Environmental sustainability: From environmental valuation to the sustainability gap

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Abstract
This paper reflects on the extensive literature on environmental sustainability that has been produced over the last two decades, and proposes a new approach for environmental policy that goes beyond the cost-benefit analysis that has proved so difficult to implement for non-marginal environmental issues. This approach combines the Safe Minimum Standard approach, which was proposed many years ago, with the concepts of environmental functions and ecosystem goods and services, which have been developed much more recently. It is shown that this approach provides the basis for a robust calculation of sustainability across different environmental themes, following which a ‘sustainability gap’, showing the extent to which this standard is not being met, may be computed. This gap may be expressed in both physical and monetary terms, which permits the formulation of sustainability performance in a scientifically robust, easily communicable indicator that may be compared with GDP. While there appear to be no insurmountable scientific or practical obstacles to the full operationalization of this approach, it remains to be seen whether human societies are sufficiently concerned about the implications of continuing environmental unsustainability to make the resources available for such operationalization, and to enact the policies to allow the sustainability standards to be met.

Keywords
environmental functions, environmental sustainability, sustainability standards, sustainability gap

I Introduction: sustaining prosperity
Climate science (IPCC, 2007), the Millennium Ecosystem Assessment (MA, 2005) and the TEEB Report (TEEB, 2010) make clear that without a radical reform of the human-nature relation – in favour of nature – human civilization is at grave threat. Rockström et al. (2009) have shown that human activities are already outside the global ‘safe operating space’ provided by natural systems in respect of climate change, biodiversity loss and the nitrogen cycle, while over increasing areas the quality and quantity of water resources (Gleick, 2009) and land degradation1 pose threats to long-term habitability as well as development.

The nub of the matter is that nine billion humans cannot live current western lifestyles, at current levels of resource depletion and pollution, and maintain a habitable planet: climate stability is clearly being undermined, and this and other pressures may then accelerate the ongoing loss of biodiversity, so that the whole

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biosphere starts to unravel. In popular parlance, it is sometimes said in response that ‘we must save the planet’. This fails to fully characterize the issue. The planet per se seems very likely to have many hundreds of millions of years ahead of it. The issue is rather saving the human, by saving those aspects of the planet on which humans depend and which are now seriously at risk. The twin anthropogenic pressures that have put such pressure on the natural environment derive from population growth and per capita environmental impact. Barring some catastrophe it seems likely that human population will reach around nine billion people in the middle of this century (UN, 2004). Clearly, were population growth to slow so that the ultimate population was smaller, the pressure on the natural environment would be less. How this might be achieved is an important subject, but is not the subject of this paper.

The subject of this paper is the huge increase in human economic activity, and the environmental impacts that this has brought in its wake, over the centuries since the start of industrialization. The appetite for further economic growth has not diminished even in the richest countries. Yet it is clear that achieving this growth in the long term requires the environmental damage caused by much current economic activity to be radically reduced; in the current jargon, such activity must be made ‘sustainable’.

This paper sets out how such sustainability may be conceived, defined and measured, so that policy-makers and the public may have some clear indicators as to whether key environmental pressures are being reduced or otherwise managed, such that the economy is on an environmentally sustainable, or less unsustainable, path.

Economics has not been good at taking environmental impacts into account. Early neo-classical economics tended to ignore it altogether, until Pigou came up with the idea of the ‘externality’ (Pigou, 1932), which relegates the environment to an afterthought, a distraction from the main focus of economics on the flow of money and markets, only to be taken into account when there was obvious ‘market failure’. This is a wholly inadequate characterization of the elementary fact that economic activity is absolutely dependent on the goods and services supplied by the natural environment. Any aspiration for sustainable economic growth must start from the recognition of the need for the sustainable use of resources and ecosystems.

It must also be rooted in basic laws of physical science: indefinite physical expansion of the human economy on a finite planet is impossible; and, from the second law of thermodynamics, all use of non-solar forms of energy creates disorder, and potential disruption, in the natural world. Nine billion people will only flourish on planet Earth in 2050 if crucial decisions about economic management are taken on the basis of a correct conception of how the human economy relates to the natural environment.

Finally, it may be noted that the paper does not propose (like Daly, 1990) that economic growth is inherently unsustainable, or (like Jackson, 2009) that it cannot be made sustainable, or (like Victor, 2008) that it should be abandoned as a public policy objective by rich countries. Rather it leaves these questions open as matters to be determined empirically, suggesting that the pursuit of environmental sustainability should now take priority over that of economic growth. The former does not necessarily rule out the latter; but if gross environmental disruption results from a failure to achieve environmental sustainability, then economic growth will not be achieved in the long term either.

The next section introduces the key idea of the environmental function, which lies at the heart of the analysis, and sections III and IV show how this idea can be used to create a framework for sustainability analysis. Environmental sustainability is then properly defined in section V, and the issues of standards, measurement and indicators for sustainability are discussed in detail in section VI. Section VII then sets out the practical issues that need to be addressed to
make the presented framework for sustainability analysis operational, and section VIII concludes.

II Ecosystem flows and human well-being

Figure 1 gives a schematic illustration of the relationship between the biosphere and the benefits it delivers to human beings. The key concept here is that of environmental functions (De Groot, 1992), as discussed further below.

The biosphere is perceived to perform a range of environmental functions related to the provision of resources, the absorption of wastes and the delivery of a range of ecosystem services. These functions are performed for species apart from humans and, over the history of life on earth, have tended to lead to the increase in the complexity and diversity of the biosphere (signified by the positive feedback from the functions box to the biosphere).

The functions provide important benefits for humans, including inputs into the economy, and the maintenance of conditions conducive to human health and to human welfare more generally. However, the scale of the human population, and of the economic activity in which it now engages, now causes negative feedback to the biosphere, which reduces its complexity and diversity – and its ability to perform the environmental functions which deliver the human benefits. This negative feedback is what Pigou referred to as an ‘externality’. The level and extent of the negative feedback is now causing climate change and biodiversity loss to such an extent as to pose a serious threat of very great damage to human welfare at a global scale. The economic approach to this issue seeks to calculate the monetary value of the damage to the environmental functions caused by economic activity, measured in terms of the loss of human benefits to which the damage gives rise, to compare this with the benefits from the economic activity, and to equate the marginal loss due to the former with the marginal gain due to the latter in order to maximize the delivery of benefits overall. While this is a reasonable way of proceeding in principle, in practice it encounters a number of major problems, related to the characteristics of the serious environmental disruption/degradation that humanity now seems to be facing:

- the results of the damage are very uncertain, but may be very large (even catastrophic);
- the results may be irreversible;
- the results will play out over the very long term;
- the results affect every aspect of human life: mortality, morbidity, migration, water/food, cultural and spiritual values.

