living beyond the planet's means (i.e. consuming or damaging at a rate exceeding what nature can regenerate), and exceeding 'safe' planetary limits (Rockström et al., 2009a, 2009b). Such evidence is reflected in the findings of numerous reports from international organisations, scientific academies and leading research institutions, as well as various studies updating (and to some degree confirming) the original arguments advanced by Meadows et al. (e.g. Randers, 2008; Turner, 2008).

To illustrate briefly: a large-scale project – the 'Millennium Ecosystem Assessment' – sponsored by the United Nations and involving 1,300 leading scientists over several years was completed in 2005. The authors of the synthesis report on *Ecosystems and Human Well-Being* observed that of the various ecosystem services[2] examined, approximately 60% were 'degraded' or being 'used unsustainably', including fresh water, capture fisheries, and air and water purification (Millennium Ecosystem Assessment, 2005). Similarly, the report highlighted evidence of an increasing 'likelihood of nonlinear changes in ecosystems (including accelerating, abrupt and potentially irreversible changes) that have important consequences for human well-being'. These include 'abrupt alterations in water quality, the creation of "dead zones" in coastal waters, the collapse of fisheries, and shifts in regional climates'. To compound problems, genetic diversity is declining, as is the number of species on the planet. It is estimated that since around 1800 'humans have increased the species extinction rate by as much as 1,000 times over background rates typical over the planet's history'. Currently, up to 30% of mammal, bird and amphibian species are threatened with extinction. And to make matters worse, the growing human population, projected to reach at least 9 billion by 2050, is bound to increase pressures on already fragile ecosystems. As a result, the earth faces another great spasm of extinction – but this time caused by humanity, not natural forces (see also Sukhdev et al., 2008).

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Related to this, a team of scientists concluded in 2002 that humanity's collective demands began to exceed the earth's regenerative capacity about 1980 (Brown, 2009, p.14). By 2009, the demands on natural systems exceeded their sustainable yield capacity by close to 30%. This means that human beings are depleting the planet's natural assets and doing so at an increasing rate. Such trends can continue only for so long before negative feedback mechanisms are triggered, critical thresholds are crossed, and irreversible ecosystem damage is inflicted. Hence, while the relevant timescales are uncertain, the long-term implications are clear.

More recently, in May 2011 the OECD published a major report on the implications of global ecological considerations for economic management, entitled *Towards Green Growth*. The study emphasises the finite nature of this planet, the vital importance to human well-being of natural capital, the huge value to humanity of the ecosystem services provided by the earth's biosphere, and the need to live within certain non-negotiable planetary boundaries. Reports such as these underscore the growing awareness amongst senior policy makers and leading economists (e.g. Arrow et al., 1995, 2004) that humanity must take resource scarcity and ecological limits seriously, and do so, as appropriate, on multiple scales: global, regional and local.

Biophysical limits

Three types of biophysical limits have been the primary focus of attention in the relevant literature over recent decades: material or resource limits; waste absorption limits; and thermodynamic limits. Let me briefly explore each of these limits.

> **With respect to specific natural resources, considerable international attention has focused in recent years on the supply and demand for fossil fuels, and especially the issue of ‘peak oil’.**

Limited resource inputs

While some natural resources are *unconditionally renewable* and essentially inexhaustible (e.g. sunlight, marine energy and wind energy), many resources required for human well-being are *non-renewable* (at least on non-geological timeframes). This includes minerals (both metallic and non-metallic) and fossil fuels (e.g. oil, gas and coal). Many other resources are *conditionally renewable*: they regenerate at relatively slow rates and are limited in supply (e.g. fresh water, soil and wood).

With respect to non-renewable and conditionally renewable natural resources, there has been vigorous debate about the following matters:

- the nature, quantity and quality of the reserves of the various minerals and fossil fuels used in production processes;
- the estimated life of these reserves at current and projected rates of consumption;
- the extent to which particular resources are *substitutable* (or likely to be substitutable with new and evolving technologies); and
- the consequences of natural resource constraints for continued economic growth (or even sustaining current consumption levels).

