# Defining and Identifying Environmental Limits for Sustainable Development

## A Scoping Study

Funded by

# Full Technical Report


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# Contents

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# Executive Summary

If the goals of sustainable development are to be achieved then we need to understand environmental limits and thresholds. In this study we review current scientific thinking on these topics and trace the implications of recent work for policies related to the protection of natural resources and the promotion of sustainable patterns of consumption and production in the UK.

Natural resource systems can provide a range of benefits to people. These include clean and regular water supply, the production of food and fibre, and the protection of communities from hazards. External pressures, such as pollution or over-use, may impact upon natural resource systems and diminish the level or quality of the benefits that they provide. Eventually people may judge that a critical point has been reached, and that the reduction in benefit is no longer acceptable or tolerable. Such a critical level can best be described as an ***environmental limit***. An important goal of sustainable development is to maintain natural resource systems above such limits.

Natural resource systems can respond to increasing external pressures in various ways. Some systems show a gradual decline in the level or quality or benefits they provide. Others show a more rapid change or even exhibit sudden collapse. Our review suggests that when a natural resource system exhibits a rapid 'regime shift', then this may be evidence of the existence of an ***environmental threshold***, marking the boundary between alternative stable states. Water quality in lake systems that are impacted by nutrient input, and marine fisheries suffering over-exploitation have all been found to show this type of behaviour. In these situations it is particularly important to define an environmental limit so we can prevent the pressures upon systems from triggering such a threshold response, because evidence suggests that when thresholds are crossed it may be difficult to restore systems to their former condition.

Although some natural resource systems can exhibit threshold types of response, the extent to which this is commonplace is uncertain. The concept of a limit is therefore more useful generally, since it focuses attention on the possibilities of system collapse and the possibly more widespread, chronic or progressive loss of integrity which natural resource systems may suffer with increasing environmental pressures.

Our review has considered the way in which ideas about limits and thresholds have been developed in relation to ideas about ecosystem health, resilience and ecosystem goods and services. We have also considered how the ideas fit in with contemporary approaches to the valuation of natural assets, and current debates about sustainable consumption and production. The ideas were developed and tested by a detailed review of current issues relating to biodiversity, land use and landscape, recreation, climate change, the marine environment, water supply and demand, pollution loads and soil.

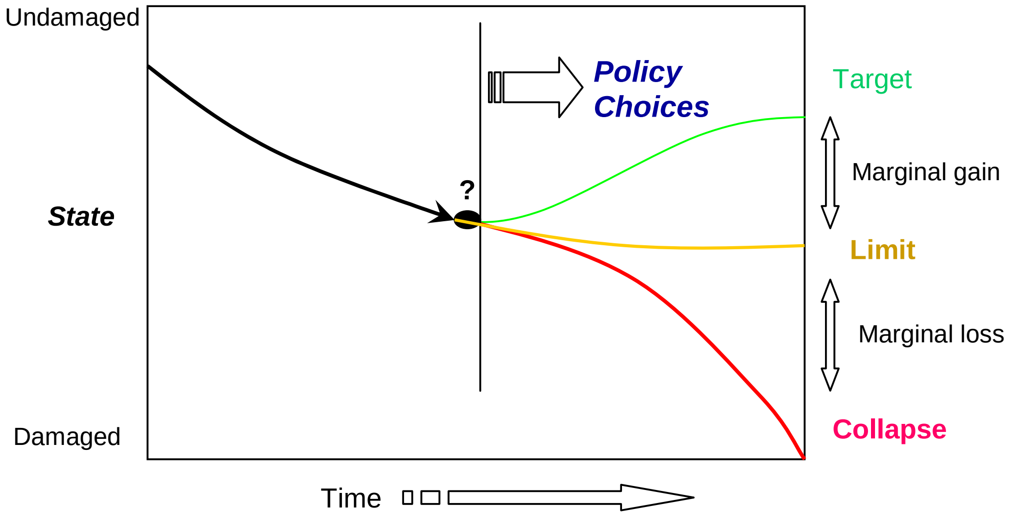
Several key conclusions emerge from the study:

- Although the terms 'limits' and 'thresholds' have been used in different ways in different areas of science, for future policy debates it is important to distinguish between them and to be consistent in the way they are used. We suggest that the notion of an environmental limit is relevant to all natural

resource systems, whether or not they show a threshold response under external pressure. **Limits are most usefully defined in terms of the point or range of conditions beyond which the benefits derived from a natural resource system are judged unacceptable or insufficient**.

- Given natural variability and the uncertainties that exist in our understanding of the behaviour of natural resource systems, it is wise to adopt a 'precautionary approach' to the definition of environmental limits. Thus while we may suggest some final limit beyond which significant harm to the system will occur, notions of wise management might suggest that we should be prepared to sustain the system at some level above this minimum. **Thus different types of environmental limit might be defined**. For example, in the fisheries literature, 'precautionary limits' or 'precautionary reference points' are set to ensure that irreversible harm does not occur to populations of economically or ecologically important species.
- While the identification of an environmental limit is important in terms of resolving questions about the sustainability of a natural resource system, it should not always be used to set management standards. Fundamentally the idea of a limit involves setting a maximum level of damage to a natural resource system that we are prepared to tolerate or accept. In management terms we might prefer to maintain the system in 'good' condition, and therefore specify management targets that are well above the agreed limit. **Thus our study suggests that discussions about environmental limits are part of wider debates about environmental targets**. Identification of an environmental limit can be useful in helping to justify where management targets should be set (See Box 1).

Box 1: Understanding Limits and Values




*Faced with the progressive loss of benefit from a natural resource system, the choice of future policy options will depend on judgements about the maximum level of damage or loss that is tolerable. Justification for the limit will depend on the consequences of exceedence expressed in terms of the marginal losses in benefit from the natural resource system that might occur if the limit is passed. Justification for managing the system at some target level well above the limit of maximum acceptable damage, will depend on the marginal gains in benefit that can be achieved by adopting such a strategy.*

The overall message from the study is that **while the definition of an environmental limit may be based on the biophysical properties of a natural resource system, its identification also depends on the way people value the outputs from it**. Thus if we view natural resource systems in terms of the benefits they can deliver, then judgments about the where a particular limit is set can be based on changes in the marginal value of those benefits, or the assessment of those benefits relative to others that people identify. Additionally, depending on the circumstances, it can be based on the application of ecological or social values. As a result, it is argued that discussion of limits requires the development of deliberative forms of decision making.

**Although the evidence base for environmental limits needs developing across all the thematic areas considered, in most cases there is sufficient understanding to begin discussing what kinds of limits might apply to the protection of natural resources.** We recommend that work should be initiated to develop guidelines for decision makers at national, regional and local scales to help ensure that development occurs within environmental limits. Thus future work on environmental limits should be directed at the scientific and institutional levels.

In relation to the promotion of sustainable patterns of consumption and production, the study also suggests that the general discussion of environmental limits would be helpful in making the case for broadening the suite of ‘decoupling’ indicators used in the UK, and in setting more precisely targets for policy in this area. We suggest that a scoping study is undertaken to determine the feasibility of extending the existing national environmental accounts as a framework for future work.

# Part I: Introduction

## Chapter 1. Context and Aim

### Introduction

1.1. Questions about environmental limits, and their implications for policies related to natural resource protection, have emerged as an important focus in discussions of how the goals of sustainable development might be achieved. The **aim of this study** is to collate and critically review recent developments across the range of discipline areas where these issues have been discussed, in order to:

a. Outline how environmental limits are identified and defined;

b. Assess the robustness of the evidence that underpins the identification of limits;

c. Identify gaps in current understandings of environmental limits;

d. Assess the need for, and feasibility of, collecting new evidence on environmental limits, including where knowledge of existing limits may be out of date;

e. Look at how the evidence used to identify current limits might be collated;

f. Identify current thinking on the application of environmental limits in policy-making; and

g. Identify where further research may be needed to look at how limits could be used in policy making.

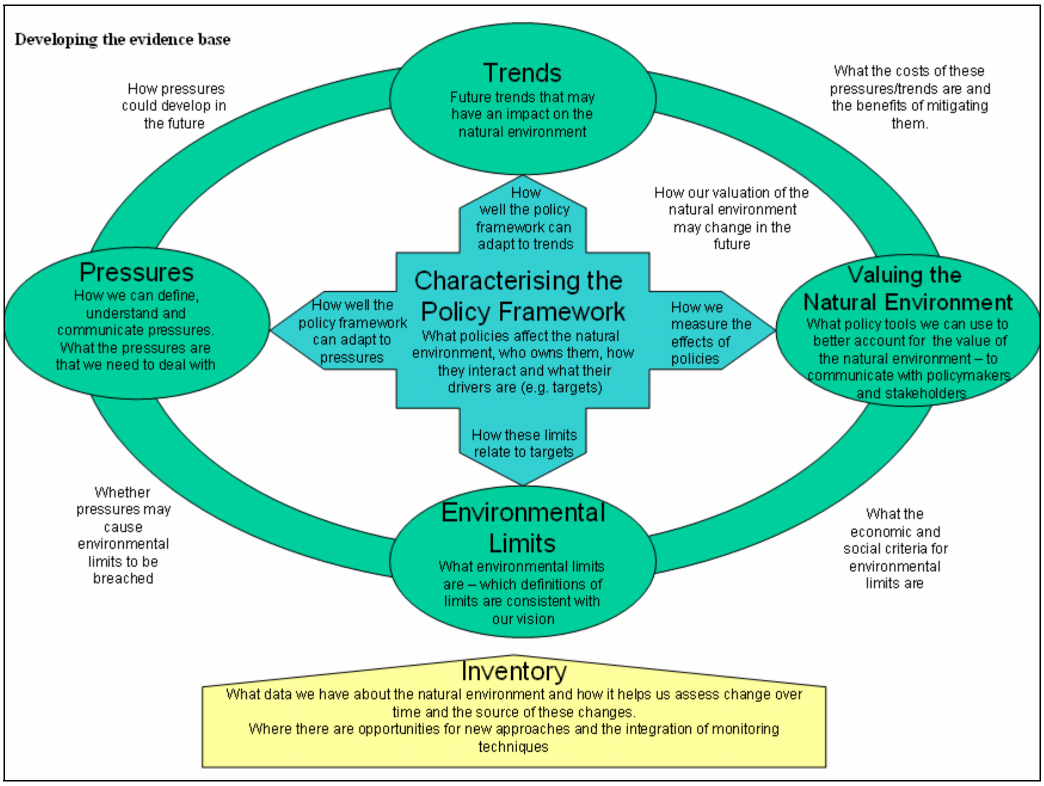
1.2. This study is part of a larger work programme initiated by the UK Department of Environment, Food and Rural Affairs (Defra), which is looking at how to develop the evidence base needed to support a strategic approach to conserving, enhancing and managing the natural environment at home and abroad[1]. The work programme covers issues related to making an inventory of natural resources, the way in which cumulative pressures upon them can be understood, the valuation of natural resources, the analysis of future trends and the examination of current policy frameworks (Figure 1.1).

1.3. The need for this study arose from commitments made in the UK Sustainable Development Strategy to:

- Make a critical review on environmental limits;
- Collate existing research and to identify shortfalls in understanding about where environmental limits exist, and where they are being exceeded; and,
- Conduct a strategic assessment of future research needs in all policy areas.

[1] http://www.defra.gov.uk/wildlife-countryside/natres/evidence.htm

Figure 1.1: The Natural Environment Programme of Defra




1.4. The concerns of the UK Sustainable development Strategy for further work on environmental limits echo those made on a broader international front. The Convention on Biological Diversity, for example, specifically flags the need to develop a better understanding of biodiversity thresholds in relation to ecosystem functioning[2]. The FAO also emphasis the importance of identifying thresholds in their discussion of biodiversity and conservation[3]. The importance of thresholds as a research priority has been emphasised by the EU, through its 6$^{th}$ Framework Programme[4], which support several major integrated projects[5] that seek to develop the concept as one of the tools for sustainability assessment, and the IGBP/IHDP in their recently announced Global Land Project[6].

## Project Structure and Outline of Final Report

1.5. The study undertook two major tasks:

a. The first was a review of relevant scientific literature describing environmental limits and thresholds. The aim was to clarify how the concepts are used, and to trace how the terms link to wider debates about ecosystem health, ecosystem resilience, ecosystem goods and

[2] http://www.biodiv.org/recommendations/?m=SBSTTA-06&id=7036&lg=0
[3] http://www.fao.org/documents/show_cdr.asp?url_file=/DOCREP/005/Y4586E/y4586e06.htm
[4] http://europa.eu.int/comm/research/environment/themes/article_1353_en.htm
[5] http://www.thresholds-eu.org/ and http://www.sensor-ip.org/
[6] http://www.glp.colostate.edu/report_53.pdf

services, sustainable consumption and production and the valuation of environmental assets.

b. The second task involved using the literature review to develop recommendations about how the current ideas about limits and thresholds can assist in the development of policy frameworks related to the protection of natural resources in the UK. The aim here was to identify what gaps in present understandings exist and what research strategies might therefore be appropriate to build the kind of evidence base required.

1.6. The brief for the study was therefore very wide ranging, and so in order that it should focus on Defra's need in this area, the work looked specifically at the key thematic areas covered by Defra's responsibilities in the area of natural resource management, namely:

a. Biodiversity;
b. Water quality, supply and demand;
c. The marine environment;
d. The soil environment;
e. Land use and landscapes (including forestry);
f. Atmosphere, including air quality, green house gas emissions and rates of climate change;
g. Emissions and ozone depleting substances
h. Recreation and access to the natural environment; and,
i. Levels of dispersal of toxic substances and the disposal of solid waste.

1.7. This document is the Final Technical Report arising from this study. In Part II we provide an account of the development of the limits and threshold concepts and their place in wider scientific debates. This material will help in terms of realising the objective for this study, namely to understand how limits and thresholds are identified and defined. In Part III, we consider combinations of the thematic topics listed above, and explore how the limits and threshold concepts have been applied and what evidence there is for their identification in each area. The materials in this section will realise objectives b through d. Finally, in Part IV we make recommendations about how the concepts of limits and thresholds might be developed and applied in a policy context in the UK context, so achieving objectives f and g.