Techniques of environmental economic valuation are unable adequately to reflect such characteristics, for a number of reasons. First, the valuation techniques are designed for marginal, reversible changes. Second, the techniques need to specify and assign values and probabilities to possible outcomes. In some cases the full set of outcomes is not even known. Third, it is necessary to adopt a discount rate to give a net present value of events happening over time. There is no agreement about the appropriate rate to use for long-term, potentially very disruptive environmental outcomes. Fourth, to perform a comprehensive analysis it is necessary to give monetary values to human life, health, cultures, holy places, and even human survival. Even if it were possible to arrive at monetary values for
such issues, which in many cases it is not, the attempt to do so is controversial and has profound ethical implications. Attempts at monetization of such categories is contested at practically every stage, increasing controversy rather than resolving it, destroying its value as a decision support tool. The question then arises, if economic valuation of big environmental issues is infeasible, how should analysts and policy-makers proceed to evaluate and resolve the very difficult issues raised by the prospect of serious and irreversible environmental damage? The remainder of this paper puts forward an alternative based on the concept of environmental sustainability.

III A framework for sustainability analysis

The difficulties in applying normal methods of environmental economic valuation to long-term and serious problems of unsustainability has led to a framework of analysis based on the concept of ‘capital’, which has been developed in a number of papers (Ekins and Medhurst, 2006; Ekins et al., 2003, 2008).

The concept of capital derives from economics, whereby capital stocks (assets) provide a flow of goods and services, which contribute to human well-being. In its narrowest interpretation capital is used to mean manufactured goods which themselves produce, or facilitate the production of, other goods and services. This kind of capital is referred to below as ‘manufactured capital’.

However, it is clear that flows of benefits derive from many other sources than manufactured capital. To reflect this, the concept of capital has been extended in a number of directions, to take into account the quality (in addition to the quantity) of labour (human capital), the networks and institutions through which labour is organized and which create the social context for economic activity (social/organizational capital), and the natural resources and environment which both provide inputs into the economic process and maintain the existence of life on earth (natural capital). Ekins and Max-Neef (1992: 147–151) put forward a ‘4-capitals model’, relating manufactured, human, social and natural capital to the process of production and the generation of human welfare. This model was elaborated further in Ekins (2000: 51ff.). The same model seems to have commended itself to Serageldin and Steer (1994: 30) of the World Bank, who write of the ‘need to recognize at least four categories of capital’, as defined in Table 1.

The four types of capital can be ranked in order of temporal priority, if not of present economic importance. Natural capital came first, providing the conditions for the evolution of humans and other life on earth. Humans then used their human capital to fashion tools and other kinds of manufactured capital out of natural capital, and grouped together to create social and organizational capital, including laws of property and a legal system to enforce them, institutions for the management of natural resources, the economy and society generally, and financial capital and the financial system through which it acts. In a modern, complex economy, the interactions between the different kinds of capital are such that it is effectively impossible to identify and separate out their individual productive capacity.

However, the existence of different forms of capital immediately raises the question as to whether it is the total stock of capital that must be maintained, with substitution allowed between various parts of it, or whether certain components of capital are non-substitutable, i.e. they contribute to welfare in a unique way that cannot be replicated by another capital component. With regard to natural capital, Turner (1993: 9–15), and Pearce et al. (1989: 127–130) before him, have distinguished between the following:

- **Weak sustainability**, which derives from a perception that welfare is not normally
dependent on a specific form of capital and can be maintained, for example, by substituting manufactured for natural capital, though with exceptions. (In Turner’s formulation, complete substitutability between the capitals, corresponding to the ‘Hartwick rule’ (Hartwick, 1977), is denoted by ‘very weak’ sustainability.)

- **Strong sustainability**, which derives from a different perception that substitutability of manufactured for natural capital is seriously limited by such environmental characteristics as irreversibility, uncertainty and the existence of ‘critical’ components of natural capital, which make a unique contribution to welfare. (For Turner, ‘very strong’ sustainability envisages no substitution between natural and other forms of capital, which implies a non-declining stock of natural capital and the maintenance of all the environmental functions to which it gives rise.)

For a more recent book length treatment of this issue, see Neumayer (2003).

The point at issue is that there may be limitations to the substitution of one form of capital for another, if one form of capital plays some unique role in welfare creation. The potential for unsustainable development lies in the loss of one or more capital stock, or in the trade-offs made

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**Table 1. Four types of capital**

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<tr>
<th>No.</th>
<th>Type</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>Manufactured capital</td>
<td>Manufactured (or human-made) capital is what is traditionally considered as capital: produced assets that are used to produce other goods and services. Some examples are machines, tools, buildings, and infrastructure.</td>
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<tr>
<td>2</td>
<td>Natural capital</td>
<td>In addition to traditional natural resources, such as timber, water, and energy and mineral reserves, natural capital includes broader natural assets, such as biodiversity, endangered species, and the ecosystems which perform ecological services (e.g. air and water filtration) that absorb and neutralize human wastes. Natural capital can be considered as the components of nature that can be linked directly or indirectly with human welfare.</td>
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<tr>
<td>3</td>
<td>Human capital</td>
<td>Human capital generally refers to the health, well-being, and productive potential of individual people. Types of human capital include mental and physical health, education, motivation and work skills. These elements not only contribute to a happy, healthy society, but also improve the opportunities for economic development through a productive workforce.</td>
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<tr>
<td>4</td>
<td>Social capital</td>
<td>Social capital, like human capital, is related to human well-being, but on a societal rather than individual level. It consists of the social networks that support an efficient, cohesive society, and facilitate social and intellectual interactions among its members. Social capital refers to those stocks of social trust, norms and networks that people can draw upon to solve common problems and create social cohesion. Examples of social capital include neighbourhood associations, civic organizations, and cooperatives. The political and legal structures which promote political stability, democracy, government efficiency, and social justice (all of which are good for productivity as well as being desirable in themselves) are also part of social capital.</td>
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between different forms of capital, and the degree to which:

- any decline represents a breach of some critical threshold;
- if not, whether any decline in one form is not compensated by increases in other forms.

The existence and nature of trade-offs needs to be understood empirically. Some critical thresholds may be amenable to largely scientific determination and description. Others may be more normative, both in terms of the existence of critical thresholds and whether there are acceptable trade-offs which would allow them to be breached. To gain insights into such issues it is clearly important to determine how to measure each kind of capital, and determine whether it is increasing or decreasing.

The focus of this paper is on critical natural capital, which generates important environmental functions as discussed below, and the use of this idea to derive a methodology to give operational meaning to the concept of environmental sustainability.