Optimists argue, for instance, that a combination of market forces (i.e. rationing by price), technological innovation and prudent policies will ensure that any scarcity of resource inputs does not seriously affect global economic growth, certainly during the 21st century. By contrast, other experts maintain that economic growth will be severely constrained by limited natural resources well before 2100, not least because of limits to substitutability and because efficiency improvements may be constrained by the very nature and properties of the physical world. Many experts are also concerned about high levels of path dependence and inertia (e.g. with respect to various energy, transport and social systems), the potentially large social, economic and political costs involved in transitioning from one technological state to another (e.g. moving from a carbon-intensive to a low-carbon economy), the risks of inducing abrupt, non-linear and disruptive changes in the key biophysical systems, and the potential for crossing irreversible thresholds. Some of these matters were addressed during the symposium on biophysical limits (e.g. see Rutledge, 2011; Saunders, 2011; Turner, 2011; Walker, 2011).

Aside from this, advocates of ‘strong sustainability’ (e.g. see Adams et al., 2009) maintain that non-substitutable resources should not be used up or destroyed. It is argued that such resources are intrinsically valuable and/or that ‘intergenerational justice imposes stewardship obligations on the current generation to preserve options for future generations’ (Hay, 2007, p.115). From this perspective, destroying non-substitutable resources (and ecosystems) is unjust because it violates the rights of future generations. Accordingly, certain resources (and ecosystems) should be preserved in perpetuity. Against this, advocates of ‘weak sustainability’ maintain that using up non-substitutable resources is acceptable, at least to a certain extent (although exactly how much is often not specified). Furthermore, preventing humanity from using resources that are potentially non-substitutable is unrealistic, impractical and costly. After all, without a universally agreed and collectively enforced approach, protecting non-substitutable resources is impossible.

With respect to specific natural resources, considerable international attention has focused in recent years on the supply and demand for fossil fuels, and especially the issue of ‘peak oil’. This has included controversy over when oil production will peak (if it has not done so already), how rapidly production levels will fall after the peak, and the likely impact on energy prices and economic activity (see Department of Energy and Climate Change, 2009). But while oil is a crucially important resource, so too is fresh water. Indeed, not merely is water an essential input into many human activities, it is largely non-substitutable and very unevenly distributed. As Howard-Williams et al. (2011) noted at the symposium on bio-physical limits, less than 3% of the world’s water is fresh, and of this less than 1% is accessible and readily usable by human beings. To compound problems, the global availability of fresh water per capita has declined markedly over the past 50 years and the rate of decline is accelerating. As a result, demand now exceeds supply in around 80 countries. Population growth and climate change will exacerbate matters, with severe water stress becoming increasingly common.

While New Zealand has a relative abundance of fresh water, its spatial distribution is highly uneven. Further, some water resources are already fully allocated and shortages are growing. Better water management is thus of crucial importance. Fortunately, this is now accepted by most, if not all, stakeholders, as reflected in the deliberations of the Land and Water Forum.

Adequate water supplies are, of course, critical for food production. Not surprisingly, therefore, the risk of resource shortages having a negative impact on global food supplies has been of growing concern (see Cribb, 2010). According to the chief scientific adviser to the British government, Sir John Beddington (2009), the global community faces a 'perfect storm' over food production within decades. Contributing factors are likely to include:

- continuing population growth, especially in South Asia and Africa;
- a continuing loss of top soil and soil fertility due to poor agricultural and land management practices, rapid deforestation, desertification and erosion, pollution, the intensification of storms and droughts, etc. (Brown, 2009, pp.32-38);
- a growing loss of agricultural land due to urbanisation and industrialisation;
- a continuing loss of wild fisheries due to pollution, over-exploitation, ocean acidification and rising sea temperatures. According to some estimates, around three-quarters of oceanic fisheries are being fished at or beyond capacity or are recovering from over-exploitation (Brown, 2009, p.15). Acidification and rising sea temperatures, amongst other things, could result in a loss of 60% of coral by 2030 (Sukhdev, 2008, p.9), with huge implications for global fish stocks;
- rising energy prices, due to peak oil;
- growing shortages of fresh water due to the effects of climate change, together with falling water tables and the loss of once huge fossil aquifers (due to the excessive mining of underground water). Declining supplies of groundwater are already contributing to the loss of millions of hectares of irrigated crop land;
- the loss of insect pollinators (especially bees) as a result of pollution and the excessive use of chemicals. Note that the value of pollination services provided by insect pollinators was estimated at €153 billion in 2005 for the main crops that feed the world (OECD, 2011);
- shortages of fertilizer (e.g. phosphate reserves are likely to be exhausted within a century or so if consumption grows at 3% per annum) (see Gilbert, 2009);
- the limits to photosynthesis (Diamond, 2005, p.491); and
- the continued diversion of crop land for bio-fuel production.