# Part II: Conceptual Frameworks

## Chapter 2. Limits and Thresholds: Definitions

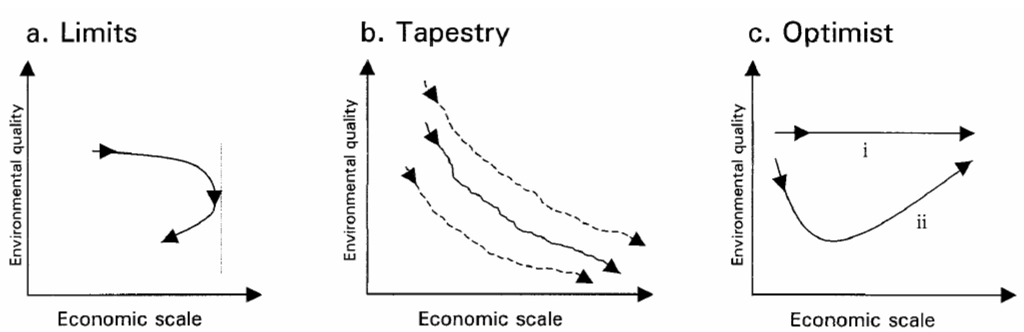
### What is an environmental limit or threshold?

2.1. The recent discussions about environmental limits and thresholds are part of a much longer and wide-ranging debate about the extent to which human development can be maintained in the light of supposed environmental constraints. Going back to the late eighteenth century, for example, Malthus (1798) considered the limiting relationships between population growth and food supply. In the twentieth century discussion of resource constraints was stimulated by the publication of "Limits to Growth" (Meadows et al., 1972) which argued that in a finite world, economic expansion could not be sustained indefinitely. Most recent notions of limits have been framed around the ideas of "ecological footprints" and "sustainable patterns of consumption and production", both of which imply that there are limits beyond which certain types of growth and development are not sustainable.

2.2. The existence and implications of any limits set by the environment on natural resource use or economic development is, however, hotly debated (Sagoff, 1995; Lomborg, 1998). In a recent review of the 'Limits' paradigm, for example, Davidson (2000) usefully contrasted the idea with two other 'metaphors' describing the possible relationship between economic growth and environmental quality (Figure 2.1), namely the 'Tapestry' and 'Optimist Models'.

2.3. In the diagrammatic representation of the alternative paradigms suggested by Davidson (Figure 2.1), 'Economic scale' is the driving variable; it represents a level of resource use and waste production. 'Environmental quality', the dependent variable, is an aggregated measure of 'diversity, resilience, and aesthetic, recreation, refuge, and ecosystem service values to humans'.

Figure 2.1: Alternative paradigms describing the potential relationship between change in economic scale and environmental quality (after Davidson, 2000).



2.4. A contemporary and widely discussed formulation of the ‘Limits’ paradigm was provided by Erlich and Erlich (1981), who used the so-called ‘rivet’ hypothesis to describe what they envisaged the impact of increasing economic scale on environmental quality to be. Each act of environmental destruction, they suggested, was like a rivet being pulled from an aircraft’s wing. At first, with the removal of the first few rivets, nothing happens. Eventually, when enough rivets have been removed, the wing collapses. Figure 2.1a therefore represents the ‘Limits’ paradigm, with its essential characteristic of abrupt catastrophic change at some upper or bounding level of economic scale which undermines the integrity of essential natural resource systems (shown by the dotted line in Figure 2.1a).

2.5. By contrast, the ‘Optimist’ paradigm (Figure 2.1c) argues that there is either no relationship between increasing economic scale and loss of environmental quality (Figure 2.1c, curve i), or that initial losses of quality can be ‘made good’ as affluence levels or technological competence increases in the longer term (Figure 2.1c, curve ii). These are a number of different formulations of this model, which need not be described in detail here; the essential point about them all is that they envisage that human inventiveness can decouple or mitigate the impacts of economic development on the environment, and in support of their arguments, they point to the fact that the catastrophic predictions of Malthus (1798), Meadows et al. (1972) and others were never realised, largely as a result of technological advances.

2.6. Against the two extremes of the ‘Limits’ and ‘Optimist’ paradigms, Davidson (2000) suggests a third metaphor, namely the ‘Tapestry’ model. According to this idea there is certainly a relationship between increasing level of economic scale and environmental quality, but the changes are gradual (Figure 2.1b). Davidson (2000) likens them to removing threads from a rich tapestry:

> *Each small act of destruction … is like pulling a thread from the tapestry. At first, the results are almost imperceptible ….If too many threads are pulled … the tapestry will begin to look worn and may tear locally* (Davidson, 2000, p. 444).

2.7. The essential characteristics of the ‘Tapestry’ model are that change is gradual rather than sudden, and that at no point is there catastrophic collapse, only the inexorable loss of environmental quality or function. Intervention or amelioration is, however, possible, as indicated by the dashed lines in Figure 2.1b, which represent different socioeconomic arrangements to the solid line. Thus, according to Davidson (2000) ‘at any economic scale there may be different levels of environmental quality, depending on the structure of production and consumption’.

2.8. Davidson’s metaphors are useful, but as with all caricatures of reality, they have shortcomings. All three models are, for example, likely to be found in the real world, given the different ways in which natural and human resource systems are coupled. Furthermore, even though model 1a seems to be the only one that implies some kind of limit, clearly the notion that there are critical or unacceptable levels of degradation are also be highly relevant in the contexts of both the 'tapestry' and 'optimist' models. How far should environmental quality be eroded before action is taken either to prevent further loss or to set in place strategies to decouple and revise further impact? In fact, Davidson's Limits model would be better described as in terms of a 'Collapse' scenario, thereby freeing up the notion of limits and thresholds to be discussed in a much wider context.

2.9. Our literature review confirms that while the concepts of environmental 'limits' and 'thresholds' have been widely discussed, the ways in which the terms have been used is not consistent across the different fields. In some areas, for example, the terms are used as synonyms, while in others they denote quite different sets of ideas. It is therefore important for this study to be clear about definitions.

**Critical points and limits**

2.10. A common idea across many of the fields reviewed by this study is that notion that when we look at the capacity of a natural resource system to deliver functions or benefits to people, there is a ***critical point or zone*** at which the benefits obtained may fall below some acceptable or tolerable level. That point may arise because:

a. The pressures upon the natural resource system may damage its capacity or integrity, so that further benefits cannot be delivered; or

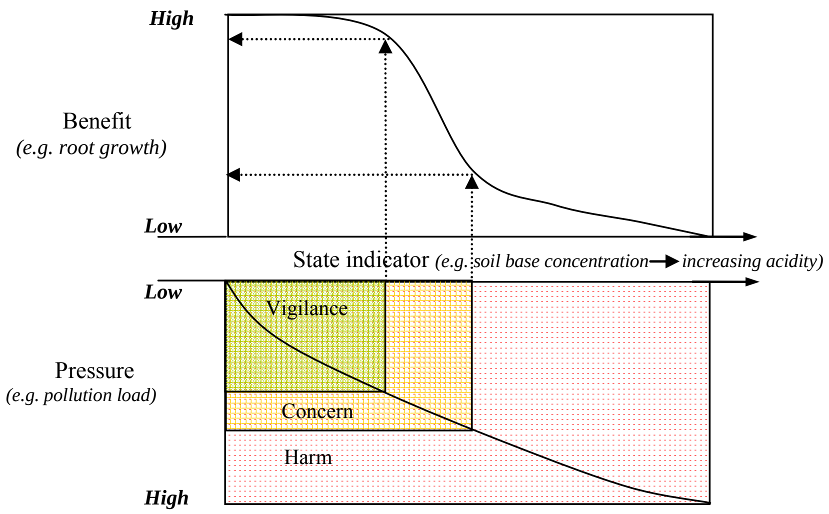
b. That while the system remains functioning, the level of benefit is judged to be unacceptable.

2.11. Depending upon the subject area being considered, that critical point or zone might be described as a 'critical load', when referring to the level of pollution by atmospheric deposition beyond which an ecosystem is damaged, or a 'limit reference point', when describing the level of fishing intensity that would damage the capacity of a stock to sustain itself. **In this study we suggest that all such critical points or levels are described as *limits***. This position is consistent with the views expressed by the *Royal Commission on Environmental Pollution*[7] in relation to the different types of standard that may be identified.

2.12. Figure 2.2 describes how the notion of a limit can be represented and qualified by means of two linked graphs. It builds on the idea that we can represent the state of the natural resource system by an indicator (e.g. soil base concentration or acidity) which is causally related to some external pressures (e.g. pollution load). The impacts of these pressures are often judged by means of an indicator that describes the level of benefits that people derive from the resource (e.g. vitality of root growth, which may impact upon ecosystem productivity or structure).

[7] Royal Commission on Environmental Pollution, Environmental Standards and Public Values, A summary of the 21st report on *Setting Environmental Standards.* http://www.rcep.org.uk/pdf/standardssummary.pdf

Figure 2.2: Relationships between pressure, state and the output of benefits in a natural resource system




There are several important features to note in Figure 2.2:

a. That the relationship between pressure and benefit can be 'non-linear', that there is not necessarily a constant reduction in benefit as pressure increases. Over parts of the range the benefit may be quite insensitive to changes in pressure; in other parts more rapid changes in benefit might be detected.

b. That while both pressure and benefit limits can be defined, they are not independent of each other. Judgements about the level of allowable pressure are determined by resolving the question of what is an acceptable or tolerable level of benefit.

c. That exceeding of a limit does not necessarily result in system collapse, but also conditions beyond which further damage to the resource is judged as unacceptable. Given the uncertainties involved in making such judgements, the limit might in fact be a range of conditions where concerns become significant, even though in practice we might identify or communicate this limit by setting a particular value.

2.13. The model shown in Figure 2.2 can be refined in many ways to accommodate the complexities of the real world. For example, it can be recognised that because decisions about limits may be uncertain, it is appropriate to adopt a more precautionary approach so that a safety margin can be built into the considerations. Thus in Figure 2.2, zones of 'vigilance', 'concern' and 'harm' have been included. The boundaries of these zones are defined by 'precautionary limit' and the 'environmental limit'.

2.14. In some literatures, the precautionary limit is referred to as the '**safe minimum standard**' (Barrens et al., 1999). Above it, in the zone of vigilance it is wise to monitor integrity of the natural resource system, but exploitation is considered largely unproblematic. Although decisions about the position of the precautionary limit are often a matter of judgement, essentially it marks the point at which it is accepted that corrective action is needed. In the zone of concern, the urgency of the action is determined by how close the system is to the environmental limit. The latter marks the point at which tangible harm to the natural resource system has occurred.

### Thresholds and regime shifts

2.15. The discussion presented so far has avoided using the term 'threshold' because, while it can be used as a synonym for 'limit', in some discipline areas it covers other ideas which are important in their own right. We will focus specifically on the problem of 'non-linear responses'.

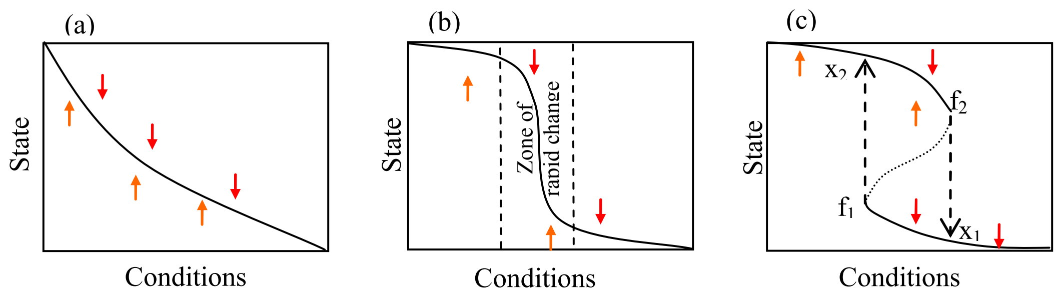
2.16. The existence of non-linear responses has been mentioned briefly in context of the model shown in Figure 2.2, where it was noted that, for the example given, the change in level of benefit was initially rather insensitive to changes in the state of the system, until a certain point was reached, after which a more rapid transformation occurred. Simple, non-linear responses of this kind are found when there is not a constant (linear) relationship between either the pressure variable and system state or between system state and level of benefit. In the real world, however, it is apparent that systems can exhibit more complex types of non-linear response than those shown, and it is with these that the term 'threshold' is often associated.

2.17. Recent reviews of threshold concepts in ecology have been provided by a number of commentators, including Beisner et al. (2003), Luck (2005), Ludwig et al. (1997), Muradian, (2001), Scheffer et al. (2001), Scheffer et al. (2003), Scheffer and Carpenter (2003), and Walker and Meyers (2004). Although the notion of thresholds has long been discussed, many trace current thinking to work such as that of Holling (1973), and May (1977). Holling's paper on resilience stimulated the exploration of the ways in which ecosystems could absorb and respond to disturbance, while that of May dealt with thresholds, breakpoints and multiple equilibrium states.

2.18. Figure 2.3 shows a range of different types of causal relationships that might exist between pressure and state. In each case the line represents the point of equilibrium between a given level of pressure and the resulting state of the system. If disturbed, the assumption is that the system will return to this equilibrium value. Systems, as noted above, can thus respond in a smooth or linear way to a change in external conditions or pressures (a), or show a more variable pattern of sensitivity (b). The important point to note in relation to the both models is that there is a 'one-to-one' relationship between pressure and state, so that when, for example, pressure is relaxed the system will move to the same state observed previously at the lower pressure level. In contrast to situations (a) and (b), system (c) illustrates a more complex type of dynamic, where sudden or 'catastrophic' change can occur.

2.19. Consider the dynamics shown in Figure 2.3 (c). Starting at point $x_1$, a change in the pressure variable alters the state of the system gradually until point $f_1$ is reached, whereupon there is a sudden jump to the state represented by point $x_2$. Moving in the opposite direction from $x_2$, the system would flip at point $f_2$ back to the conditions represented in point $x_1$. Systems with behaviour (c) are often said to show 'hysteresis'. Points $f_1$ and $f_2$ are known as bifurcations, and the dotted line joining the marks the boundary between two different 'domains of attraction'. These are represented by the small arrows indicating the direction in which the system would move if displaced to that point by some disturbance.

Figure 2.3: Three contrasting system responses to changed external conditions



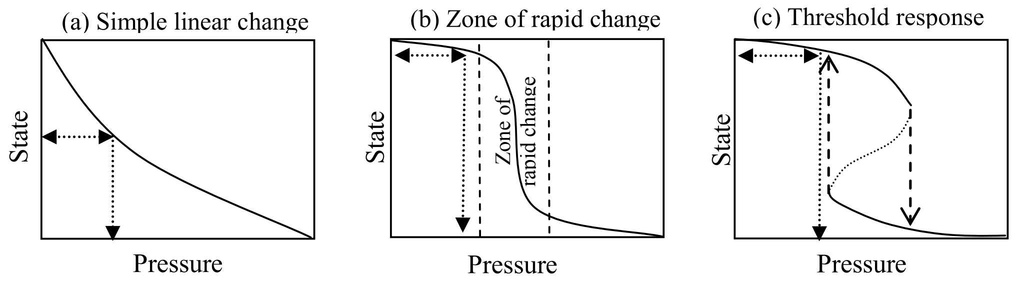

Each graph plots the way the equilibrium environmental state changes in relation to some controlling variable. The ↑↓ indicate the direction in which the system would move if disturbed from the equilibrium line.