**IV Characteristics, functions and values of nature**

Conceiving of nature as ‘natural capital’ indicates the importance of elements of nature (such as minerals, ecosystems and ecosystem processes) to human economies and societies. Natural ecosystems are defined by a number of environmental characteristics which, in turn, determine the ecosystems’ capacity to provide goods and services. These environmental characteristics are manifold (for example, De Groot, 1992, lists 53, classified in nine groups), which can be related in turn to the three fundamental environmental media (air, water, land) and the life they support, through the habitats they sustain. The four media of Table 2 become the basis of the natural capital framework developed later in the paper.

De Groot defines environmental functions as ‘the capacity of natural processes and components to provide goods and services that satisfy human needs (directly and/or indirectly)’ (De Groot, 1992: 7). The ‘goods’ (e.g. resources) are usually provided by the ecosystem components (plants, animals, minerals, etc.) and the ‘services’ (e.g. waste recycling) by the ecosystem processes (biogeochemical cycling).

Environmental functions have been identified and classified in a number of different ways. De Groot et al. (2002) divide them into four categories:

1. *Regulation functions*: regulation of essential ecological processes and life-support

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**Table 2. Characteristics of natural capital**

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<tr>
<th>Medium</th>
<th>Main characteristics determining functioning of the (eco)system (after De Groot, 1992)</th>
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</thead>
<tbody>
<tr>
<td>Air</td>
<td>Atmospheric properties and climatological processes (e.g. air quality, precipitation, temperature, wind)</td>
</tr>
<tr>
<td>Water</td>
<td>Hydrological processes and properties (e.g. water reservoirs, runoff, river discharge, groundwater table, water quality)</td>
</tr>
</tbody>
</table>
| Land   | - Bedrock characteristics and geological processes (e.g. minerals, tectonics)  
        |   - Geomorphological processes and properties (e.g. weathering, albedo)  
        |   - Soil processes and properties (e.g. texture, fertility, biological activity) |
| Habitats | - Vegetation characteristics (e.g. structure, biomass, evapotranspiration)  
         |   - Flora and fauna (e.g. species diversity, dynamics, nutritious value)  
         |   - Life-community properties (e.g. food chain interactions, decomposition)  
         |   - Conservation value/integrative aspects (e.g. integrity, uniqueness) |
systems (bio-geochemical cycling, climate regulation, water purification, etc.);

(2) Production functions: harvesting from natural ecosystems of, for example, food, raw materials and genetic resources;

(3) Habitat functions: provision by natural ecosystems of refuge and reproduction-habitat to wild plants and animals and thereby contribution to the (in situ) conservation of biological and genetic diversity and evolutionary processes.

(4) Information functions: provision of many possibilities for recreation and aesthetic enjoyment, cultural and historical information, artistic and spiritual inspiration, education and scientific research.

An important basic distinction may be drawn between the ‘functions of’ natural capital and the ‘functions for’ humans which it generates (see also O’Connor, 1996, 2000, for development and discussion of this distinction). The ‘functions of’ natural capital (which correspond to De Groot’s Regulation functions, or the Life-Support functions in Figure 1) are the basic processes and cycles in the internal functioning of natural systems which are responsible for sustaining and maintaining the stability and resilience of ecosystems (Holling et al., 1995). The ‘functions for’ humans are those which provide resources for, and absorb the wastes from, human activities (the Source and Sink functions in Figure 1, or largely the Production and Regulation functions in De Groot’s classification), and provide human welfare in other ways. They are more or less synonymous with the provision of ecosystem goods and services which, originating with Daily (1997), has become another major way of conceptualizing these issues (see MA, 2005; TEEB, 2010).

Without the ‘functions of’ natural capital, no other category of functions would be able to exist on a sustained and systematic basis. This implies that the economic and other welfare which derives from the ‘functions for’ humans is dependent on the ‘functions of’ natural capital, irrespective of whether people want them, know about them, or perceive them or not. Humanity’s primary dependence on the ‘functions of’ natural capital reflects the fact that, however they may perceive themselves, humans are a part of, and not apart from, nature. A strength of the functional approach, compared to that based on ecosystem goods and services, is that it emphasizes the distinction between functions ‘of’ nature, and functions ‘for’ humans, and the primacy of the former.

The ‘functions for’ people, however they are categorized, all contribute directly in some way to human welfare. As noted above, some act as inputs to, or waste absorbers from, the economy, others help to maintain human health, or contribute to other aspects of human welfare. If environmental functions (both the life-support functions ‘of’ natural capital, and those that provide directly ‘for’ people) contribute to human welfare, then they have value.

De Groot (1992: 130) has identified nine different types of values of environmental functions, grouped under the three dimensions of sustainable development:

- Ecological (conservation and existence values);
- Social (human health, personal, community and option values);
- Economic (consumptive, productive and employment values).

These values are a direct source of human welfare. Conservation value principally resides in the Regulation life-support functions. Existence value reflects the welfare people derive from simply knowing that some environmental function, or part of nature, exists. Many environmental functions contribute directly or indirectly to human health. Many environmental functions, especially the Habitat and Information functions, contribute to community well-being. Option value derives from the concerns
that people have to maintain environmental functions for possible use by future generations. The economic values of consumptive and productive use mainly derive from the source and sink environmental functions. Employment values derive also from the service environmental functions (e.g. the dependence of much tourism on unspoilt natural areas).

Figure 2 brings together these different ways of conceptualizing and classifying the functions, attributes and values of natural capital. It may be interpreted as follows.

There are social, economic, ethical and environmental influences on the natural capital stock, the elements of which are matter, energy and ecosystems, which include human-cultivated ecosystems (e.g. plantation forests, crops). These elements are caught up in natural processes which sustain the ecosystems and all life within them, which are collectively called the ‘functions of natural capital’, and which may also be described as Regulation, Habitat or Life-Support functions. They both sustain ecosystems and give them resilience.

The elements and functions of natural capital generate a range of environmental functions for people. These functions include those earlier classified as Habitat, Production and Information functions, or as Source, Sink and Service functions, with the latter split into Life-Support, Scenery and Site functions. In this case the Habitat and Life-Support functions for people depend on the continuing operation of the Habitat and Life-Support functions related to ecosystems. Both the functions of natural capital and the functions for people are contingent on spatial factors, because the ecosystems and other physical elements of natural capital which produce them exist in particular places and are dependent on particular climatic and other physical conditions. Analysis of environmental functions must therefore pay attention to the relevant spatial scale.

The functions for people generate human welfare, some through the economy, some which contribute directly to human health, and some which generate other kinds of welfare. The core of the environmental problem is that in its use of environmental functions for people, particularly those which generate economic welfare, humanity is having a negative impact and influence on the natural capital stock, and, particularly, on the functions of this stock which are responsible for ecosystem stability and resilience. But in the long term the welfare-generating ‘functions for people’ will only be sustained through the continued operation of the life-support ‘functions of nature’. The purpose of stressing in Figure 2
the distinction between the fundamental ‘functions of’ natural capital and the more obvious ‘functions for’ people is that the former are so often not perceived, and therefore valued, by human society until the function is damaged or lost.