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Obviously, any serious and protracted global food shortages could have major economic, social and political consequences – including the risk of civil disorder and violent conflict. If sufficiently widespread or destabilising, such developments are bound to slow economic growth, if not provoke a worldwide recession. Having said this, net food exporters, like New Zealand, stand to gain financially from such shortages (and the related price increases). But any such benefits need to seen against an otherwise potentially bleak global context, with severe human suffering. Avoiding such a scenario will require prudent management of key global resources, not least fresh water, soil, agricultural land and wild fisheries. Thus far, the track record has not been encouraging.

Waste absorption limits

While the planet's natural resources are limited, so too are its 'sinks'. In other words, the capacity of the biosphere to absorb or assimilate the waste and pollution generated by economic activity is constrained. Hence, even if the scarcity of certain resource inputs does not constrain economic growth and human activity over the foreseeable future, waste absorption limits may well have adverse consequences (see Reynolds, 2011). The limited capacity of the biosphere to absorb humanity's increasing greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), is perhaps the greatest single threat on the horizon. Currently, atmospheric concentrations of CO_2 are rising rapidly (at around 2.5 parts per million per annum); within a few years they will reach 400 parts per million (or more than 40% above pre-industrial levels). Global mean surface temperatures, which have already risen by about 0.8°C over the past century, are projected to increase by at least another 2°C by 2100, unless GHG emissions are substantially reduced. Such warming and related climate changes will have serious and potentially irreversible consequences, including substantial sea-level rise, more severe storms and droughts, and a massive loss of biodiversity. By the end of the century, the sea level could be as much as a metre higher (and possibly more). Such a rise will cause huge and widespread damage to coastal infrastructure and settlements (including roads, railway lines and ports), and inundate many river deltas and low-lying islands. It is hard to believe that such damage could occur without having negative impacts on global economic growth, as well as human well-being. Despite these risks, few governments have implemented significant or effective policy measures to reduce GHG emissions.

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Thermodynamic limits

According to Herman Daly (1973, 2010), the laws of thermodynamics place an absolute limit on the efficiency with which resources can be utilised, thereby constraining the potential for long-term exponential economic growth. For instance, in keeping with the first law, the production of material objects requires an irreducible minimum quantity of resources, while the second law (or the law of entropy) means that the same matter-energy cannot be used repeatedly for similar purposes.

But whether (and/or at what point) these thermodynamic limits are likely to affect economic activity remains debatable. Hay (2007, p.114) highlights various counter-arguments to the claimed constraints imposed by the first law of thermodynamics. First, as economies have grown richer, the demand for services has increased much faster than for products. Since the provision of services typically requires fewer material inputs, any constraints imposed by thermodynamic limits are likely to lessen over time (or at least be delayed). Second, there has been a steady increase in resource efficiency over recent decades, the product of continuing innovation and human ingenuity. Thus far, there has been no evidence that productivity improvements are slowing down or facing insurmountable physical barriers.

Regarding the second law, the concern is that energy is dissipated through the production process while, at the same time, natural resources are degraded. Ultimately, it is argued, this will limit economic growth. But the counter-argument is that solar energy can be used to recover wastes and recycle dissipated materials (Hay, 2007, pp.114-5). The only constraint, from this perspective, is the amount of energy that can be captured from the sun. This will depend primarily on the level of technology – and this continues to expand. In short, there is no evidence to date that the laws of thermodynamics have constrained global economic growth or that they will do so in the near future. But over the longer term our confidence probably needs to be more tempered.