2.20. For many ecologists[8] (e.g. Scheffer et al., 2001; Scheffer et al., 2003; Walker and Meyers, 2004)) systems showing the types of behaviours illustrated in (c) are said to exhibit a '**threshold response**'. The key point these authors make is that, unlike systems (a) and (b) in Figure 2.3, for (c) there is a range of conditions for over which **two** stable states can occur, and the one which one prevails depends on the 'path history', that is the trajectory by which the system approached that point.

2.21. The distinction between the three situations illustrated in Figure 2.3 can be illustrated by considering the case of shallow lakes, subject to human induced eutrophication. Scheffer et al. (2001) for example, suggest that the 'pristine' state of shallow lakes is normally one with clear water and the presence of submerged vegetation. If there is increased nutrient input, then at first the clarity of the water is hardly affected. However, beyond a certain nutrient threshold the lake shifts from a clear to a turbid state, and under such conditions the submerged plants disappear, as algal booms reduce light levels. Interestingly, if nutrient inputs are subsequently reduced, clear water conditions are not restored until lower concentration levels are achieved than those which triggered the shift to turbid conditions in the first place. This hysteresis effect is, according to Scheffer et al. (2001) brought about by a range of ecological mechanisms that prevail under each regime (clear vs. turbid), which make each of the alternative states self-stabilising.

[8] This is a position particularly associated with the group known as the 'Resilience Alliance', see http://www.resalliance.org/ev_en.php?ID=1_201&ID2=DO_ROOT

Figure 2.4: Limit and Threshold Identification




In each case the dotted lines represent some kind of limit beyond which system is judged to be damaged or at risk.

2.22. The implications of the different types of response shown in Figure 2.3 are important:

- In situations (a) and (b), assuming that the level of the pressure variable can be manipulated, then a target state can be achieved and any disturbances will re-establish the equilibrium state for that point.
- In situation (c), when the system is at a point close to one of the bifurcations then even a small disturbance may cause the system to flip to the alternate state, and it may be that much additional management input is required to restore it to the former condition. In some circumstances it could be that no 'reverse shift' can be engineered, even if pressure ameliorates. In this case, the bifurcation represents a 'point of no return'.

2.23. Although the existence of thresholds that separate alternative stable states may be significant for the way we approach the management of natural resource systems, it is clear that the idea of limits cannot be applied exclusively to systems showing these kinds of dynamic. For example in Figure 2.4 although system (a) does not exhibit a regime shift, and is therefore not formally associated with any kind of threshold, increasing environmental pressure may eventually reduce benefits to an unacceptable level so that a limit may be defined (cf. Barrens et al., 1999). Similarly, in situation 4(b), the 'zone of rapid transition' may mark the boundary between states that have fundamentally different implications for the people or organisms that are affected by them, so that we would not want this zone of transition to be crossed. Once again a critical level or limit might be identified. This is the position advocated, for example, by Huggett (2005) and Radford and Bennett (2004), and is implicit in the way the critical loads concept is applied (see Chapter 11). Finally, all situations may eventually lead to a point of no return if the system collapses.

### Defining key terms

2.24. On the basis of the discussion presented above, it therefore seems necessary to apply the terms 'limits' and 'thresholds' carefully, and certainly not without some qualification to convey precisely what is implied. It would also seem that while some commentators have done so, they should ***not*** be used as synonyms. Thus we suggest that:

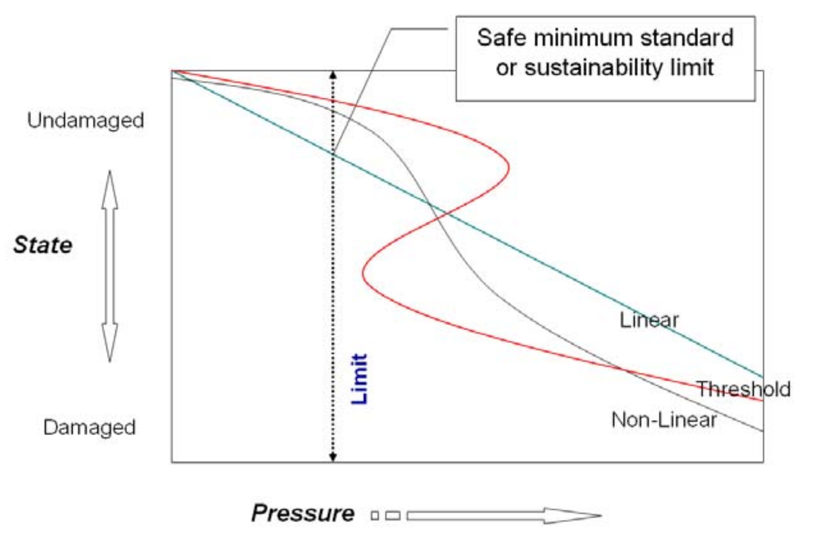
- The term **limit** is used to refer to the level of some environmental pressure, indicator of environmental state or benefit derived from the natural resource system, beyond which conditions which are deemed to be unacceptable in some way. The term can be applied irrespective of the type of dynamic exhibited by the system (linear response, simple non-linear response, threshold response).
- The term **threshold** is reserved to describe situations in which a distinct regime shift between alternative equilibrium states exists, which may or may not be reversible.

2.25. Furthermore, we suggest:

- The term **non-linear response** is used to describe any system in which the relationship between an environmental pressure and the resulting change in system state is not constant in its effect. A threshold, separating alternative stable states is merely one type of non-linear response. The term '**tipping point**' can be used to identify the boundary of the zone where a rapid change in state may occur.
- Different types of limit may be defined in order to cope with the risks associated with loss of ecosystem function or benefit, such as a '**safe minimum standard**', a '**precautionary limit**' or a '**precautionary reference point**'.

2.26 Used in this way, therefore, the term limit is more equivalent to the idea of a 'safe minimum standard' or 'sustainability limit', which indicates a boundary that we judge as unacceptable or dangerous to cross irrespective of the type of response that the natural resource system shows to increasing environmental pressures (Figure 2.5).

Figure 2.5: Relationship between thresholds and limits and different types of system response to environmental pressures.



# Chapter 3. Identifying Limits and Thresholds

## Introduction

3.1. Although it is important to clarify the different ways in which the terms 'limit' and 'threshold' are used, the more fundamental task for this study is to explore how actual limits and thresholds might be identified and justified. In this Chapter, we therefore compare and contrast some alternative conceptual frameworks that can assist in this task. The frameworks explored are those associated with notions of 'ecosystem health', 'ecosystem resilience', 'ecosystem goods and services' and 'sustainable consumption and production'.

3.2. The review task is a challenging one, because the topic areas that we have been asked to think about are varied and have different relationships to the organisational frameworks to be considered. Nevertheless, it is possible to identify a clear message from the materials examined. We will argue that the identification of limits, and by implication the way we deal with potential thresholds, cannot be determined solely by an understanding of the biophysical structure of the natural resource system itself. Rather, to define limits we must focus on natural resources as part of 'coupled social-ecological systems' and explore the way people view the potential benefits that these systems can deliver. We will suggest that the frameworks dealing with ecosystem goods and services and patterns of sustainable consumption and production are currently the most useful for taking the discussion of environmental limits and thresholds forward in the UK.

### *Ecosystem Health*

3.3. Raffaelli et al. (2004) have recently provided an extensive review of the topic of 'ecosystem health', and suggested that while many different definitions exist, there are a number of shared common elements. These include

- the capacity for 'self-organisation';
- signs of structural integrity;
- the lack of 'ecosystem distress';
- resistance to disturbance; and
- the ability to recover after perturbation.

Thus, following Costanza (1992), Rapport et al. (1999) asserts that:

> *An ecological system is said to be healthy and free from "distress syndrome" if it is stable and sustainable – that is if it is active and maintaining its organisation and autonomy over time and is resilient to stress (Costanza, 1992, p.9).*

3.4. The discussion of ecosystem health is of interest for the present study because the concept clearly embodies the proposition that there is some limit beyond which the integrity or functioning of an ecological system can become so damaged that it cannot easily or quickly recover. However, given the availability of the review by Raffaelli et al. (2004), it is not necessary to describe the concept in further detail here. Rather, it is more appropriate to build on their work and consider some of the messages that arise from both their study and other recent literature dealing with the concept of ecosystem health.

3.5. An important conclusion that can be drawn from the ‘ecosystem health’ concept is that although it is an attractive idea, a review of progress in the field suggests that ***fundamentally it remains a metaphor***. Much of the discussion surrounding it is theoretical in character, with discussion drawing on empirical studies to illustrate rather than to test key propositions. The paradigm is limited as a practical tool because, while it stresses the importance of understanding what makes ecological systems resilient to disturbance, it provides few guidelines that can be used to predict how real systems will behave or where the limits actually are.

3.6. As the reviews of Raffaelli et al. (2004) and others (Rapport, 1999 and Wilcox, 2001) demonstrate, when people attempt to operationalise the notion of ecosystem health, they generally resort to the identification of indicators. The difficulty they face is that since the concept of ecosystem health is such a broad one, there is no agreed set of indicators that can be used to assess it. Thus, since virtually any ecosystem parameter can be used to represent ‘ecosystem health’ it is hard to see what we actually achieve by accepting the metaphor. The paradigm provides few guidelines, for example, to suggest how limiting values for these indicators can be specified, or to explain what kinds of structures make some systems more resilient to disturbance than others.

3.7. Lackey (2001) provides a critique of the concept of ecosystem health, which builds on earlier discussions of Sueter (1993), Wilkins (1999) and others. The problem with operationalising the concept of ecosystem health is that it assumes that ecosystems are discrete entities like organisms, rather than abstractions imposed on nature by the human mind. Thus, ecosystems, Lackey (2001) suggests, are ‘context-specific entities’ which cannot be identified ‘without a science or policy concern’. As Sueter (1993) has argued, the notion of an ecosystem may some have ‘heuristic problem solving value’ but it is not ‘analogous to the patient in medicine’.

3.8. If we cannot be precise about where the boundaries of an ecosystem are, then the critics of the ecosystem health paradigm would suggest that it is not possible to specify in advance what conditions might constitute the ‘health’ of the system and therefore how one might measure it. The difficulty of assessing ecosystem health is, in fact, acknowledge by Raffaelli et al. (2004) who argue that the concept has concentrated too much on the ecological component of ecosystems, with the actions of people simply viewed as some external driver affecting the integrity of the system. They argue that a broader analysis of socio-economic context is needed to capture the complexity of real world situations, and argue for a new approach based on the analysis of social welfare or utility.

3.9. As implied above, Lackey (2001) and other critics of the ecosystem health paradigm also argue that the specification of what constitutes a 'healthy ecosystem' is not value free, and that an explicit recognition of societal values is important in framing possible policy strategies. While advocates of the ecosystem health concept also acknowledge the importance of understanding public values (e.g. Rapport 1999, Wilcox, 1999) this does not, unfortunately, overcome the problem of where the boundaries of any coupled ecological-social system might lie, or how its dynamics and the threats to its integrity can be characterised in terms of any analogy with 'health'. Moreover, by moving the debate on from 'natural' systems, whose structures are disturbed or disrupted by human action, to systems in which people are fundamentally a part, notions of 'reliance' and 'integrity' are expanded to include social and economic criteria that go far beyond anything that can easily represented as fundamental parts of 'ecosystem structure'. **We conclude therefore that presently the concept of ecosystem health has little to offer in terms of understanding where the environmental limits or thresholds might lie.** In the sections that follow we explore alternative organisational frameworks.

### Thresholds, Resilience and Coupled Socio-Ecological Systems

3.10. The need to consider the coupling of social and ecological systems has been identified as an urgent priority by a number of organisations. The recently announced 'Global Land Project'[9] (GLP), for example, which is a joint initiative promoted by the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP), takes as its starting point the proposition that it is possible that there is some limit or threshold at which the Earth System (which includes all its biophysical, economic, technological and societal elements) can no longer absorb the impact of human activity, and that this represents the 'sustainability limit'. The sponsors observe, however, that on the basis of current knowledge, we cannot say where such a limit lies, and propose that the Global Land Project should investigate the problem from a 'land-systems perspective'.

3.11. Initiatives such as the GLP indicate that international research agendas are now developing a broad interdisciplinary conceptualisation of the threshold and limits problem. This trend is also illustrated by the way in which the characterisation of thresholds and resilience first formulated in the systems literature have developed from ones which focus mainly on the structure of ecological systems to include social, cultural and economic dimensions. For some (e.g. Folke et al., 2002) this development is so significant that resilience has become a 'conceptual foundation' for sustainable development.

3.12. Discussions of resilience are closely linked to the identification of threshold responses, because the former deals explicitly with the properties of systems that make them resistant to disturbance, while the latter is put forward as a consequence that the mechanisms which promote resilience have been overcome. Broadly, resilience is the capacity of a system to absorb shocks

[9] http://www.glp.colostate.edu/report_53.pdf

while maintaining function (Walker et al., 2004). For Folke et al. (2002) it also includes the degree to which the system is capable of self-organization; and, the extent to which the system can build capacity for learning and adaptation.

3.13. In order to begin to understand what properties of 'coupled social-ecological systems' might promote resilience, Walker and Meyers (2004) have developed a database of systems that exhibit at least two distinct alternate regimes (i.e. which demonstrate a threshold response). Using the typology shown in Figure 3.1, 97 case studies have been described using the criteria shown in Table 3.1[10].