The identification of environmental functions and the natural capital that is required for them is largely an objective exercise informed by environmental science, although there remain large areas of uncertainty or even ignorance concerning the causes, effects and dynamics of the ‘functions of’ natural capital that sustain ecosystems. On the other hand, the perception and valuation of what the functions actually deliver to human life and society is a subjective matter. For those functions that contribute to the economy through market transactions, the conventions of market valuation may permit their value to be expressed in money terms and directly compared with other sources of economic value. For the functions that contribute to human health and wider human welfare, and especially those that sustain ecosystems, the application of such conventions is problematic, both in theory and practice (as briefly discussed above, and see Faucheux et al., 1998). Decision making in these situations is likely to need other criteria and considerations. One of these may be the concept of environmental sustainability, which is the subject of the next section.

V Defining environmental sustainability

From a human point of view what matters about the environment is not particular stocks of natural capital per se, but the ability of the capital stock as a whole to be able to continue to perform the environmental functions which make an important contribution to human welfare. Hence it is logical to define environmental sustainability as the maintenance of important environmental functions, and hence the maintenance of the capacity of the capital stock to provide those functions. This is towards the strong end of the weak-strong sustainability distinction referred to above. It does not envisage as necessary a completely non-declining natural capital stock (i.e. it is not in line with ‘very strong’ sustainability), because some may be redundant in respect of some environmental functions, and environmental functions are not necessarily uniquely performed by particular stocks of natural capital. It may be that other types of capital may engender flows that are acceptable substitutes for some environmental functions.

Nor does it envisage the maintenance of all environmental functions, because equivalent welfare may be generated over the long term by other capital stocks (i.e. there is some substitutability between natural and other capitals), while it also need not be assumed that all environmental functions are so important for human welfare that they must be maintained.

However, substitutability between different kinds of capital needs to be empirically shown before such substitution is brought about, especially if it is irreversible; and continuing ignorance about many aspects of ecosystem function argues for precaution in permitting the loss of natural capital. It is also clear that De Groot’s four categories of environmental functions relate to very different aspects of the natural capital providing them, and therefore criteria for their importance, or criticality, and sustainable use need to be assessed in very different ways, bearing in mind also that each of the criteria needs to be interpreted in a way that reflects the essentially dynamic nature of ecosystems:

- for Regulation functions (e.g. maintaining ecosystem resilience, waste recycling, erosion-prevention, maintenance of air-quality) criteria like maximum carrying capacity, conservation of biodiversity, and integrity of essential life-support processes are involved;
- for Habitat functions (e.g. conservation of species) a spatial dimension is added (e.g. minimum critical ecosystem size);
• for Production functions (e.g. resource-extraction) the maximum sustainable yield level is an important criterion;
• for Information functions criteria are more driven by and derived from social science (perception of valuable landscapes; cultural and historic value; etc.).

In a situation of complete knowledge about the contribution of different functions to human welfare, their importance could be evaluated in these terms and the functions thereby deemed to be of high importance related back to the particular stocks of environmental capital which are responsible for them. Unfortunately there is enormous uncertainty about which functions are important for human welfare and why, especially concerning those Regulation and Habitat functions which are believed to sustain life-processes, which compounds the difficulty of quantifying their contribution to human welfare. Although techniques of monetary valuation can capture some environmental values, both the techniques and the numbers they produce remain contested and fraught with problems of interpretation. Rather than using such techniques it seems preferable to identify as ‘important’, or critical (and therefore essential for environmental sustainability), any environmental functions:

1. which cannot be substituted for, in terms of welfare generation, by any other function, whether environmental or not;
2. the loss of which would be irreversible;
3. the loss of which would risk, or actually entail, ‘immoderate losses’.

The simultaneous coincidence of uncertainty, irreversibility and possible large costs, or immoderate losses, has long been recognized as an important consideration for environmental policy. Ciriacy-Wantrup’s (1952) classic work prefigured many of the current concerns of sustainability with his development of the concept of ‘the safe minimum standard’ (SMS).

Bishop (1993) brings the SMS approach into the context of current environmental discourse by relating it to sustainability:

To achieve sustainability policies should be considered that constrain the day to day operations of the economy in ways that enhance the natural resource endowments of future generations, but with an eye towards the economic implications of specific steps to implement such policies.

(Bishop, 1993: 72)

Here the safe minimum standard has been converted into a sustainability standard. In the terms previously discussed, those activities that entail the possibility of irreversible effects and immoderate costs are now identified as environmentally unsustainable. The SMS approach suggests that policies that constrain or transform those activities towards sustainability should be considered in a framework which seeks to avoid intolerable costs and to achieve the sustainability standard in a cost-effective way, rather than trying to derive the standard itself from normal principles of cost-benefit analysis.

With the present uncertain state of knowledge about ecosystems, and environmental functions generally, it is very difficult to judge which are critical and which are not. It is likely, for example, that all the Regulation ‘functions of’ natural capital are critical, because it is not clear how natural systems would operate with impaired functions, although recent research suggests the existence of environmental thresholds and irreversible change when resilience is lost (Carpenter, 2001; Holling et al., 1995, 1996; Kates and Clark, 1996; Scheffer et al., 2001). There is likely to be some, and perhaps considerable, ecological redundancy – not all species that occur in a given habitat are actually critical to the functioning of that habitat. However, it is not at all clear ex ante which species are, or might be, redundant. Science therefore suggests great caution in categorizing environmental functions (and, by extension, elements of natural capital such as individual species) as ‘non-critical’,
because of the danger that the loss of such functions may give rise to unsustainable effects.

However, in many cases, especially where the non-Regulation functions are concerned, what counts as an ‘unsustainable effect’ rather than a sustainable economic cost is a matter of judgement which can only partially be resolved by science. Ethics and the attitude to risk also play a significant role here. It is important that the basis of judgement is articulated clearly, especially as to who is responsible for the effects and who is bearing the costs, and differentiating the contributions played by science, ethics and risk acceptance or aversion.

If the key consideration for environmental sustainability is the maintenance of the functions that are important for human welfare, then in the first instance at least it is on the ‘functions for people’ on which attention should be focused. It was noted above that the principal contributions of these functions related to the economy (with a further convenient division into Source and Sink functions), human health and other kinds of human welfare. It was also seen that the ‘functions for people’ were fundamentally dependent on the Life-Support ‘functions of nature’. This suggests that principles of environmental sustainability will need to maintain important environmental functions as follows:

- Source functions – the capacity to supply resources;
- Sink functions – the capacity to neutralize wastes, without incurring ecosystem change or damage;
- Life-Support functions – the capacity to sustain ecosystem health and function;
- Other human health and welfare functions – the capacity to maintain human health and generate human welfare in other ways.