Establishing safe biophysical boundaries

Increasing attention has been given in recent years to determining 'safe' global biophysical limits (or planetary boundaries). The relevant literature is evolving, and many questions remain unanswered. Among the most comprehensive efforts to delineate such limits is the work of a distinguished team of scientists led by Johan Rockström (2009a, 2009b). The group has identified nine planetary boundaries (see Table 1). These include atmospheric CO2 concentrations, extinction rates, global freshwater use, the quantity of phosphorus flowing into the oceans, and so forth. Their analysis suggests that humanity is already transgressing at least three of these boundaries (i.e. with respect to climate change, the rate of biodiversity loss and changes to the global nitrogen cycle). As one might expect, the proposed parameters have prompted vigorous debate (e.g. Schlesinger, 2009). After all, determining what is safe is not just a scientific exercise. It also involves ethical judgements, some of which are profoundly difficult. For instance:

- How much harm, and of what kind, is morally acceptable? To be more specific, how many species should we be prepared to sacrifice on the altar of human 'progress'?
- What risks should we be willing to tolerate? For example, should we be prepared to take the risk of inducing the irreversible melting of a major ice sheet, such as the Greenland or the West Antarctic ice sheet – with the prospect, eventually, of a multi-metre sea-level rise?
- What costs should we be willing to bear in order to protect the interests of future generations and preserve non-human species?
- What safety margin should we incorporate into any internationally agreed limits or thresholds in order to reduce the chances of abrupt, non-linear changes, other unexpected outcomes, and wider systemic risks?

Such questions are not amenable to simple answers. Yet they deserve our urgent attention. After all, the best available evidence suggests that if we persevere with existing policy settings we will face mounting environmental problems and run very serious risks. While the topic of planetary boundaries was briefly canvassed at the Wellington symposium, it needs much more sustained, rigorous and interdisciplinary analysis.

Biophysical limits and economic growth

Thus far I have briefly discussed the nature of the earth's limited resources and sinks, and their implications for human activities. As will be evident, there is no consensus on whether long-term exponential economic growth is technically feasible. Many experts are sceptical. As the distinguished economist Lord Stern (2009, p.10) has put it: 'A picture of indefinite expansion is an implausible story of the future.'

Table 1: Planetary boundaries

Earth-system process	Parameters	Proposed boundary	Current Status	Pre-industrial value
Climate Change	(i) Atmosphere carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rates 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 in 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 concerntration in the atmoshphere on a regional basis	To be determined		
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system	To be determined		

Boundaries for processes in light blue have been crossed

Source: Rockström et al., 2009b, p.473

But if continuing global growth is feasible at least, say, over the 21st century, it seems reasonable to conclude that such an outcome will be possible only if human activities are utterly consistent with the assimilative and regenerative capacities of the earth's biosphere. Above all, this means that growth must be *decoupled* from its negative ecological impacts and physical (or resource) throughputs. Where such impacts or resource use already exceed safe and sustainable parameters, such decoupling must occur in *absolute*, not just *relative*, terms. In other words, there must be an absolute reduction in environmental pressures per unit of output (e.g. GHG emissions or carbon intensity per unit of output), not merely improvements in ecological impacts and/or resource use per unit of output.[3] Relative reductions will not be enough, certainly if overall output is increasing more rapidly than the improvements in resource efficiency or environmental impact per unit of output. As Jackson (2009, p.71) explains, for absolute decoupling to occur, the rate of relative decoupling must exceed the rate of increase in overall output (or GDP).

Moreover, to sustain growth over lengthy time periods, ever more extensive absolute decoupling will be required (i.e. across an ever wider range of environmental impacts). In practical terms, this means that the current carbon-intensive and resource-intensive global economy must be transformed through the application of resource-conserving technologies into one characterised by low resource intensity and minimal environmental impacts. Such an economy will need to reuse or recycle virtually all its natural resource inputs; rely primarily, if not solely, on renewable sources of energy; preserve critical (or non-substitutable) natural capital; and ensure that all forms of pollution and other environmental impacts – including GHG emissions – remain within safe biophysical limits.