Table 3.1: Criteria used to classify threshold responses in coupled social-ecological systems (after Walker and Meyers, 2004)

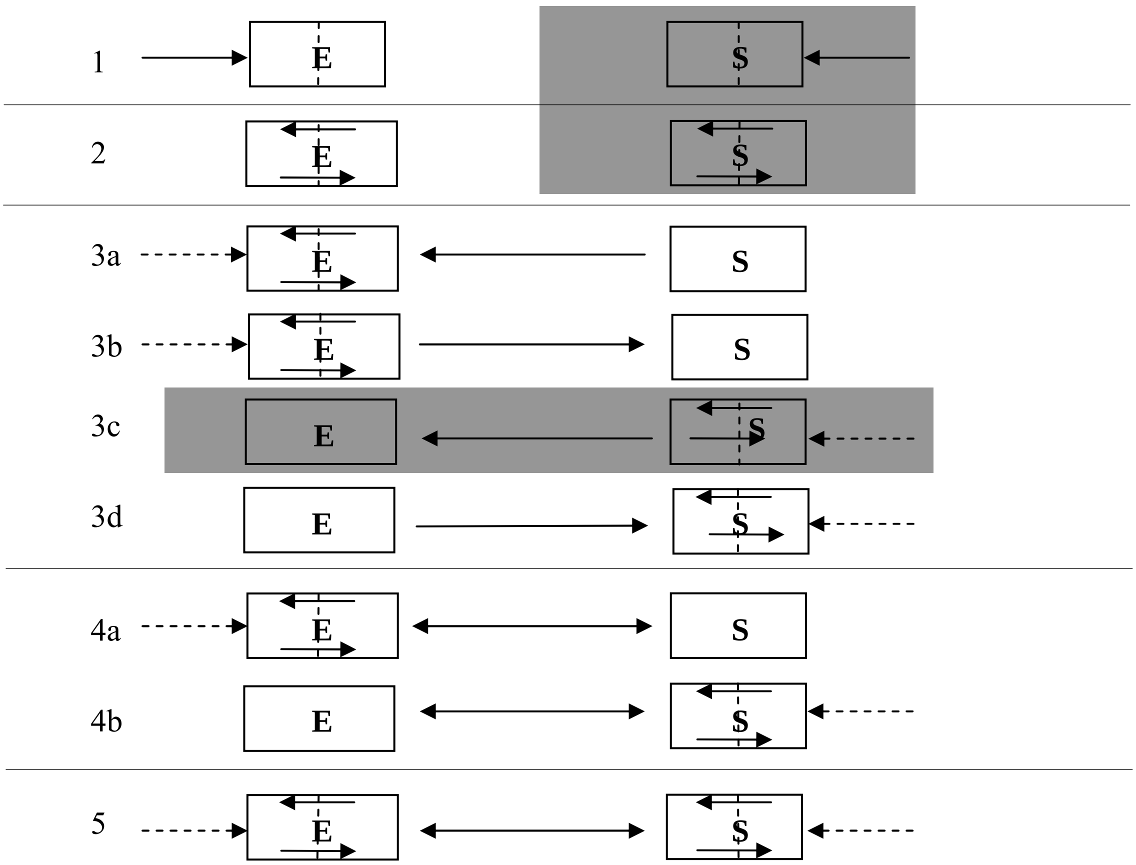
| | |
|---|---|
| Title of Example | Short title including description and location of the shift |
| Certainty of shift | Proposed or demonstrated |
| Location | Detailed location of the example |
| System type | Social–Ecological, Ecological or other |
| Ecosystem type | Ecosystem type either where the change of state has occurred, or that is linked to the changed social state (e.g., forest) |
| Type of resource use | Primary use of the resource (e.g., livestock production) |
| Ecosystem services | Benefits that people derive from the ecosystem (e.g., food, water) |
| Resource users | Agents who use the ecosystem services (e.g., subsistence farmers, fishers) |
| Ownership and user rights | Type of ownership of the resource, or the rights of the users |
| Spatial scale | Scale at which the shift has occurred |
| Number of possible regimes | Number of alternate regimes in the example |
| Time scale of change | Time taken for the shift to occur |
| Reversibility | Reversibility of the state shift (e.g., irreversible, reversible with hysteresis) |
| Background | Information relevant to the example (e.g., site description, history) |
| Rules | Laws, regulations, norms or taboos that led to the regime shift |
| Alternate regimes | Alternate regimes of the system |
| Fast or dependent variable(s) | Variables of concern that are radically altered during the shift (e.g., species composition, productivity) |
| Slower or Independent Variable(s) | Variables that lead to the shift and define the position of the threshold (e.g., phosphorus concentration) |
| Disturbance or threshold trigger(s) | Variables that trigger the changes in the Slower or Independent Variables (e.g., climate change, market forces) |
| External / Internal Trigger(s) | Are the triggers external drivers or internal processes? |
| Mechanism | Process by which the triggers, fast/dependent variables and slower/independent variables interact to effect the shift |
| Management decisions in each regime | Relevant management or policy decisions, including incentives, subsidies, sanctions, and monitoring of the resource and resource users |
| Reference(s) | Full references and codes for the type of evidence presented |
| Keywords | Keywords to aid searching |

[10] http://www.resalliance.org/

Figure 3.1: Threshold Database: Regime Shift Category Descriptions and Diagram (after Walker and Meyers, 2004)

All of the possible interactions between social (S) and ecological (E) systems in relation to threshold shifts. Systems that have undergone a threshold shift to an alternate regime are split with a dashed line. The arrows within the boxes indicate that feedback mechanisms operate within the system. The arrows connecting the social and ecological systems show the direction of interaction between the systems in the development of regime shifts. Dashed arrows indicate that external influences may or may not contribute to the regime shift. The shaded categories are not included in the database, but are shown here for completion.

1: Externally driven shift in ecological system; no interaction with society.
2: Internally driven shift in ecological system; no interaction with society.
3a: Society drives a shift in ecological system; no feedback to society.
3b: Shift in ecological system impacts on society (but no shift).
3d: Ecological system drives a shift in social system; no feedback to ecosystem.
4a: 2-way interaction between ecology and society; shift in ecological system only.
4b: 2-way interaction between ecology and society; shift in social system only.
5: 2-way interaction between ecology and society; shifts in ecological and social systems.



3.14. On the basis of a review of the first 64 case studies that were entered onto the thresholds database, Walker and Myers (2004) note that while more examples need to be considered, some preliminary conclusions can be drawn, namely:

a. That neither thresholds nor resilience are constant properties, and that the extent to which resilience changes as thresholds appear is unknown;
b. That although systems exhibiting both reversible and irreversible regime shifts were examined, no system attributes could be identified that would enable the type of threshold behaviour to be predicted;
c. Changes in scale appear to influence resilience and the positions of thresholds;
d. That as thresholds are crossed different types of feedback are observed within the system depending on which regime prevails;
e. That regime shifts can be triggered by external shocks or by gradual change in some controlling variable;
f. That management difficulties often arise because the possibility of threshold responses are unexpected or ignored; and,
g. The consequences of crossing a threshold are context dependent, in that they are determined by what people judge the significance of the regime shift to be in a particular situation at a particular time

To this list we may also add the rather disappointing conclusion of Carpenter et al. (2005) that in practical terms, the only sure way to identify a threshold is to cross it. A further problem that this analysis of thresholds poses is that it tends to narrow the discussion of resilience down to issues surrounding what might trigger a regime shift. The discussion overlooks the fact that questions about resistance to disturbance from equilibrium are also relevant to systems that do not show such multi-state behaviour.

3.15. Work such as that of Walker and Meyers (2004) is important because it grounds theoretical ideas about resilience and thresholds on empirical data. Scheffer and Carpenter (2003) also recognise the importance of linking theory to observation, and have suggested a number of lines of evidence that can provide 'hints' of alternative stable states. **However, despite these efforts, we are still a long way from any clear generalisations about what makes one system more resilient than another, or where the limits of resilience in a given system may lie.** As Carpenter et al. (2001, p941) note in order to understand a system's resilience it seems 'one must specify which system configuration and which disturbances are of interest'.

3.16. Carpenter et al. (2005) have acknowledged that direct measurements of resilience in social-ecological systems remain difficult, and suggest that in order to make progress we must search for indirect measures or 'surrogates' through such strategies as stakeholder assessments, model exploration, historical profiling and case study comparison. Following Folke et al. (2002), Carpenter et al. (2005) also argue that in the context of social-ecological systems, appropriate resilience building measures will include promoting social and economic structures that allow adaptive or flexible approaches to the management of environmental systems. Such claims about the importance of social and institutional context for understanding resilience echo those who have sought to describe what is meant by ecosystem health.

3.17. **From our review of the recent literature we therefore conclude that despite its promise, the notion of *resilience* presently has little to offer in terms of any secure, general understanding how environmental limits or thresholds might be identified, or what makes one system more resistant to disturbance than another.** What is equally clear, however, is that some kind of framework for understanding the linkage between environmental and social systems is required if we are to begin to manage natural resource systems in a sustainable way.

## The Millennium Assessment and the Concept of Ecosystem Goods and Services

3.18. The concept of 'ecosystem goods and services' is the third framework through which we explore how environmental limits and thresholds might be defined and managed, and in particular how one might understand the linkage between social, economic and ecological perspectives.

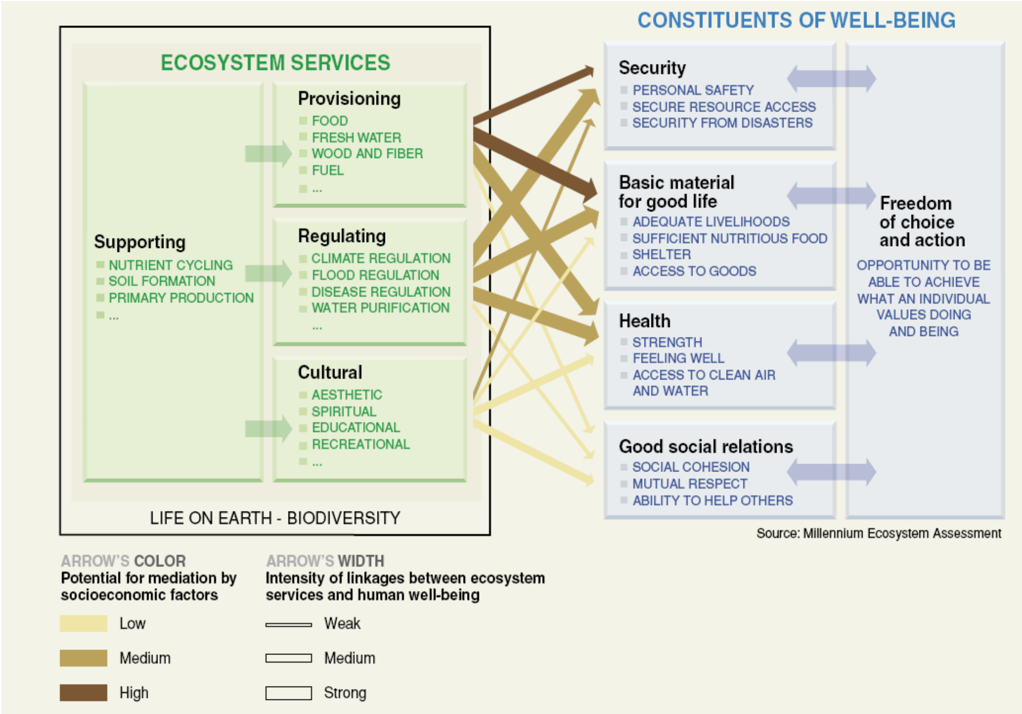
3.19. The notion that ecosystems can generate goods and services grew out of the idea that ecosystems and the biological diversity contained within them can provide a stream benefits to people. Following Mooney and Ehrlich (1997), Cork et al. (2001) trace the development of the concept to the 1970 report Study of Critical Environmental Problems (SCEP, 1970), which first used the term '*environmental services'*. Holdren and Ehrlich (1974) went on to refine the list of services originally proposed, referring to them as '*public service functions of the global environment'*. Westman (1977) later reduced this to '*nature's services'* and finally the term '*ecosystem services'* was used by Ehrlich and others in the early 1980s (Mooney and Ehrlich, 1997). The current status and application of the concept is described in the recent work of Daily (1997), the collection of papers edited by Costanza and Farber (2002), the WSTB (2004) and the Eftec (2005) Report on the valuation of ecosystem services commissioned by D*efra*.

3.20. Notwithstanding the literature that has grown up around the topic, there is now more widespread interest in the concept of ecosystem goods and services as a result of the recently published 'Millennium Ecosystem Assessment'[11] (MA). This international initiative, which has been based on contributions of over 1300 researchers over a five year period, is central to current debates about nature-society relations, and in particular the way the environment is valued.

3.21. The most recent publication generated by the MA, '*Living Beyond Our Means: Natural Assets and Human Well-being'*, the MA Board (MA, 2005a) provides a conceptual map of the relationships between ecosystem functions and the benefits people and societies derive (Figure 3.2).

[11] http://www.millenniumassessment.org/en/index.aspx

Figure 3.2: Linkages between Ecosystem Services and Human Well-being (MA, 2005a)




Four major categories of benefit are identified, namely:

i) Supporting functions, such as nutrient cycling, soil formation and primary production;

ii) Provisioning functions, such as the production of food and fibre;

iii) Regulation functions, covering the role that ecosystems have in controlling climate, disease, flooding and water supply; and,

iv) Cultural functions, which include spiritual, aesthetic, educational and scientific roles that ecosystems can fulfil.

Using this classification, the MA provides a global analysis of the current status of ecosystem functions (Table 3.2), and highlights those which are currently being degraded largely as a result of the human pressures on the service exceeding its limits. The assessment has shown that at global scales, about 60% of the services identified have been and continue to be undermined by human impact. The MA goes on to explore how this situation might develop through a set of possible future scenarios.

Table 3.2: Global Status of Ecosystem Services (MA, 2005a)

An upwards arrow indicates that the condition of the service globally has been enhanced and a downwards arrow that it has been degraded. Definitions of "enhanced" and "degraded" for the three categories of ecosystem services shown in the table are provided in the note below. Supporting services, such as soil formation and photosynthesis, are not included here as they are not used directly by people.