A number of principles of environmental sustainability have been put forward which relate to the generic environmental functions of resource supply, waste absorption and life-support. For example, Daly (1991), working with a ‘strong’ to ‘very strong’ sustainability framework, has suggested four principles of sustainable development:

1. limit the human scale (throughput) to that which is within the earth’s carrying capacity;
2. ensure that technological progress is efficiency-increasing rather than throughput-increasing;
3. for renewable resources harvesting rates should not exceed regeneration rates (sustained yield); waste emissions should not exceed the assimilative capacities of the receiving environment;
4. non-renewable resources should be exploited no faster than the rate of creation of renewable substitutes.

These principles are also among the rules that Turner (1993: 20–21) has formulated ‘for the sustainable utilization of the capital stock’, the others of which are: correction of market and intervention failures; steering of technical change not only to increase resource-using efficiency but also to promote renewable substitutes for non-renewable resources; taking a precautionary approach to the uncertainties involved.

Of these rules, the correction of failures, the nature of technological progress and the steering of technical change are more do to with achieving sustainability than defining principles for it, and are best handled separately. Moreover, rules 2, 3 and 4 may be seen as elaborations of rule 1 relating to carrying capacity. However, in view of the complexity of applying the concept of carrying capacity to human activities, it seems desirable to express it more specifically in terms of those environmental problems that appear most pressing. Such considerations enable the Daly/Turner rules to be reformulated into a set of seven sustainability principles which cover the four core categories of environmental
functions (shown in brackets after them) and which are intended to ensure the maintenance of those that are critical, identified by the type of their contribution to human welfare:

(1) Anthropogenic destabilization of global environmental processes such as climate patterns or the ozone layer (in these cases from excessive polluting anthropogenic emissions into the atmosphere) must be prevented. (*Life-Support*)

(2) Critical ecosystems and ecological features must be absolutely protected to maintain biological diversity (especially of species and ecosystems). (*Life-Support*)

(3) The renewal of renewable resources must be fostered through the maintenance of soil fertility, hydrobiological cycles and necessary vegetative cover and the rigorous enforcement of sustainable harvesting. (*Source*)

(4) Depletion of non-renewable resources should seek to balance the maintenance of a minimum life-expectancy of the resource with the development of substitutes for it. (*Source*)

(5) Emissions into air, soil and water must not exceed their critical load, that is the capability of the receiving media to disperse, absorb, neutralize and recycle them, without disturbing other functions, nor may they lead to life-damaging concentrations of toxins. (*Life-Support/Human Health*)

(6) Landscapes of special human or ecological significance, because of their rarity, aesthetic quality or cultural or spiritual associations, should be preserved. (*Other Welfare*)

(7) Risks of life-damaging events from human activity must be kept at very low levels. Technologies which threaten to cause serious and long-lasting damage to ecosystems or human health, at whatever level of risk, should be foregone. (*All*)

As noted, of these seven sustainability principles, 3, 4 and, to some extent, 2 seek to sustain resource functions; 5 seeks to sustain waste-absorption functions; 1 and 2 seek to sustain life-supporting environmental services, and 6 other services of human value; and 7 acknowledges the dangers associated with environmental change and the threshold effects and irreversibilities mentioned above.

These relations between environmental functions and the sustainability principles are shown in Table 3 and related to environmental themes. The principles give clear guidance on how to approach today’s principal perceived environmental problems. They may need to be supplemented as new environmental problems become apparent.

The application of these sustainability principles permits critical environmental functions, and the critical natural capital which performs them, to be tentatively (because of uncertainties)
identified. In this identification it is necessary to pay close attention to the space and scale over which the function is being performed. Given the interconnections between ecosystems, it is possible that what seems like quite a ‘local’ environmental function is in fact dependent on environmental factors and processes that operate a considerable distance away, or are part of global or regional environmental systems. The application of these principles to environmental functions and the natural capital stock which gives rise to them enables critical natural capital (CNC) to be identified.

Clearly these sustainability principles interact at a deep level with many economic and social dimensions, which are beyond the scope of this paper. Guiding human economies and societies to operate in line with these principles will require many other economic and social factors to be taken into account, and may not be feasible without fundamental changes in human aspirations, institutions and modes of social organization.

**VI Deriving environmental sustainability standards**

An important part of the identification and description of CNC is the derivation, on the basis of the above sustainability principles, of specific sustainability standards which define the minimum conditions for the CNC to perform its critical environmental functions. The standards may be expressed as indicators of the state of the CNC (e.g. quality of air or water, concentration of greenhouse gases), or of the pressure upon it (e.g. emissions into air or water). An enormous amount of work has now been done to define environmental indicators related to the key environmental themes. One example is the matrix of the ‘top 60’ indicators related to 10 policy fields, as identified by Scientific Advisory Groups convened by EUROSTAT (EC/EUROSTAT, 1999: 8). Such indicators have become the staple of such regular publications as the European Environment Agency’s Environmental Signals reports (EEA, 2009) and the OECD’s Environmental Data Compendium (OECD, 2008).

It may be noted that, for the first five sustainability principles (related to Sink, Source and Life-Support functions, and to pollution impacts on human health), biophysical standards can be derived largely through reference to natural science, invoking the seventh principle to cope with risk and uncertainty when necessary. Because of uncertainty, it is particularly difficult to define criticality in relation to biodiversity.

The sixth sustainability principle is somewhat different from the others in that it deals with environmental functions that are exclusively concerned with human welfare, rather than the maintenance of ecosystems, and the value of which is more personal and subjective than the two source sustainability principles 3 and 4.

Once the standards according to these principles and criteria have been defined, then the difference between these standards and the environmental state or pressure indicator showing the current situation may be described as the ‘Sustainability Gap’ (SGAP), in physical terms, between the current and a sustainable situation (Ekins and Simon, 1999). SGAP indicates the degree of consumption of natural capital, either in the past or present, which is in excess of what is required for environmental sustainability. For the state indicators, the gap indicates the extent to which natural resource stocks are too low, or pollution stocks are too high. For pressure indicators, the gap indicates the extent to which the flows of energy and materials which contribute to environmental depletion and degradation are too high. SGAP indicates in physical terms the extent to which economic activity is resulting in unsustainable impacts on important environmental functions.

The SGAP idea can be developed further to give an indication of the time that would be taken, on present trends, to reach the standards of environmental sustainability. Thus Ekins and Simon (2001: 11ff.) use calculations of various
stresses across seven environmental themes in the Netherlands for two years, 1980 and 1991, measured in various ‘theme equivalent’ units (taken from Adriaanse, 1993), to derive both SGAPs and Years-to-Sustainability (YS) indicators for each theme.