Both the scale and rate of the decoupling required over the next few decades it vastly greater than anything so far achieved in human history. It will entail much more than is currently envisaged in the sustainable development strategies which various countries have enunciated (e.g. see Frame and Bebbington, 2011). And the changes must be global in nature, not limited to a subset of jurisdictions.[4]

Take, for instance, atmospheric CO2 concentrations: as noted earlier, these are now close to 400 parts per million, or nearly 50 parts per million above what Rockström et al. (2009a, 2009b) and Hansen et al. (2008) regard as 'safe' (or at least low enough to minimise the risk of large-scale, abrupt and irreversible environmental damage). Yet to stabilise CO2 concentrations at 350 parts per million (or even close to this level) will require massive cuts in emissions (especially, but not solely, in the developed world). In fact, negative net emissions globally will ultimately be necessary for a protracted period. This will not be possible without a dramatic fall in the carbon intensity of world output. Whether such reductions are achievable is open to debate. Many experts are sceptical, for either technical or political reasons. Jackson (2009) highlights the daunting nature of the challenge:

1. Global carbon intensity declined by almost a quarter from just over 1

kilogram of carbon dioxide per $US in 1980 to 770 grams per $US in 2006 (p.69). But while carbon intensity has declined on average by 0.7% per year since 1990, the global population has increased by 1.3% per annum and average per capita income has increased by 1.4% (in real terms) per annum. As a result, there has been a net increase of 2% per annum in CO2 emissions (p.79).

2. To meet an atmospheric stabilisation target of 450 parts per million (for CO2), annual emissions need to be reduced at an average rate of 4.9% per year until 2050. Given population growth (of about 0.7% per annum) and income growth (of about 1.4% per annum), this requires a technological (or carbon-intensity) improvement of 7% per annum: this is ten times faster than the current rate of improvement. Put differently, by 2050 the average carbon content of economic output will need to be less than 40g of CO2 per $ of output, a 21-fold improvement on the current global average.
3. Achieving an even lower, and safer, stabilisation target for CO2, such as 350 parts per million, would be even more demanding.

Overall, then, the challenges ahead are formidable, not least because the global economy is characterised by substantial path dependence (e.g. due to the long lifetime of most physical infrastructure, including carbon-intensive energy systems). Moreover, continuing economic growth will make it harder to achieve the emissions reductions required to stabilise CO2 concentrations. Yet without growth, moving to a safe concentration level will also be hard. This is because a dynamic and flexible global economy is needed if low-carbon technologies are to be developed and adopted on the scale and with the speed required. Quite apart from this, low or zero global growth will lock large numbers of people into absolute poverty (i.e. unless there is a considerable redistribution of income and wealth between developed and developing countries and within the developing world).

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Plainly, our capacity to decouple growth from environmental impacts will depend significantly on innovation and related technological advances. As the OECD (2011, p.10) has argued:

> Existing production technology and consumer behavior can only be expected to produce positive outcomes up to a point; a frontier, beyond which depleting natural capital has negative consequences for overall growth. We do not know where this frontier lies in all cases but we do know that the ability of reproducible capital to substitute for (depleted) natural capital is limited in the absence of innovation. By pushing the frontier forward, innovation can help to decouple growth from natural capital depletion.

But developing and implementing new technologies and achieving the necessary improvements in the management of the planet's natural resources will require major policy changes. To quote the OECD again:

> A green growth strategy is centred on mutually reinforcing aspects of economic and environmental policy. It takes into account the full value of natural capital as a factor of production and its role in growth. It focuses on cost-effective ways of attenuating environmental pressures to effect a transition towards new patterns of growth that will avoid crossing critical local, regional and global environmental thresholds … It is about fostering economic growth and development while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies (ibid., pp.10, 18).
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> The central feature of a green growth framework … is recognition of natural capital as a factor of production and its role in enhancing well-being. … Natural capital contributes to production by providing crucial inputs, some of which are renewable and others which are not. It also influences individual and social welfare in various ways, through the effect that the environment has on health, through amenity value and through the provision of ecosystem services … the contribution of natural capital to production is often not priced and the contribution of natural capital to individual welfare is not appropriately valued. (pp.20, 23)
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> Greening growth will require much more efficient use of resources to minimise environmental pressures. Efficient resource use and management is a core goal of economic policy and many fiscal and regulatory interventions that are not normally associated with a 'green' agenda will be involved. And in every case, policy action requires looking across a very wide range of policies, not just traditional 'green' policies (p.10).