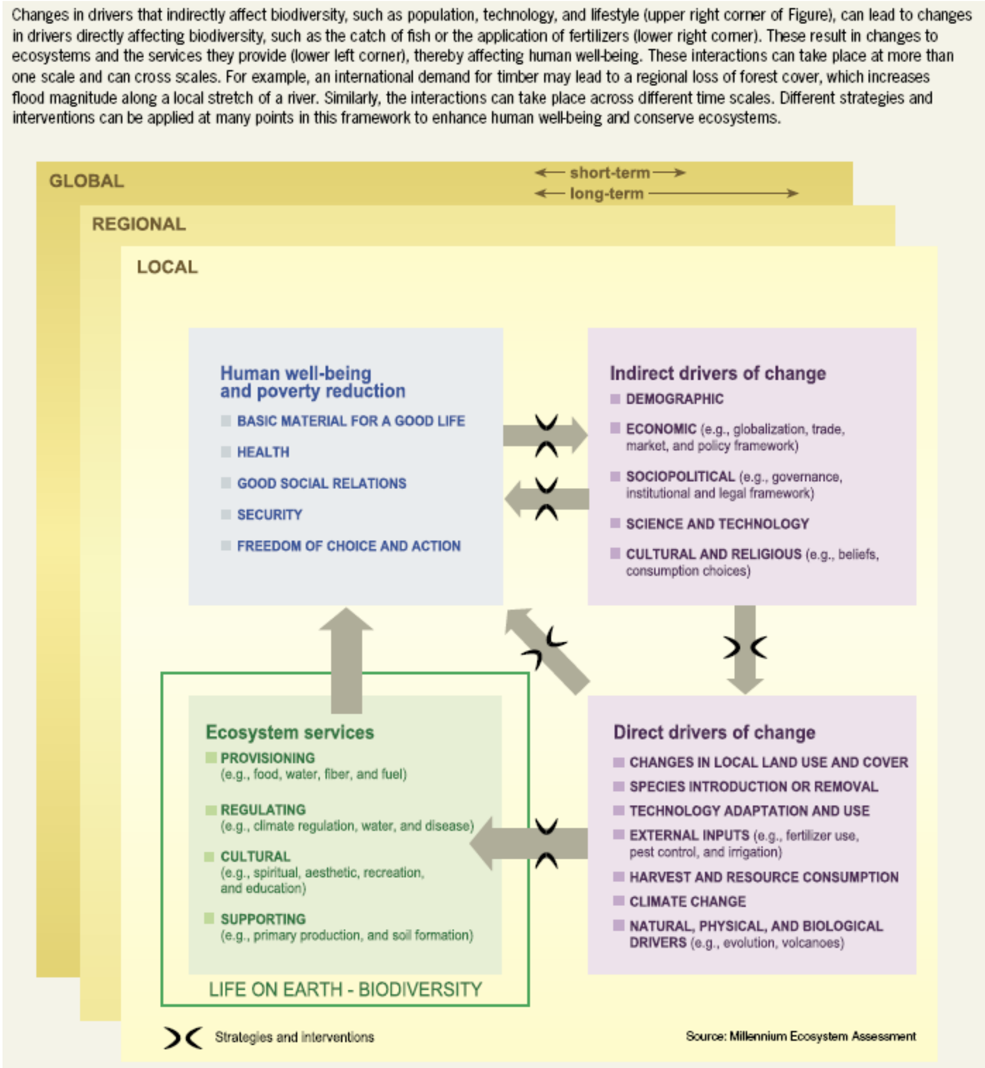
| Service | Sub-category | Status | Notes |
|---|---|---|---|
| **Provisioning Services** | | | |
| Food | crops | ▲ | substantial production increase |
| | livestock | ▲ | substantial production increase |
| | capture fisheries | ▼ | declining production due to overharvest |
| | aquaculture | ▲ | substantial production increase |
| | wild foods | ▼ | declining production |
| Fiber | timber | +/– | forest loss in some regions, growth in others |
| | cotton, hemp, silk | +/– | declining production of some fibers, growth in others |
| | wood fuel | ▼ | declining production |
| Genetic resources | | ▼ | lost through extinction and crop genetic resource loss |
| Biochemicals, natural medicines, pharmaceuticals | | ▼ | lost through extinction, overharvest |
| Water | fresh water | ▼ | unsustainable use for drinking, industry, and irrigation; amount of hydro energy unchanged, but dams increase ability to use that energy |
| **Regulating Services** | | | |
| Air quality regulation | | ▼ | decline in ability of atmosphere to cleanse itself has declined |
| Climate regulation | global | ▲ | net source of carbon sequestration since mid-century |
| | regional and local | ▼ | preponderance of negative impacts |
| Water regulation | | +/– | varies depending on ecosystem change and location |
| Erosion regulation | | ▼ | increased soil degradation |
| Water purification and waste treatment | | ▼ | declining water quality |
| Disease regulation | | +/– | varies depending on ecosystem change |
| Pest regulation | | ▼ | natural control degraded through pesticide use |
| Pollination | | ▼[a] | apparent global decline in abundance of pollinators |
| Natural hazard regulation | | ▼ | loss of natural buffers (wetlands, mangroves) |
| **Cultural Services** | | | |
| Spiritual and religious values | | ▼ | rapid decline in sacred groves and species |
| Aesthetic values | | ▼ | decline in quantity and quality of natural lands |
| Recreation and ecotourism | | +/– | more areas accessible but many degraded |

Note: For provisioning services, we define enhancement to mean increased production of the service through changes in area over which the service is provided (e.g., spread of agriculture) or increased production per unit area. We judge the production to be degraded if the current use exceeds sustainable levels. For regulating services, enhancement refers to a change in the service that leads to greater benefits for people (e.g., the service of disease regulation could be improved by eradication of a vector known to transmit a disease to people). Degradation of regulating services means a reduction in the benefits obtained from the service, either through a change in the service (e.g., mangrove loss reducing the storm protection benefits of an ecosystem) or through human pressures on the service exceeding its limits (e.g., excessive pollution exceeding the capability of ecosystems to maintain water quality). For cultural services, degradation refers to a change in the ecosystem features that decreases the cultural (recreational, aesthetic, spiritual, etc.) benefits provided by the ecosystem.

[a] Indicates *low to medium certainty*. All other trends are *medium to high certainty*.

3.22. The structure of the MA, with its requirement that all evidence should be peer reviewed, together with the wide international support that the initiative received, means that both the conceptual approach and the results have considerable authority. While the Assessment has drawn upon concepts such as ecosystem health and resilience, it is also a much looser and simpler theoretical framework that places the analysis of the relationship between ecosystems and human well being at its centre. As a result, it is more pragmatic and empirical in its outlook compared to the other frameworks. The clear demonstration of the importance of ecosystem services for human well-being means that using the ideas of the MA, a much stronger case for the environment can potentially be made. Its key ideas can also be more easily communicated and used by decision makers and policy advisors.

Figure 3.3:The Conceptual framework of the MA, linking biodiversity, ecosystem services, human well-being and drivers of change (MA, 2005a)



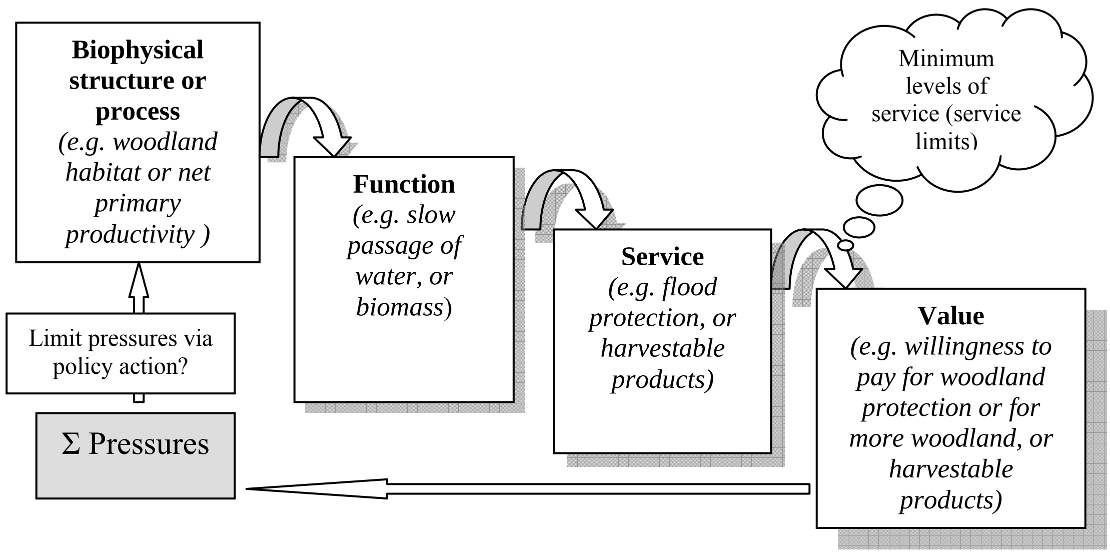

3.23. An overview of the strengths and weaknesses of the MA from a UK perspective, have been given by Georgina Mace, at a recent workshop sponsored by the Global Biodiversity Sub-Committee of the Global Environmental Change Committee[12]. Amongst the strengths identified are the consistency of its approach, its interdisciplinary character, and the template it offers for refining the analysis at global, regional and local scales (Figure 3.3). Important weaknesses include the fact that it is incomplete. This situation arises because at a conceptual level understandings of the links between the pressures and impacts and between services and human well-being are often only partial. It also arises because important data are lacking, particularly those relating to the condition of ecosystems themselves, and the values that people place upon their services.

[12] http://www.ukgecc.org/

3.24. The issue of how we value ecosystem goods and services is one that is thrown in to particularly sharp focus by the MA, and the Initiative is likely to give considerable impetus to those seeking to develop and apply tools for making better monetary valuations of the environment. The problems we face in making valuations of environmental assets is, however, part of a much wider debate, and for clarity we will treat this topic and the role that limits and thresholds play in the discussions separately in Chapter 4 of this Report. At this stage it is more appropriate to discuss the conceptual advance that the notion of ecosystem services seems to represent.

3.25. Figure 3.4 outlines the essential logic that underlies the idea that the biophysical structures or processes associated with ecosystems can give rise to sets of functions that may provide services that are valued by people. Thus a biophysical structure, such as woodland cover, may have the functional ability of slowing the passage precipitation through a river basin, and this function may in turn give rise to the service of flood protection to which people might ascribe a value.

Figure 3.4: The relationship between biophysical systems, functions, services and values




3.26. Alternatively, a process, such as primary productivity, may provide biomass that can harvested, and those products may also have a value to society. In both situations, depending on the values assigned and the minimum levels of service required or the risks of continue supply that might be perceived, society may take a view of how particular or cumulative pressures that impact on the biophysical system should be modified.

3.27. **Thus, despite the weaknesses of the MA noted above, the logic of ecosystem goods and services that underlies it has much to recommend it in terms of communicating to people what is important in the context of natural resource protection and ultimately what environmental limits**

**might exist.** While we may accept that ecosystems are holistic, complex systems, the framework focuses attention on the 'causal chain' that gives rise to a specific service. It also emphasises that decisions about minimum levels of that service and the values placed upon it are fundamentally determined by people, and cannot be decided on 'scientific' grounds alone. The framework creates a space in which resource managers and policy advisors can open a dialogue with people or groups who depend on a given service, or whose activities might impact upon it, to determine an appropriate strategy through which it might be sustained.

3.28. An important strength of the MA is that it not only stresses the importance of engaging with the social and economic context in which natural resource systems are set, and identifies tools and approaches by which the issues that arise at the interface of people and the environment can be addressed. The MA advocates, for example, a series of 'norms' for decision-making that include asking of a given assessment the following:

- Did it bring the best available information to bear?
- Did it function transparently, use locally grounded knowledge, and involve all those with an interest in a decision?
- Did it pay special attention to equity and to the most vulnerable populations?
- Did it use decision analytical frameworks that take account of the strengths and limits of individual, group, and organizational information processing and action?
- Did it consider whether an intervention or its outcome is irreversible and incorporate procedures to evaluate the outcomes of actions and learn from them?
- Did it ensure that those making the decisions are accountable?
- Did it strive for efficiency in choosing among interventions?

Table 3.3: Applicability of decision support methods and frameworks (after MA, 2005b)

| | | | | | Scale of Application | | |
|---|---|---|---|---|---|---|---|
| Method | Optimization | Equity | Thresholds | Uncertainty | Micro | National | Regional and Global |
| Cost-benefit analysis | + | + | – | + | ✓ | ✓ | ✓ |
| Risk assessment | + | + | ++ | ++ | ✓ | ✓ | ✓ |
| Multi-criteria analysis | ++ | + | + | + | ✓ | ✓ | |
| Precautionary principle[a] | + | + | ++ | ++ | ✓ | ✓ | ✓ |
| Vulnerability analysis | + | + | ++ | + | ✓ | ✓ | |

[a] The precautionary principle is not strictly analogous to the other analytical and assessment methods but still can be considered a method for decision support. The precautionary principle prescribes how to bring scientific uncertainty into the decision-making process by explicitly formalizing precaution and bringing it to the forefront of the deliberations. It posits that significant actions (ranging from doing nothing to banning a potentially harmful substance or activity, for instance) may be justified when the degree of possible harm is large and irreversible.

**Legend:**
++ = direct application of the method by design
+ = possible application with modification or (in the case of uncertainty) the method has already been modified to handle uncertainty
– = weak but not impossible applicability with significant effort

3.29. The MA then goes on to identify the types of deliberative tools that are currently available (Table 3.3). These can be used to gather appropriate information and opinion through pubic participation so that different planning options can be evaluated, and to ensure the overall transparency of the assessment. In the present context it is important to note that the exploration of thresholds (and implicitly limits) is a key task in the scheme suggested, and that decisions about them are largely context specific.

3.30. We will return to the possible management approaches and policy responses that might be built on the approach suggested by the concept of ecosystem goods and services in Part IV of this Report, and will conclude this review by exploring the final framework of understanding offered by notions of 'sustainable consumption and production'.

**Sustainable Consumption and Production**

3.31. As part of our review of the concept of environmental limits and thresholds, we though it valuable to explore the recent literature dealing with notions of sustainable consumption and production (SCP). Consideration of these materials is important because it brings out current debates about the levels and rates of consumption of physical resources (e.g. water, minerals, etc.) and the pressures that production might have on the wider physical and biological environment through the generation of waste (e.g. carbon emissions on climate).

3.32. The central focus of debates about SCP is the assertion that wise environmental stewardship requires Societies to 'achieve more with less'[13]. There is, of course, much disagreement about how this can be achieved, or how progress towards this goal can be measured, as evidenced by the recent review by Cohen (2005). However, common to all strategies is the notion that despite human development, we need to create some kind of 'ecological space' to ensure the integrity of the life support systems on which we all depend. The identification of the limits that enclose this space is seen as a key, but unresolved research issue. Nevertheless, the imperative of changing consumption and production patterns is one of the overarching objectives of and essential requirements for sustainable development, as recognized by the Heads of State and Governments in the Johannesburg Declaration[14].

3.33. Upham (2006) suggests that a number of different approaches to the problem of how to achieve sustainable patterns of consumption and production have been suggested. One strategy has been to propose principles or general rules that are intended to apply across an economy, or all human economies in aggregate (Table 3.4). The advantage of such approaches is that the principles (if accepted) can provide a framework in which performance indicators can be developed. Upham (2006) also notes that the different approaches to developing rule sets also tend to treat the idea of thresholds and limits differently. Thus (Table 3.4):

[13] http://www.sustainable-development.gov.uk/documents/publications/strategy/Chap%203.pdf
[14] http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/POIChapter3.htm

- Environmental-economic and ecological-economic approaches tend to establish substitution rules for non-renewables, with rules for renewables involving measures of non-deterioration, often over time scales that are not precisely defined.
- Ecological approaches tend to relate human materials use to the magnitude of natural flows, using ‘nature’ as a reference point. These rules emphasise regeneration capacity for renewable resources, vulnerability of natural systems to extraction of non-renewables, and assimilative capacity in the context of the production of wastes.
- The precautionary approach assumes that thresholds for both non-renewables consumption and their downstream emissions will often be contentious and/or difficult to establish. It asserts that decisions about consumption and production limits involves choices about which natural and social features are to be sustained, what form that should take, and how resources or losses are allocated. As a result the approach emphasises negotiation, flexibility and adaptability rather than prescription.