Columns 1 and 2 of Table 4 show Adriaanse’s environmental stresses, and Column 3 gives his sustainability standards, calculated from an assessment at the time of sustainable environmental pressures or states (where the standards relate to global environmental issues such as climate change, the Netherlands’ standard assumes corresponding standards for other countries – the Netherlands, or any other country, cannot effectively address such issues on its own). The next two columns calculate the SGAP for each theme for each year, where SGAP is the distance in theme equivalent units between current conditions and the sustainability standard. Thus in the SGAP columns the standard is subtracted from the stress for each year. The next two columns normalize this SGAP (NSGAP) as shown. It can be seen that the NSGAP for climate change, for example, was reduced by 17% from 1980 to 1991, while that for disturbance increased by 30%. Thus, for climate change, on a continuation of the 1980–1991 trend, the Netherlands would reach its calculated sustainability standard in 54 years. Clearly, whether the climate change problem overall was ‘solved’ in this period would depend on whether the standard for the Netherlands turned out to be sufficiently stringent, as well as whether other countries also reduced their emissions to attain their corresponding standard by the end of the period. The total NSGAP is obtained by simply summing the individual SGAPs, implying that, in the absence of a robust weighting methodology, all the environmental issues have the same importance for sustainability. It can be seen that the total NSGAP over the period 1980–1991 was

### Table 4. Various sustainability measures for the Netherlands

<table>
<thead>
<tr>
<th>Environmental Stress (ES)</th>
<th>Sustainability Standard (SS)</th>
<th>Sustainability Gap (SGAP) (ES-SS)</th>
<th>Normalized SGAP (100*SGAP/SS), EPeq</th>
<th>Years to Sustainability (YS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate change, Ceq</td>
<td>1980</td>
<td>286</td>
<td>1980</td>
<td>2760</td>
</tr>
<tr>
<td></td>
<td>1991</td>
<td>239</td>
<td>1991</td>
<td>229</td>
</tr>
<tr>
<td>Ozone depletion, Oeq</td>
<td>20000</td>
<td>8721</td>
<td>20000</td>
<td>8721</td>
</tr>
<tr>
<td>Acidification, Aeq</td>
<td>6700</td>
<td>4100</td>
<td>6300</td>
<td>3700</td>
</tr>
<tr>
<td>Eutrophication, Eeq</td>
<td>302</td>
<td>273</td>
<td>216</td>
<td>187</td>
</tr>
<tr>
<td>Dispersion, Deq</td>
<td>251</td>
<td>222</td>
<td>239</td>
<td>210</td>
</tr>
<tr>
<td>Waste disposal, Weq</td>
<td>15.3</td>
<td>14.1</td>
<td>12</td>
<td>12.3</td>
</tr>
<tr>
<td>Disturbance, Neq</td>
<td>46</td>
<td>57</td>
<td>37</td>
<td>48</td>
</tr>
<tr>
<td>TOTAL</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>

\(^{1}\)The second entry in this column has converted the NSGAP to index numbers, with 1980=100

Source: Ekins and Simon (2001: 14, Table 4)
reduced by 18%. The final column gives the years required to reach the sustainability standard (to reduce SGAP and NSGAP to zero) for each environmental theme, given the trend established from 1980–1991. It can be seen that the total NSGAP will be reduced to zero after 51 years, although individually climate change, eutrophication, dispersion and waste disposal will still not have reached their sustainability level by then.

It may also be noted from Table 4 that the various measures cannot all be derived for all the environmental themes. For ozone depletion, the sustainability standard of 0 means that no figure for normalized SGAP can be derived, although there is no problem computing the years to sustainability (YS). For disturbance the increasing trend from 1980–1991 means that no figure for YS can be given. However, in this case there is no problem with normalizing the stress, and the increasing trend is factored into the total normalized figures, increasing the length of time before sustainability overall will be reached (removing disturbance from the total actually reduces the time before sustainability is reached to 43 years). Both the trend in the normalized SGAP (NSGAP) and Years to Sustainability (YS) indicators give useful information on the achievement of sustainable development.

In fact the reduction in NSGAP in relation to some base year (here 1980) and the YS indicators could provide easily communicable information against which progress towards environmental sustainability could be monitored, both by individual environmental theme and in aggregate. There have been increasing calls for such an indicator to compare with, and offset the influence of, GDP. An index like NSGAP, and the trends derived from it, do not require scientifically dubious conversions of different environmental impacts to a common environmental unit (such as, for example, the ‘global hectare’ unit of the ‘ecological footprint’, developed by Wackernagel and Rees, 1996), but still enables aggregate progress towards environmental sustainability to be expressed, analogously to the way the UNDP’s Human Development Index in its annual Human Development Report (UNDP, 2010) combines indicators of income, health and education to indicate progress on human development. Some such way of simplifying the message presented by frameworks of indicators in the environmental field is likely to be necessary if the policy objectives of sustainable development are to be widely understood.

The SGAP indicator can also be expressed as a ratio of output to show the ‘unsustainability intensity’, comparable to the energy intensity, of economic activity, which is widely used in economic and environmental policy-making. Ekins and Simon (1999) further show how maintenance and restoration costs can be used to convert the SGAP into a monetary figure (M-SGAP), which may be directly compared with GDP, and which is discussed further below.

### VII The practical analysis of critical natural capital and strong sustainability

These ideas may be drawn together into a framework (called the CRITINC framework, after the project that developed it; see Ekins et al., 2003) for the classification of CNC as set out in Figure 3, in which the upper rows of Level 1 are the nine ecosystem characteristics listed in Table 2 which give rise to the environmental functions emanating from natural capital, including cultivated natural capital. Below these ecosystem characteristics (and on the right of the figure) are characteristics of the non-living human-made environment (e.g. landscape features such as stone walls, or features of the built environment), which also give rise to environmental functions.

The functions emanating from these environmental characteristics are classified in four categories: source (the capacity to supply resources); sink (the capacity to neutralize wastes, without incurring ecosystem change or damage);
life-support (relating to ecosystem health and function); and functions for human health and welfare. Thus the first three sets of functions are purely environmental in their formulation, while the fourth function category is specifically concerned with impacts on people. The matrices in Level 1 show which characteristics give rise to which functions. The entries in the matrices may be descriptive and/or quantitative. They are likely to contain state indicators of the natural capital stock from which the relevant function emanates. The functions deriving from the non-living human-made environment are likely to be largely functions in the fourth category connected to history, culture, amenity and aesthetic appreciation.

Moving down to Level 2, the sustainability concern (or theme) with regard to the source functions is depletion. It may be that particular state indicators from the Level 1 matrices encapsulate the resource provision from particular functions (e.g. stocks of fish), in which case these indicators can be reproduced here to give a matrix of state indicators for the source functions. Similar matrices of state indicators may be produced for the sink (e.g. concentration of pollutant in a lake), life-support (e.g. species diversity in an ecosystem, landscape patchiness/mosaic, number of reserves or similar elements in the landscape that can provide ecological memory to disturbed areas, the number of corridors for birds, plants, wildlife, etc.) and human health and welfare (e.g. existence of human-made landscape features) functions.