The report goes on to outline in detail the kinds of policies needed to ensure that natural capital and ecosystem services are properly managed. In brief, such policies include:

- the proper pricing of pollution and the use of natural resources (e.g. via taxes and tradable permits) in order to internalise negative environmental externalities, minimise the over-exploitation of scarce natural capital and ensure that the true value of ecosystem services is reflected in decision-making frameworks;

- better regulatory standards to minimise ecological damage and enhance economic efficiency;
- the removal of subsidies that encourage pollution and the excessive extraction of natural resources;
- a new regime of metrics for measuring economic, social and environmental progress (see Stiglitz et al., 2009); and
- financial compensation for the least advantaged groups in society so that the distributional consequences of change are minimised.

Failure to implement such policies will almost certainly reduce incentives for business to invest in low-carbon technologies and new ways of using natural resources more efficiently. It will also undermine efforts to shift patterns of public investment (especially with respect to transport and energy infrastructure). And without a massive shift in private and public investment (and hence in production and consumption patterns), it is highly likely that an increasing number of 'safe' biophysical boundaries will be crossed (locally, nationally and globally). Eventually, the negative biophysical feedbacks from such overshooting will undermine global economic growth, if not generate a major economic crash.

But while it is easy to itemise the policies required for greater environmental (and hence economic) sustainability, most of the policies in question pose significant technical and design challenges. For example:

- What criteria should we use to determine the appropriate quality standards for water, air and soils, and how should these standards be enforced?
- How should we value natural capital and ecosystem services? For instance, in addition to the value derived from the direct and indirect uses of such capital, what weight should be given to non-use values (such as 'existence' values)?
- How should we determine the appropriate amount to charge polluters? For instance, with respect to climate change, how should we decide the monetary value of the environmental damage caused by rising concentrations of GHGs, and hence the cost that polluters should pay for each unit of emissions?
- What approach should be adopted when there is inadequate information about the natural rate of regeneration (of various kinds of natural capital) or the assimilative capacity of local ecosystems?

A common theme in the relevant literature ... was that the main barriers to adopting sustainable policies are political and institutional, not technical. Put bluntly, we have the means, but not the will.

- What new metrics for assessing environmental and social progress are required? And by what yardsticks should we measure and assess economic performance?
- In the case of global public goods (or common-pool resources), effective policy interventions to protect such goods will require international cooperation and collaboration. But how is this to be achieved? How are the required governance arrangements to be constructed?

There is, of course, no lack of thoughtful answers to such questions. And during the symposium on biophysical limits a variety of ideas, approaches and governance models were advanced (e.g. Dinica, 2011). Reference was also made to local and international examples of good practice with regard to sustainable resource management (e.g. Reynolds, 2011). Equally, however, it is evident that current policy frameworks and governance arrangements are not adequate to address the magnitude, range and urgency of the biophysical constraints facing humanity. Much needs to be done, not least to enhance public understanding of the nature of the problems confronting policy makers and build consensus amongst key stakeholders on cost-effective policies for delivering green growth.

The political feasibility of sustainability

This takes us to the heart of the matter: what is politically possible and will it enable global sustainability? It is here that much pessimism abounds. A common theme in the relevant literature and during the symposium was that the main barriers to adopting sustainable policies are political and institutional, not technical. Put bluntly, we have the means, but not the will.