3.34. In contrast to the normative approaches outlined above, other attempts to conceptualise sustainable consumption and production have involved the development of indicators based on *per capita* area measures, such as the Ecological Footprint. This has been used most recently WWF (see WWF, 2002) to argue that given present and projected levels of consumption and production there is a risk of collapse of human welfare by 2030.

3.35. The concept of the ecological footprint was initially developed and quantified in the early 1990s based on the idea of ‘carrying capacity’ (Rees and Wackernagel, 1994). As Jørgensen et al. (2002) note, however, it is a ‘concept in the making’ and it changed and improved throughout the 1990s, culminating in publication of an estimate of the footprint for the global population (Wackernagel et al., 2002). The ‘ecological footprint’ proposed is an aggregated measure based on six categories: cropland, grazing land, forest land, fishing grounds, built-up land and energy. The footprint for the first five categories represents the per capita area needed for a unit of production, while that for energy is the area of forest required to absorb carbon dioxide emissions resulting from the consumption of fossil fuels, excluding the proportion that is absorbed by the oceans (estimated to 35%).

Table 3.4: Comparison of Sustainability Principles (ater Upham, 2006)

| ***Ecological economic approach (I) (Goodland and Daly, 1996)*** |
|---|
| 1. Maintenance of per capita manufactured capital (e.g. artefacts, infrastructure).<br>2. Maintenance of per capita renewable natural capital (e.g. healthy air, soils, natural forest).<br>3. Maintenance of per capita non-renewable substitutable natural capital (at present values, to account for increasing scarcity).<br>4. Maintenance of non-substitutable, non-renewable natural resources (e.g. waste absorption by environmental sinks such as rivers, oceans etc. Zero deterioration implies no net increase in waste emissions beyond absorptive capacity |
| ***Ecological economic approach (II) (Holdren et al, 1992)*** |
| 1. Limit levels of harm to those that are tolerable on a consistent basis (i.e. levels that are non-cumulative) in return for the benefits of the activity that causes the harm.<br>2. Limit the degradation of monitorable environmental stocks of "essential" resources only, to not more than 10% per century, to give societies the time to develop substitutes and alter related systems. |
| ***Ecological economic approach (III) (Weterings and Opschoor, 1992)*** |
| 1. No exhaustion of renewable resources, and residual stocks of non-renewables sufficient for 50 years' use.<br>2. No accumulation of pollution or lasting effects for future generations.<br>3. Encroachment relates to interventions that affect natural structures and systems. Loss of acreage must not exceed the area added or restored by natural or artificial means. |
| ***Environmental economic approach (I) (Jacobs, 1991)*** |
| 1. For *renewable* resources harvest or use rate should not exceed the regeneration rate<br>2. For *non-renewable* resources, maintenance of the stock level relative to demand.<br>3. For *waste assimilation capacity*, sustainability is maintained when the rate and concentration of non-persistent waste discharges remain within the assimilative capacity of the environmental medium.<br>4. For *life support services* maintenance of a set of "life support indicators" |
| ***Environmental economic approach (II) (Ekins, 1994; 1996)*** |
| 1. Destabilisation of global environmental features must be prevented, by maintaining biodiversity, preventing of climate change and protecting the ozone layer.<br>2. Important ecosystems and ecological features must be absolutely protected to maintain the functional biological diversity that underpins the productivity and resilience of ecosystems.<br>3. The renewal of renewable resources must be ensured by maintaining soil fertility, hydrobiological cycles and necessary vegetative cover, and by the rigorous enforcement of sustainable harvesting.<br>4. Depletion of non-renewable resources should balance the maintenance of a minimum life expectancy for the resource with the development of substitutes for it.<br>5. Emissions into air, soil and water must not exceed critical load, that is the capability of the receiving media to disperse, absorb, neutralise and recycle them, nor may they lead to life-damaging concentrations of toxins.<br>6. Risks of life-damaging events from human activity must be kept at low levels. Technologies with high damage potential, even if low risk, should be foregone. |
| ***An ecological approach (Moser and Narodoslawsky, 1993)*** |
| 1. Anthropogenic material fluxes must not exceed the local assimilation capacity of natural cycles, and should be smaller than natural perturbations in material flows.<br>2. Anthropogenic material flows must not alter the content and quality of natural storage systems, such as aquifers and fossil raw material deposits.<br>3. Renewable resources must only be extracted at a rate not exceeding local fertility.<br>4. The natural variety of species and landscapes must be sustained and improved. |
| ***A precautious approach (Upham, 1999 and 2001, after Holmberg, 1995 and Holmberg et al. 1996)*** |
| 1. Conceptual research and sectoral negotiation is needed to establish emissions and consumption quotas, with supporting fiscal or other regulatory incentives, to bring the human economy within the critical levels of large-scale environmental systems.<br>2. Indicating sustainability requires absolute measures of material input and waste outputs to air, water and land, as well as the same relative to business or economy performance. Waste output means all unwanted emissions to air, water and land. Non-waste output (products) will consist of input material less waste output material.<br>3. Substitution of biologically-derived materials for mined and some synthetic materials, and increased use of this bio material, may be desirable if the material can be biodegraded, is grown on degraded land, or otherwise has a lower impact than the mined or synthetic materials. Consumption targets, quotas and indicators should reflect this. |

3.36. The calculation of aggregated measures such as the "Ecological Footprint" is not, however, without its critics (see for example, van den Bergh and Verbruggen (1999), and the subsequent special issue of *Ecological Economics* devoted to the topic[15]). Arguments ranged against it include not only those relating to its meaning and construction, but also to the sensitivity it has to the calculation method. For example, Jørgensen et al. (2002) show that the index is highly sensitive to the calculation method and that alternative methods can show that future global population demand will not exceed the Earth's biological capacity.

3.37. The approach represented by the UK Framework for Sustainable Consumption and Production[16] reflects a number of the themes outlined above. It identifies, for example, three key objectives involving:

- The 'decoupling' of economic growth from environmental impacts,
- The identification of the key impacts associated with the use of particular resources; and,
- An increase in the efficiency of resource and energy use.

The document then presents a series of indicators covering economy-wide and household consumption and national production to address the decoupling issue. Thus indicators such as domestic materials consumption are plotted as indexed time series with GDP, and assessed as to whether they show absolute or relative decoupling[17].

3.38. The question of how limits and thresholds are defined is particularly relevant in the context UK Framework for Sustainable Consumption and Production. As Elkins (2003), for example, has argued, unless a particular indicator is related to a thresholds (i.e. a limit) of sustainable use, one cannot make the judgement that it shows sufficient relative or absolute decoupling to support the conclusion that more sustainable patterns of consumption and production have been achieved. The need to reference indicators to thresholds is indeed recognized in the framework for SCP[18], where it is also noted that 'ecological processes are non-linear and we know little about thresholds and environmental limits' (D*efra*, 2005, p.6). One of the key points made during the consultation stage before publication of the framework was that the indicators need to provide clearer guidance on progress towards sustainability by linking them to ecological limits or long term targets.

3.39. Along with the other organisation frameworks considered in this report, the various attempts to specify and measure what is implied by the notion of sustainable patterns of consumption an production show that it is a useful

[15] *Ecological Economics*, 2000, Vol. 32

[16] See for example, D*efra* (2003) Changing Patterns, The UK Framework for Sustainable Consumption and Production, http://www.defra.gov.uk/environment/business/scp/pdf/changing-patterns.pdf, and http://www.defra.gov.uk/environment/statistics/scp/download/scp_rpt200506.pdf

[17] Absolute decoupling occurs when there is either no or a negative correlation between the pressure indicator and GDP; relative decoupling occurs if the rate growth in the pressure indicator is less than GDP.

[18] http://www.defra.gov.uk/environment/statistics/scp/download/scp_rpt200506.pdf

vehicle for thinking about problems of limits and thresholds. However, it is apparent that a number of theoretical and practical problems remain. It is useful to express them in the context of the UK Framework:

- If we accept the normative aspects of the Framework, that sustainable consumption and production is a function of decoupling economic growth from environmental impacts and improving the efficiency of energy and resource use, does the present approach capture all the important aspects that need to be measured?
- Through what causal chains are these pressure indicators that are currently used linked to other systems or processes that deliver benefits to people, and how might the integrity of those systems be threatened by present or increased levels of consumption or production?
- How does use information about pressures on systems that deliver benefits to people to specify limits for consumption and production indicators?
- Given that the environmental pressures arising from consumption and production may impact upon a number of systems that deliver benefits to people then, if we use information about those impacts to define sustainability, how and who should decide what priorities should prevail and what types of value are applied?
- How do we achieve an integrated view of the pressures resulting from patterns of consumption and production at different geographical scales, to ensure that unevenness of outcomes does not disadvantage particular groups?

3.40. We will explore the types and adequacy of evidence that might be used to support the identification of SCP limits as one of the outputs from this study, and will return to questions posed above in Part IV of this Report. A particular line of investigation will be the extent to which thinking about ecosystem goods and services and the limits associated with them might be used as a starting point for defining limits for monitoring sustainable patterns of consumption and production. It will also be valuable to reflect on whether the rigours of the ‘decision making criteria’ identified by the Millennium Assessment for ecosystem goods and services can be applied more generally to monitoring patterns sustainable consumption and production.

# Chapter 4. Values and the Problem of Limits and Thresholds

## Introduction

4.1. Although the problem of how environmental assets and natural resources are valued is not part of the brief for this study, the conclusion reached in Chapter 3 that it is unlikely that thresholds or limits can be defined only in biophysical terms, points to the fact that the issue needs to be considered nevertheless. The significance we attached to both continuous changes in state and a catastrophic regime shifts depends on value people attach to the loss of outputs or benefits. Thus, before we explore the evidence base about limits and thresholds in more detail, we must examine how thinking about them is also informed by recent debates concerning problem of valuing environmental assets and the changes associated with them.

## Types of Value

4.2. In their introduction to a special issue on the dynamics and value of ecosystem services, Costanza and Faber (2002) ask the question, 'what do we mean by the 'value' of nature?' While values are commonly expressed in monetary terms, Costanza and Faber (2002) argue, values can also be assigned using other types of criteria.

4.3. The nature of the valuation problem that the assessment of the different ecosystem goods and services poses has been discussed by a number of authors. De Groot (2006) has summarised a position that is commonly taken which argues that three types of value can be identified, namely:

a. **Economic value,** which is expressed in terms of the monetary value people or societies are prepared or able to attach to the different functions.

b. **Ecological value**, which is an expression of the importance of the ecosystem, determined by such criteria as the integrity of, for example, its regulatory functions, and by ecosystem properties such as diversity and resilience; and

c. **Socio-cultural value,** which is determined by considerations such as equity or justice, or conceptions of natural systems that are rooted in religious, cultural or philosophical beliefs.

4.4. The need to separate out these different dimensions of value can best be illustrated by reference to the problem of economic valuation and its limitations. As we shall see, much of the argument turns on what happens when environmental thresholds or limits are approached.

4.5. Environmental economists (e.g., Turner et al., 1994; Pearce, 1998; Eftec, 2005) have suggested that conceptually the Total Economic Value (TEV) of an ecosystem good or service can be calculated from the sum of 'use', 'non-use' and 'option' values (Table 4.1), and have gone on to identify the types of valuation tool that can be used to estimate the different types of value in a given situation.

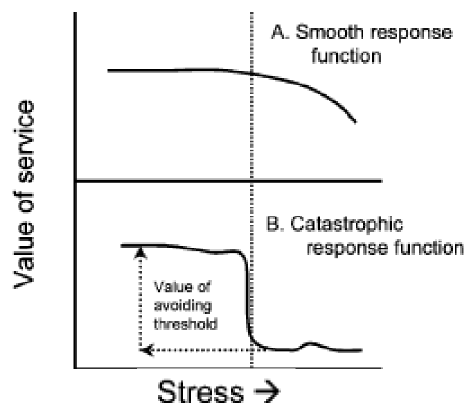
Table 4.1: Components of Total Economic value (TEV) (after, Eftec, 2005)

| **Components of TEV** | | **Basis** |
|---|---|---|
| Use values | Direct use value | Derived, for example, from the consumptive use of resources; and, |
| | Non-direct use value | Based on the regulating or supporting functions that ecosystems provide. |
| Non-use values | Existence value | Based on the satisfaction that an individual or group derives simply from the existence of the natural system; |
| | Bequest value | Derived from the value attached to being able to pass the resource on to future generations; and, |
| | Altruistic value | Arising from the knowledge that others may benefit from the availability of a given goods and services. |
| Option value | | Refers to the fact that an individual might place a value on being able to make use of a given resource at some future point in time. |

4.6. A discussion of the merits of the techniques that can be used to calculate the TEV is not necessary here. Rather, it is sufficient to note that they all share the common goal of attempting to produce an estimate of value in monetary terms, whether it be based on direct market valuation if a real market exists for that a good or service, or by more indirect valuation methods (e.g. *Willingness to Pay* or *Willingness to Accept*) if they do not. The important thing to note is that in applying these techniques, the aim is not to calculate the absolute value of a given ecosystem function to people, but only the ***marginal*** value. The latter expresses the value that attaches to an additional unit of the service, when all other factors are held constant. It is useful to calculate because it allows one to compare the marginal benefits that a consumer would derive from a given ecosystem good or service, against the benefits that might arise from some other expenditure.

4.7. As Limberg et al. (2002) point out, however, all valuation is essentially about 'the 'difference' something makes', often to well-being, and go on to suggest that the analysis of marginal value is only possible when coupled social-ecological systems are far from an unstable threshold (Figure 4.1). Thus they describe a 'marginal regime', in which there is high degree of certainty and predictability in understanding the relationships between the different part of the coupled system, and so individuals are

Figure 4.1: Value responses under marginal and non-marginal regimes (after Limberg et al., 2002)




Situation A represents the 'marginal regime' where the differences value due to increasing stress can be valued in monetary terms; situation B is the 'non-marginal regime' well placed to make decisions about trade-offs and substitutions. In such a regime, it is argued, marginal values can be based on the analysis of human preferences. Close to an unstable threshold, however, other criteria appear to apply.

4.8. In the proximity of an unstable threshold, where systems can alternate between two or more equilibria, we enter what Limberg et al. (2002) call a 'non-marginal regime'. Here the assumptions needed to calculate the marginal economic value are longer valid. The criteria used to make judgements about the gains and losses resulting from small disturbances under the predictable conditions of the marginal regime, cannot easily be made, because disturbances of the same magnitude can trigger potentially catastrophic events. When faced with collapse of an ecosystem, Limberg et al. (2002) suggest that questions of trade-offs and substitution of benefits no longer apply.