Depletion is caused by economic activities of production and consumption. On the left of Level 2 is a physical economic input-output (I-O) table. The rows of the I-O table are of depletable resources and, further down, of polluting emissions. The columns of the I-O table are of the usual economic sectors and final demand categories (including households). The resource rows show the inputs of the various resources into the different economic sectors and
final demand, giving entries for the depletion of the source functions by particular economic activities, and the totals then feed across to the source functions, to form Impact Matrix A. Depleting activities can also affect sink functions (Impact Matrix B). The classic example is the depletion of water resources. For example, reducing the water flow in a river can greatly reduce the river’s ability to neutralize pollution. Depleting activities can also have an impact on life-support functions (where, for example, it reduces biodiversity) and human health and welfare functions (e.g. where water abstraction dries up rivers, or construction projects destroy valuable landscapes), and these are represented in the Impact Matrices C and D (see Ekins and Simon, 2003).

The relationship of the economic accounts to environmental flows in this way was advocated by the UN Statistical Office in 1993 (UN, 1993), since when there has been considerable development of physical I-O tables (PIOT), and environmentally extended input output (EEIO) accounting, to match the monetary I-O tables which are a standard feature of national economic accounting. Thus Vaze (1998) presents Environmental I-O Tables for the UK, in which emissions are disaggregated by economic sector and presented very much as shown in the left-hand section of Figure 3. The German PIOT described by Stahmer et al. (1998) constructs a full materials flow for the German economy. The resource flows (measured in tonnes) appear beneath the usual economic rows of the monetary I-O tables and feed across through into the economic sectors as in Figure 3. Pedersen (1994) shows how in a similar statistical structure for Denmark the inputs of 25 different types of energy into 117 different production sectors, with the resulting air emissions, can be shown.

Other recent developments of EEIO accounting may be mentioned here, although detailed discussion of this topic is beyond the scope of this paper. One application, as in the EIPRO project (IPTS/ESTO, 2006), combines input-output analysis with life-cycle analysis to compute the environmental impacts of products that include their indirect as well as their direct impacts. The ongoing EXIOPOL project has extended this approach through the construction of a full global EEIO economic and environmental database. Such databases also permit the calculation of environmental impacts in other countries due to imports. In an application of this approach, Wiedmann et al. (2008) showed that if the CO\(_2\) emissions of the UK were computed on a consumption basis (i.e. on the basis of emissions from domestic consumption plus net imports), then UK emissions had increased by 18% from 1992 to 2004, rather than falling by 5% if calculated on a production basis, which include emissions from exports but not imports. It may be noted that the calculations of Table 4 are based on territorial (production) impacts or emissions, but in principle such a table could also be computed on a consumption basis if desired, although data limitations in many (especially developing) countries would make such exercises challenging and very approximate in practice, and would require extensive inferences and assumptions about data to be made.

Figure 3 is therefore very much in line with and a development of, rather than a departure from, current environmental-economic accounting practice, in which these physical flows are related not only to the economic sectors from which they derive, but also to the environmental functions on which they impact.

In addition to causing depletion of resources, and their resulting impact on environmental functions, economic activities also emit pollutants, and these are shown in Figure 3 in the ‘Pollutants per sector’ matrix, where the rows are different pollutants, and the columns are the economic sectors feeding down from those of the I-O table. At the right of the ‘Pollutants per sector’ matrix is a column totalling all the different pollutants (including net exports and imports of pollutants). The different pollutants that are the rows of the ‘Pollutants per sector’ matrix then feed across to the different environmental
functions. They may have an impact on the source functions (e.g. acid pollution may kill trees, water pollution may kill fish), and these impacts are recorded in Impact matrix A'. The total depletion of source functions, recorded below Impact Matrix A', is therefore made up of the depletion recorded in both matrices A and A'.

The pollutants will be received by different environmental media and this is recorded in Impact Matrix B', as per the sink functions. The columns of pollutants in this matrix, appropriately weighted, will add to give the total pollutants per environmental theme. The pollutants may also have an impact on life-support functions (e.g. carbon dioxide on climate regulation) and these are recorded in Impact Matrix C'. Pollution may also have impacts on human health and welfare functions (e.g. air quality and respiratory disorders, making places unsuitable for recreation, or reducing visibility of landscapes). These impacts are recorded in Impact Matrix D'.

So far the information system described has simply recorded the impacts of activities of depletion and pollution on different environmental functions. Level 3 of Figure 3 introduces the concept of sustainability.

As noted at the start of this paper, sustainability with reference to human situations is widely recognized to have economic and social, as well as environmental, dimensions. However, the focus of this paper is environmental sustainability, and the economic and social dimensions of sustainability are only considered where they are affected by the use of natural capital. Thus economic sustainability, on the left of Figure 3, is only relevant here insofar as it is affected by the negative impact of human activities on environmental functions. Similarly, on the right of Figure 3, social sustainability is only relevant here insofar as it is affected by the negative impact of human activities on environmental functions for human health and welfare (e.g. the loss of recreation opportunities in the natural environment may lead to vandalism or other antisocial behaviour).

In line with the seven principles of environmental sustainability laid out earlier, it is possible to derive sustainability standards for the use of the Source and Sink functions, and sometimes for the Life-Support and Human Health and Welfare functions. Some of these standards will be locally specific (e.g. critical loads of particular ecosystems); some will be framed in national terms (e.g. air-quality standards for human health); some may be related to global impacts (e.g. carbon emissions consistent with climate stability). These standards may be expressed in terms of state or pressure indicators, where the former shows the minimum threshold of the natural capital stock that is necessary for the function to be maintained, and the latter shows the maximum pressure that the natural capital stock can withstand, while maintaining the function.

The difference between the current situation, the state of the natural capital stock, or the pressure being put upon it, and the sustainability standard, may be described as the ‘sustainability gap’ (SGAP) for that function, as discussed above. SGAPs will be expressed in physical terms and may be interpreted as the physical ‘distance’ to environmental sustainability in relation to the present situation and practices. It is these physical ‘distances’ that indicate that critical natural capital (CNC) is being depleted.

The purpose of the framework of Figure 3 is to enable the actual stock of CNC which is being depleted to be identified, by tracing back the functions to the environmental characteristics from which they derive. The framework also permits the depleting activity to be identified so that policy can be targeted where desired.