Politically, the capacity to implement fundamental policy shifts is limited by institutional resistance (particularly from powerful vested interests), global coordination problems and weak international institutions, and human myopia and self-interest. These political constraints are most evident in the faltering efforts to ensure the sustainable management of our global common-pool resources, especially the atmosphere and oceans. Governance issues of this nature were the focus of several of the presentations at the symposium (Dinica, 2011; Hatfield-Dodds, 2011; McGinnis, 2011; Reynolds, 2011; Walker, 2011)

With respect to climate change, for example, policies to reduce GHG emissions have been thwarted or diluted across most of the democratic world because of four politically salient and deeply entrenched asymmetries (Boston and Lempp, 2011). First, there is a voting asymmetry: future generations, unlike current generations, do not have a vote, yet their interests are profoundly affected by the decisions being taken currently. Second, there is a cost-benefit asymmetry: the costs of action to reduce GHG emissions are certain, visible, direct and immediate, whereas the benefits of such action are less certain, intangible, indirect and long-term. Third, reducing emissions will impose significant costs on powerful, concentrated interests (e.g. the fossil fuel industry). By contrast, the beneficiaries of such measures are dispersed over time and space, and have much less incentive to organise to protect their interests. Finally, as noted earlier, there is an accounting asymmetry: for firms and governments the loss of financial assets counts, the loss of natural capital does not. For such reasons, policy measures that make sense in environmental terms, and indeed also economically on a long-term basis, are extremely difficult to implement. Moreover, there are no simple or easy solutions to the four asymmetries identified above. If there were, we would surely have discovered them by now.

Such considerations lead to a further troubling question: will modern civilisation destroy itself? After all, previous civilisations have mismanaged their environments and suffered dire consequences – the Sumerians, Babylonians and Mayans, to name but a few (Brown, 2009; Diamond, 2005). The main difference is that these civilisations had much less knowledge about the consequences of their actions than we do today. But knowledge is one thing; a willingness to act prudently is quite another. Thus, as Brian Walker (2011) observed at the symposium on biophysical limits: 'we lack the necessary, effective global governance to allow our unprecedented information and technology to provide, in time, a solution to the global sustainability crisis … There is a grave danger of a long nightfall if we fail – climate change, disease, famine, migration and state failure have together triggered long dark ages in the past; all five are now active'. Similarly, to quote Daniel Rutledge (2011): 'We can choose to acknowledge limits and change our systems (institutions, values) accordingly and thus avoid undesirable outcomes (collapse). Or not … The *Limits to Growth* and more recent research on many topics convey a common message: the longer we delay action the less likelihood we have of achieving desirable future outcomes due to inertia in the global system.'

Conclusion

In summary, the evidence suggests that maintaining global economic growth over an extended period of time will only be possible under very strict conditions; above all, the resilience of vital ecosystem services and biophysical systems must be protected. Currently, these conditions are not being met: collectively, humanity is overshooting critical biophysical parameters (on multiple scales) and seriously degrading ecosystems on a planetary-wide basis. This can continue only for so long. Eventually, the negative impacts will overwhelm our capacity to cope, and de-growth will become inevitable. The resulting social and political tensions will be immense – and probably unmanageable. As Paul Hawken has put it: 'At present we are stealing the future, selling it in the present, and calling it gross domestic product. We can just as easily have an economy that is based on healing the future instead of stealing it. We can either create assets for the future or take the assets of the future. One is called restoration and the other exploitation' (quoted in Brown, 2009, p.15).

A critical challenge over the coming decades will be not only to deepen our understanding of the biophysical properties and limits within which humanity must live, but also to design and implement new governance arrangements to ensure that these limits are respected and any overshooting is minimised. This will require a concerted effort to learn from our experience with existing policy models and frameworks and then apply this learning with wisdom and skill. But new approaches will also be needed, especially if the crucial global collective action problems – like climate change and the protection of marine ecosystems – are to be addressed effectively and expeditiously. This will require an unprecedented level of international cooperation and solidarity. Is this a realistic possibility? Let us hope so.

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2 There are four main kinds of 'ecosystem services': provisioning services (e.g. the production of energy, food, water and life-saving drugs); regulating services (e.g. water purification, pest and disease control, and climate regulation); supporting services (e.g. seed dispersal); and cultural services (e.g. recreational and spiritual benefits).

3 For non-renewable resources, absolute decoupling will be essential eventually, whether desired or otherwise.

4 This point is important because in recent decades many developed countries have reduced their energy consumption (and carbon intensity) per unit of output, but much of this reduction has been the result of 'the outsourcing of heavy industrial activity to emerging economies', especially China (IIER, 2011). As a result, there are now large embedded energy transfers occurring from developing to developed economies.

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