### Marginal and Non-Marginal Regimes

4.9. The distinction that Limberg et al. (2002) make between these marginal and non-marginal regimes reflects a much wider debate between the environmental economists on the one hand and ecological economists on the other (cf. Pearce, 1998). While the former argue that economic valuation is possible *and essential* in all situations, the latter hold that in some contexts, particularly those where these unstable threshold regions exist, such economic valuation is not always applicable or at least not the only criteria that may be applied.

4.10. From the ecological economic perspective, in situations where marginal economic valuation is not appropriate, other types of valuation, such as social and ecological are claimed to be more useful. Limberg et al. (2002) argue, for example, that 'As the ecosystem is forced away from the neighbourhood of a singular stable equilibrium, the relevant value concepts shift from utility to risk avoidance' (Limberg, et al., 2002, p418). For them risk avoidance strategies equate more strongly with ecological values that emphasise properties such as resilience and ecosystem integrity, or environmental space (cf. Deutsch et al., 2003; de Groot et al., 2003; Spangenberg, 2002). A similar position is advocated by Chee (2004). Risk avoidance also corresponds to applying the types of ethical criteria emphasised by those who advocate social valuation, since rights and environmental justice issues may arise if the loss or collapse of ecosystem function impinges on human health or welfare (Bührs, 2004). Under such situations, limits in the form of 'safe minimum standards' might therefore be proposed.

4.11. In circumstances where ecological economists argue that ecological and social valuable is more applicable, then a range of participatory methods, such as citizens' juries, probabilistic risk analysis, multi-criteria decision analysis and scenario planning are appropriate (Chee, 2004; de Groot et al., 2003; Wilson and Howarth, 2002; Peterson et al., 2003), and these can sit alongside the methods proposed for the analysis of TEV described above. This broad approach is consistent with the one advocated through the 'decision making criteria' suggested by the Millennium Assessment (see paragraphs 3.18 – 3.30, above).

4.12. It is important to note that the distinction between marginal and non-marginal regimes does not imply that ecological and social criteria are only applicable in situations where catastrophic collapse is threatened. Rather, it is suggested, that in these situations economic valuation is more difficult and so these other types of consideration are likely to be more dominant. However, by no means all agree with Limberg's et al. (2002) proposition of marginal and non-marginal regimes. Pearce (2004) has, for example, provided a powerful critique of key elements of the position is taken by ecological economics, and has cautioned about the dangers of 'building a science on limited rather than general ecological behaviour' (Pearce, 2002, p43). For him, economic valuation is applicable under *all* circumstances.

**Implications**

4.13. In the exploration of the evidence base that follows, we will consider both the extent to which limits and threshold concepts have been discussed in each of the thematic areas, and what role valuation of outputs or benefits might play in identifying and defining them. A key focus will be on the types of valuation criteria applied, how those values have been assigned.

# Part III: Exploring the Evidence Base

## Chapter 5. Exploring the Evidence Base: Biodiversity

### Introduction

5.1. Amongst the many literatures that have discussed the ideas of limits and threshold that relating to biodiversity is among the most extensive. As we have seen in Chapters 2 and 3, systems ecology has spawned a substantial body of theoretical work addressing such issues as stability and resilience at the species and community levels. At the species level the concept of limits is relevant in terms of understanding, for example, the minimum population sizes necessary to prevent extinctions. Threshold responses are sometimes evident in situations where interactions between species, such as competition, occur. At the habitat level a number of limits in terms of the structure of habitat mosaics have been suggested, but few threshold-type responses triggered by habitat change have been identified.

### UK Biodiversity Action Plan (BAP)

5.2. In terms of developing a systematic approach to the problem of understanding relevant limits at the **species level**, we are particularly fortunate in this country in terms of the information resources that are available through the UK Biodiversity Action Plan (BAP) website[19]. At present 364[19] species-level action plans have been developed; these cover species that are of conservation concern at global or national scales[20]. The recent targets review[21] of the species action plans provides a useful summary, and in particular can be used to identify the types of factor that presently limit BAP species populations (Table 5.1).

5.3. In order to appreciate the implications of these data it is important to clarify the terminology relating to what the BAP process refers to 'targets' and what we refer to here as a 'limit'. Table 5.1 shows the number of BAP species in each taxonomic group that were assigned to the different 'target types' in the tranche of work that has led up to the 2005 review. The latter describe what aspects of the ecology of the species that needs to be managed if its conservation status is to be improved. The term 'target' is thus used in the sense of an 'objective'. The original target categories identified in the review are:

- Maintain current range
- Expand current range
- Increase population size
- Maintain current population size

[19] http://www.ukbap.org.uk/default.aspx, esp.: 45 Habitat Action Plans, 364 Species Action Plans and 123 Local Biodiversity Action Plans
[20] For inclusion criteria see: http://www.ukbap.org.uk/GenPageText.aspx?id=60
[21] http://www.ukbap.org.uk/GenPageText.aspx?id=98

- Establish an ex-situ conservation programme
- Improve habitat quality
- Maintain habitat extent
- (blank)

Table 5.1: Limiting factors for BAP Species by Taxonomic Group, derived from the original BAP targets.

| Taxon | Maintain current range | Expand current range | Increase population size | Maintain current population size | Establish ex-situ conservation programme | Maintain habitat extent | Improve habitat quality | (blank) | Grand Total |
|---|---|---|---|---|---|---|---|---|---|
| Flowering plants | 63 | 61 | 20 | 15 | 22 | | | | 181 |
| Beetles | 37 | 34 | 23 | 14 | | | | | 108 |
| Moths | 34 | 23 | 28 | 2 | | | | | 87 |
| Mosses | 29 | 12 | 18 | 7 | 23 | | | | 89 |
| Birds | 15 | 22 | 27 | 22 | | 1 | | | 87 |
| Mammals | 16 | 8 | 12 | 10 | | | | | 46 |
| Lichens | 28 | 16 | 13 | 5 | 1 | | | | 63 |
| Ants/Bees/Wasps | 24 | 17 | 16 | 2 | 2 | | | | 61 |
| Molluscs | 12 | 5 | 6 | 8 | | | | | 31 |
| Liverworts | 11 | 5 | 6 | 1 | 5 | | | | 28 |
| True flies | 16 | 6 | 9 | 1 | | | | | 32 |
| Butterflies | 10 | 10 | 1 | 2 | | | | | 23 |
| Fungi | 12 | 3 | 5 | 1 | 1 | 1 | | | 23 |
| Stoneworts | 1 | 7 | 1 | 7 | | | | | 16 |
| Crickets / Grasshoppers | 4 | 6 | 2 | 1 | 2 | | | | 15 |
| Fish | 3 | 5 | 1 | 5 | | | | | 14 |
| Amphibians | 3 | 3 | 1 | 1 | | | | | 8 |
| Spiders | 2 | 3 | 2 | 2 | 1 | | | | 10 |
| Reptiles | | 1 | 2 | 2 | | | | 1 | 6 |
| Corals | 2 | | | 2 | | | | | 4 |
| Crustaceans | 1 | | | 1 | 1 | | | | 3 |
| Sea anemones | 2 | 1 | | 1 | | | 1 | | 5 |
| True bugs | 1 | 1 | 1 | | 1 | | | | 4 |
| Bryozoan | 1 | 1 | | | | | | | 2 |
| Worms | 2 | | | | | | | | 2 |
| Damselflies / Dragonflies | 1 | 1 | 1 | | | | | | 3 |
| Algae | 2 | 1 | | 1 | | | | | 4 |
| Stoneflies | 1 | | | | | | | | 1 |
| Grand Total | 333 | 252 | 195 | 113 | 59 | 2 | 1 | 1 | 956 |

Source: http://www.ukbap.org.uk/GenPageText.aspx?id=98; Note species may be subject to more than one type of target, and so the total number of targets identified excess the number of BAP species.

5.4. Inspection of these categories shows that notions of limits are implicit in the approach adopted. About 60% of the species originally covered appear to have limits associated with their biogeographical range, whereas around 30% appeared to have limits associated with population size.

5.5. The information currently being collated by the 2005 review will be richer than that available for the initial set of targets. For example, although the categorisation of species by these different target types will be reduced to the categories of maintaining or increasing population and range, there is the opportunity to add new types of target (e.g. in relation to such factors as fragmentation). The review will go on to identify whether it is likely that by meeting the revised targets, BAP status for the species will be achieved in the long term, and geographical priorities for action.

5.6. The evidence base that is emerging in the UK at the species level will represent an important resource. The problem it poses, in terms of supporting decision making at strategic scales, is how to aggregate information so that it is more manageable. Clearly information about limits at the species level can be summarised by functional or taxonomic group, or by geographical region. Aggregation of information at the **habitat level** is also an efficient way forward.

5.7. In parallel to the review of BAP targets for species, a similar review was initiated in 2005 for habitats in the UK. Ostensibly the review will explore the initial targets set for the BAP Priority Habitats (Table 5.2) and collate the new information along the same lines as that described for species. The limiting factors identified in the original tranche of targets were mainly related to habitat quality, although maintenance and expansion of extent also accounted for a significant proportion of the categories. The target categories to be used for the 2005 review are:

- Achieving condition;
- Maintain extent;
- Restoration; and
- Expansion.

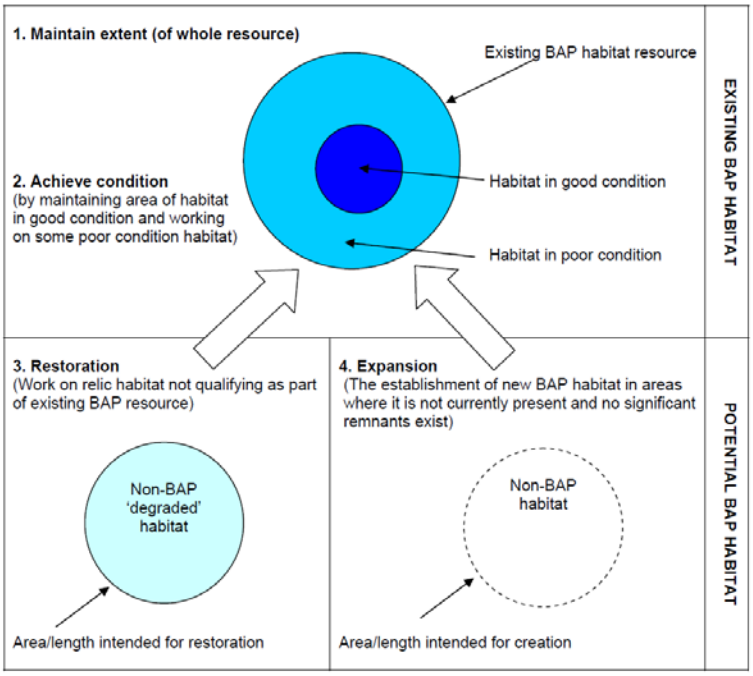
5.8. The relationship and definition of these categories is illustrated in Figure 5.1. These are more complex than those used for species targets, but nevertheless contain implicit information about the types of limit that apply at habitat scale. Indeed, since the targets review is asking lead partners to specify both a baseline 2005 area target, and target areas for 2010 and 2030 it is likely that the assumptions on which these estimates are based will come under close scrutiny.

Table 5.2: Limiting factors for BAP Species by Taxonomic Group, derived from the original BAP targets.

| **Priority Habitat Name** | **Improve habitat quality** | **Maintain habitat extent** | **Expand habitat extent** | **Maintain habitat quality** | **Maintain habitat quality** | **(blank)** | **Grand Total** |
|---|---|---|---|---|---|---|---|
| Lowland beech and yew woodland | 4 | 2 | 4 | | | | 10 |
| Upland mixed ashwoods | 6 | 2 | 2 | | | | 10 |
| Wet woodland | 6 | 2 | 2 | | | | 10 |
| Maritime cliff and slopes | 3 | 1 | 1 | 2 | | | 7 |
| Coastal sand dunes | | 2 | 2 | 2 | | | 6 |
| Lowland calcareous grassland | 4 | 1 | 1 | | | | 6 |
| Lowland dry acid grassland | 4 | 1 | 1 | | | | 6 |
| Lowland meadows | 4 | 1 | 1 | | | | 6 |
| Lowland raised bog | 4 | 1 | | | | 1 | 6 |
| Purple moor grass and rush pastures | 4 | 1 | 1 | | | | 6 |
| Upland hay meadows | 4 | 1 | 1 | | | | 6 |
| Ancient and/or species-rich hedgerows | 2 | 3 | | | | | 5 |
| Machair | 4 | 1 | | | | | 5 |
| Native pine woodlands | 1 | 1 | 3 | | | | 5 |
| Upland heathland | 3 | 1 | 1 | | | | 5 |
| Blanket bog | 3 | 1 | | | | | 4 |
| Coastal and floodplain grazing marsh | 1 | 1 | 1 | 1 | | | 4 |
| Coastal saltmarsh | 1 | 1 | 1 | 1 | | | 4 |
| Coastal vegetated shingle | 1 | 1 | | 2 | | | 4 |
| Limestone pavements | 1 | 1 | | 2 | | | 4 |
| Lowland wood-pasture and parkland | 1 | 1 | 1 | 1 | | | 4 |
| Saline lagoons | | 2 | 2 | | | | 4 |
| Upland oakwood | 2 | 1 | 1 | | | | 4 |
| Chalk rivers | 2 | | | 1 | | | 3 |
| Eutrophic standing waters | 1 | | | 2 | | | 3 |
| Littoral and sublittoral chalk | 1 | | | 2 | | | 3 |
| Lowland heathland | 1 | 1 | 1 | | | | 3 |
| Mesotrophic lakes | 1 | | | 1 | 1 | | 3 |
| Mudflats | 1 | 1 | 1 | | | | 3 |
| Reedbeds | 1 | 1 | 1 | | | | 3 |
| Sabellaria alveolata reefs | | 1 | 1 | 1 | | | 3 |
| Sabellaria spinulosa reefs | | 1 | 1 | 1 | | | 3 |
| Tidal rapids | | 1 | | 2 | | | 3 |
| Upland calcareous grassland | 1 | 1 | 1 | | | | 3 |
| Aquifer fed naturally fluctuating water bodies | 1 | | | 1 | | | 2 |
| Fens | 1 | 1 | | | | | 2 |
| Lophelia pertusa reefs | 1 | 1 | | | | | 2 |
| Maerl beds | | 1 | | 1 | | | 2 |
| Modiolus modiolus beds | | 1 | | 1 | | | 2 |
| Seagrass beds | 1 | 1 | | | | | 2 |
| Serpulid reefs | | 1 | | 1 | | | 2 |
| Sheltered muddy gravels | | 1 | | 1 | | | 2 |
| Sublittoral sands and gravels | | 1 | | 1 | | | 2 |
| Cereal field margins | 1 | | | | | | 1 |
| Mud habitats in deep water | | 1 | | | | | 1 |
| Grand Total | 77 | 46 | 32 | 27 | 1 | 1 | 184 |

Source: http://www.ukbap.org.uk/GenPageText.aspx?id=98; Note habitats may be subject to more than one type of target, and so the total number of targets identified excess the number of BAP priority habitats.