Assuming that SGAP does not represent an irreversible effect, it will be possible, through abatement or avoidance activities (for environmental pressures) or restoration activities (for environmental states) to reduce the SGAP such that the sustainability standard is achieved. These activities may have a cost. For every...
(non-reversible) SGAP, therefore, there will in principle be a sum of money corresponding to the least cost, using currently available technologies, of reducing the physical SGAP to zero. This cost, for each function, may be termed the monetary SGAP, or M-SGAP. It may be computed by compiling an ascending marginal abatement (or resource efficiency) cost curve for the technologies which need to be deployed to reach the sustainability standard. Such a curve has become familiar through that for CO$_2$ compiled both globally and for different countries by Enkvist et al. (2007). The purpose of such indicators would be both to suggest targets for public policy, the achievement of which would indicate a situation consistent with environmental sustainability, and to indicate the costs of that achievement, on the basis of current technologies, which is clearly of interest for policy-making.

Because the M-SGAPs for different functions are all expressed in the same unit, it would be convenient to aggregate them to compute an overall Gross SGAP, or G-SGAP, for the economy as a whole. This could then be used to indicate the economic ‘distance’ to environmental sustainability in relation to the present situation and practices. However, it should be noted that in environmental systems non-linearities may be common (see, for example, Ruitenbeek et al., 1999), with the result that the cost of closing an SGAP may not be the simple aggregate of the costs of the different measures that are required, and, if there are interactions between different environmental themes, the total costs of closing SGAPs for a number of themes may not be the aggregate of closing them separately. The difference is similar to that between the partial and total economic estimates is the reason that the G-SGAP would not be the total costs of closing the SGAP even if there were no environmental non-linearities and interactions).

However, with this caveat in mind, and given the communicating power of an aggregate indicator, it may be that the G-SGAP still provides a useful indication of the kinds of investment that will be required in order to close the SGAPs. It may also be noted that G-SGAP will decrease either as the environment improves (reducing the ‘physical’ sustainability gap), or as technologies of abatement, avoidance or restoration become cheaper. Expressed as a ratio, G-SGAP/GDP may indicate the ‘intensity of environmental monetary unsustainability’, comparable to the physical unsustainability intensity mentioned earlier. This would enable the overall environmental impacts of different economies to be compared.

Where environmental policy reduces the SGAP, the environment will change, providing new information for policy-making in the next period. Intertemporal comparisons of the SGAP indicators between periods will give insights into how the indicators in the four different categories are related to each other (see Ekins and Simon, 1999, 2001, 2003, for further discussion of the thinking behind the SGAP concept and details as to how the indicator may be derived).

For some of the Life-Support (e.g. in relation to the population of a certain species in an ecosystem, or to the incidence of human diseases) and Human Health and Welfare (e.g. in relation to the preservation of landscape or the existence of opportunities for environmental recreation) functions it may be impossible to identify a ‘sustainability standard’. It may be that, for some of these functions, their loss would represent a sustainable economic cost (meaning that it represents a loss of welfare, which was presumably outweighed by the benefits of the activity which caused it), rather than an indication of unsustainability (which would be the case if the losses
were irreversible and ran a risk of immoderate losses in the future). Instead of sustainability standards, for these functions Figure 3 would record trends (e.g. in health or sickness). A negative trend would give cause for concern, and if continued long enough might be considered to lead to an unsustainable situation, without any particular threshold of unsustainability being identifiable.

**VIII Conclusions**

The economic valuation of environmental functions is highly problematic because of their non-marginal nature, and the potentially very large costs to which their loss could give rise. Economic valuation is ill suited to issues and circumstances of this sort, which may be better addressed through the definition and attainment of ‘safe minimum standards’ (SMS).

The approach set out in the previous section requires the setting of environmental sustainability standards across all major environmental themes and the generation of data to show whether and to what extent they are being exceeded, and the costs of reducing impacts to the sustainability level. This approach is already being taken in an ad hoc manner for a number of issues, as has been noted. What is now required is its systematic application, and the widespread communication of the indicators that may be derived from it.

This task presents many practical challenges, mainly in terms of data generation, but also in terms of needing to increase understanding of ecosystem functions and processes, especially with regard to the role of biodiversity. However, as the development of climate science and GHG accounting protocols over the past two decades have shown, the sustained application of scientific investigation could enable this approach to be put into practical effect.

Whether human societies will choose to commit the substantial required scientific resources for such investigation, and whether they choose to protect the environment on the basis of the sustainability standards that it suggests, depends on the extent to which they value ecosystems and environmental functions. Values are a moral as well as an economic category, and humans do not generally employ an economic logic in assessing moral values, for example as they relate to friends and family or to such issues as justice, democracy and human rights. However, societies today do not tend to assign ecosystems and their functions much moral value. Currently they tend to be regarded as only having economic value. The evidence at present suggests that societies do not give environmental functions high enough economic values to prevent them being traded off for other benefits, resulting in their inexorable degradation and loss.

It is arguable that generating sufficient political will to resolve the environmental crisis will require recognition that environmental sustainability has both a high moral and economic value. Unless this is achieved it is possible that ecosystems will be eroded to the extent that they can no longer perform the environmental functions needed for large human populations to survive in the long term.

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**Notes**

2. Analysis of this kind is carried out with reference to prices and other economic conditions in an equilibrium. Such analysis is not appropriate where the effects are potentially so large and pervasive that they would fundamentally change this equilibrium, such that a new set of prices and quantities would be established were they to be accounted for.
3. See, for example, the debate between Nordhaus (2007) and Dietz and Stern (2008) about the appropriate discount rate for the calculation of damages from climate change.
4. The MA (2005: 50) ecosystem services are grouped into very similar categories to De Groot’s functional classification: namely (with De Groot’s most similar category in brackets) Supporting (Habitat), Provisioning (Production), Regulating (Regulating), Cultural (Information).

5. See, for example, Stiglitz et al. (2009).


7. It may be noted that this is in fact the way practical policy-making has proceeded in a number of areas. For example, the UNECE Second Sulphur Protocol was intended to reduce depositions of sulphur dioxide across Europe such that no ecosystems would experience exceedance of their critical load (see http://www.unece.org/env/lrtap/fsulf_h1.htm); and the Copenhagen Accord of 2009 (see http://unfccc.int/resource/docs/2009/cop15/eng/107.pdf) acknowledged that emissions of greenhouse gases (GHGs) should be controlled such that the global average surface temperature rise was limited to 2°C. This implies a maximum further emission of GHGs of something less than half a trillion tonnes of carbon (Allen et al., 2009), which in principle could be divided between different countries. Such calculations underpin the sustainability standards in Table 3.

8. It needs to be stressed that environmental sustainability is a dynamic concept. Ecosystems that generate goods and services or functions develop, evolve and go through cycles of buildup, deterioration and reorganization. Hence, the physical ‘distances’ indicated by SGAP may vary both in time and space. Policy-makers need to monitor and understand the dynamics of the ecosystems that generate the flow of goods and services and interpret the SGAP figures accordingly.

References