Figure 5.1: Relationship between habitat targets used in 2005 BAP Habitats Review (source: 2005 BAP Targets Review Lead Partner Guidance Notes).




5.9. As with the BAP species-level, data from the 2005 Targets Review for habitats are not yet available, and so it has not been possible to explore them in any further detail. However, given the information currently available the following recommendations can be made in terms of how both these types of information might usefully be collated and extended:

a. The review will provide a rich evidence base relating to the factor currently thought to be limiting BAP species and habitats, and this provides a good foundation on which further thinking about these limits can be undertaken. **When it is published the materials should be reviewed to identify the robustness of the evidence base about the targets, and to identify what gaps are apparent:**

- It will be valuable to look at the coverage of responses to the question of whether the targets for both species and habitats are likely to be achieved by 2030, to determine if and how such evidence has been assembled. This question is likely to expose some of the significant knowledge gaps in the evidence base that need to be addressed through future work.
- It will be valuable to look at how the original targets have been revised up or down, in the light of the scientific or practical experience gained by attempting to implement them, in order to explore the assumptions that lead partners have used in the revision process.

**b. As part of the reporting process, De*fra* should ensure that the information on limiting factors for species and habitat viability that**

**are contained in the target descriptions, are summarised, and linked to the types of information contained in the species and habitat action plans which document the pressure upon them.** D*efra* should:

- Encourage the evidence about pressures and threats to be documented. These materials will assist D*efra* in linking their other work on environmental pressures to the consequence for species- and habitat-level biodiversity in the UK.

c. **Since it is important that thinking about possible limits is embedded in wider decision making, there should be a sections of the species and habitat action plans that flag up the evidence upon which the judgement about the 'target action' is based**.

- This material should explain how the decision about the suitable target level (e.g. minimum viable population size or range, etc.) was made, and what risks are associated with it, and whether the species is likely to exhibit any kind of 'threshold response'.
- Where possible this information should be referenced to a regional geographical framework, to support the development of local BAP initiatives. By collating the information about pressures (see b above) and limits at regional scales, D*efra* can provide a useful tool for helping people to include knowledge about limits in their decision local decision making.

d. **Since it is likely, given the nature of the BAP Process, that these limits will mainly be determined using ecological criteria, it would be valuable to initiate a study to identify what the contribution individual species or species groups make to the generation of ecosystem goods and services, so that the benefits of achieving and exceeding the targets identified can be communicated. The costs of recovery can also to be looked at in relation to the benefits that might be realised.**

- It is unlikely that all species targets are compatible (e.g. predator vs prey species) and some resolution of potential conflicting limits may be necessary.
- At the habitat level it would be valuable if the role that Broad and Priority Habitats to wider ecosystem services at different geographical scales could be documented so that the risks associated with them (e.g. climate change, alien species) can be assessed. Our review suggests there is little systematic information available about the relationship between Priority and Broad Habitats and the benefits they provide to society.

5.10. A final point to note about the 2005 BAP Habitat Review is that in revising the targets at species and habitat level, uncertainties associated with the judgments will be exposed. This process will identify areas where the existing evidence base is deficient and where future research is necessary.

## Giving Guidance

5.11. The systematic information collected through the BAP process will give a rich body of information on an important group of species and habitats. However, as we look to ways in which future development in the UK can be achieved in ways that respect biodiversity limits, it is clear that the evidence base required must extend far beyond that needed for the BAP process. What kinds of biodiversity limits need to be respected, for example, when general issues or strategies in the countryside are being considered?

5.12. A review of biological 'thresholds', and their relevance for conservation and land planning, has recently been undertaken by the US Environmental Law Institute (ELI, 2003). Their aim of the review was to "determine whether a body of knowledge has emerged within the scientific community relevant and applicable to national land use decision making, specifically pertaining to biological conservation thresholds". The review covered the period 1990-2001, but drew upon earlier key sources where it was appropriate. It focused on habitat fragmentation and landscape ecology issues related to the spatial relationships between landscape elements over large geographical areas, with particular reference to the United States.

5.13. In reviewing the ELI (2003) study, it should be noted that while it used the term 'thresholds' it was not dealing with systems showing alternative stable states, but used it as a synonym for 'limit'. The study found:

a. That there was "adequate information on potential ecological threshold [limit] measures for habitat patch area, percent of suitable habitat, edge effects, and buffers." ; while,

b. Information available for corridor size was "deficient".

5.14. The ELI (2003) study noted that in terms of thresholds (or limits) related to habitat patch size, a range of species specific thresholds could be identified, but no generic minimum habitat patch size appeared to exist. The amount of habitat required was related to taxonomic group, body size, feeding behaviour and dispersal strategy. However, from the information available, it appeared that about 75% of the species considered had minimum patch size requirements of less than 55 hectares. The information on which this guideline was based mainly related to birds and mammals; few of the available studies dealt with plants, insects and fish. Similar 'rules of thumb' that could be used as a starting point for conservation were also suggested for habitat proportion, edge influences, riparian buffer width and landscape connectivity.

5.15. In the UK we lack systematic evidence of the kind assembled by the US Environmental Law Institute, although there is some evidence to suggest that general limits can be identified. Thus Peterken (2002), for example, has suggested that in the context of woodlands at least, minimum area requirements can be suggested for dormice (20ha) and most bird species (10ha). In terms of isolation between woodland patches, he notes that female red squirrels will not travel more than 680m in one day, and dormice rarely colonise woodland more than 800m for their established territory. Plants associated with ancient woodlands rarely colonise new woodland if it is more than 200m from a source. Finally, he suggests that for most woodland animal populations to function as if they were within one patch, a woodland cover at the landscape scale of about 30% is needed.

5.16. Using the outcomes of the UK BAP Targets review[22] as a basis, it would be useful to extend the study of limits related to habitat patch size and isolation to species and habitats more typical of the wider countryside. The existence of a minimum patch size or significant isolation effect is evidence that a species may exhibit a non-linear response to these factors. However, it does ***not*** follow that their populations may also exhibit threshold dynamics. Lindenmayer and Luck (2005), and Huggett (2005), for example, have reviewed the empirical evidence supporting the existence of ecological thresholds for a range of species and suggest that on the basis of Australian experience, there is evidence to both support and counter the proposition that threshold responses exist in ecological systems at the species level.

5.17. For example, Radford et al. (2005) and Drinnan (2005) presented evidence for threshold responses in a range of bird, amphibian and plant species. The former showed that, as predicted from model-based studies, in the landscapes of north central Victoria bird species richness showed a marked decline as woodland cover was below 10%. Drinnan (2005) showed that in a fragmented urban landscape near Sydney, species richness declined markedly in patch sizes smaller than 4ha for birds and frogs, and 2ha for plants and fungal species. He also identified a threshold at 50ha for interior woodland species. By contrast, Lindenmayer and Lauk (2005) did not find any evidence of threshold relationships for bird and reptile assemblages in plantation landscapes in New South Wales.

5.18. Lindenmayer and Luck (2005) identify a range of factors that could explain the differences observed between studies. These include the type of species assemblage or species under investigation, the type of threshold measure applied, the timing and duration of the landscape change being considered, and the intensity of the landscape change within the study area. They also note that threshold responses may be more difficult to detect for species groups or assemblages, compared to single species, because they may not exhibit a common response event though they may have a number of other similar traits. **Clearly much further work is required to determine what types of issue may be involved.**

5.19. While many of the studies of biological threshold concentrate on the effects of the spatial pattern of habitat patches, it is important to note that both patch history and context may also affect the extent to which threshold responses can be identified. In the UK, the importance of patch condition is particularly evident in terms of the influence of management history, which may completely override the effects of size and isolation. Thus even small and isolated ancient woodland patches may support a more diverse range of plant

[22] http://www.ukbap.org.uk/GenPageText.aspx?id=98

species, as a result of the continuity of forest cover since at least 1600, compared to larger forest patches of more recent origin. In such contexts the size of such remnant patches in terms of the protection that they afford from surrounding influences may be the most significant factor. Studies such as those recently conducted by Kirby et al. (2005), Grove et al., 2004; and Bateman et al. (2004) on the effects of management practices on agricultural surrounding patches of ancient woodland show how the nature of the boundary zone may potentially impact on woodland condition. Fertiliser drift, may, for example, penetrate up to 30 m into the woodlands, resulting in eutrophicaton of soils and modification of the characteristic woodland flora.

## Conclusions

5.20. Our review of limits and thresholds as they apply to biodiversity issues at the species and habitat level suggests that few generalisations can be made. Observed responses appear to be species and habitat specific, and may be heavily dependent upon the spatial and temporal scales considered. The uncertainties involved in defining limits largely arise from lack of basic information at species and habitat level, and in particular, long term monitoring data.

5.21. Nevertheless, in the UK we are well placed to develop the evidence base that is available to decision makers, by exploiting information that is emerging from the 2005 BAP Target Review. The data presently being collated will allow gaps in the existing information base relating to key limiting factors such as population size and habitat extent to be identified for an important group of species and habitats, and this could provide a platform for developing a similar body of information for the more common species and habitats found in the wider countryside.

5.22. The pragmatic approach suggested here needs to provide a platform for developing a systematic understanding of the relationship between species and habitats and the output of ecosystem goods and services so that a better case for the BAP limits can be made.

# Chapter 6. Exploring the Evidence Base: Land Use and Landscape

## Introduction

6.1. The exploration of limits and threshold concepts in relation to land use and landscape is amongst the most challenging of all the areas that has been reviewed by this study. On the one hand, many of the issues that need to be considered overlap with the other thematic areas, such as biodiversity, water and soil, and are therefore partially covered elsewhere. On the other, since it is clear that in the 'real world' these issues often have to played out alongside each other, they must be considered in an integrated or holistic way through the 'prism' of land cover or landscape. Thus there is the problem in this review section of 'knowing where to stop'. In order to constrain the discussion, we have focused our review of land cover and landscape issues around the notion of 'multifunctionality' and posed the question - *in multifunctional land use mosaics or landscapes, what kind of limits and thresholds can be identified?*

## Multifunctional Land Use

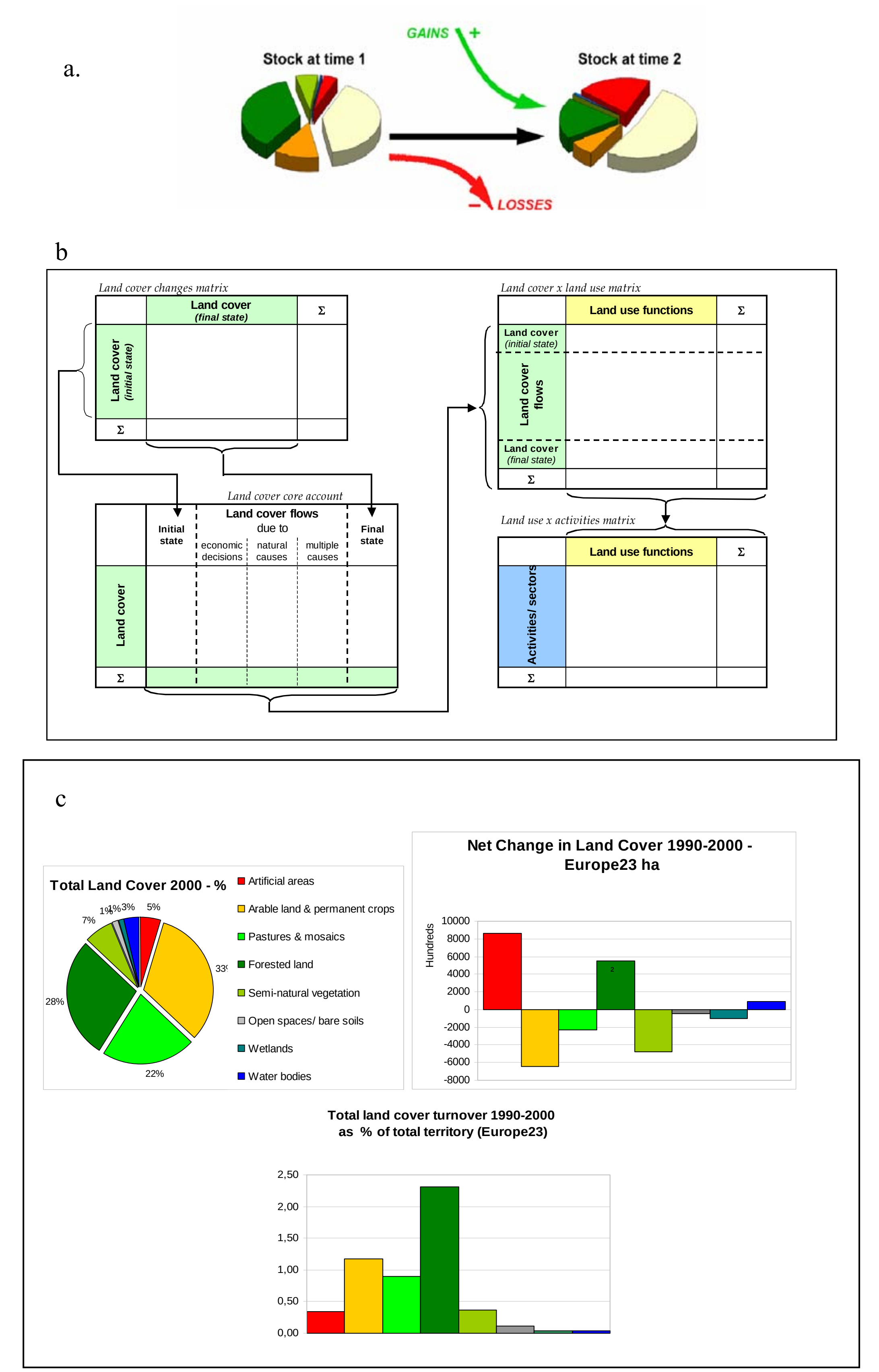
6.2. The term 'multifunctionality' is used to describe situations where people achieve or attempt to achieve multiple goals in their use of a parcel of land or the wider landscape. In the rural areas of Europe and many other parts of the world, multifunctionality, is the norm since rarely do individual land parcels have only one purpose or use. However, it has become the focus of discussion in much of the recent research literature (see for example, Brandt and Vejre, 2004; Helming and Wiggering, 2003), because people and communities increasingly need to find ways of sustaining a range of benefits or outputs from a given area. The problem of limits arises because, in a mixed land cover mosaic, use conflicts may arise.

6.3. A tool to look at the dynamics of multifunctional land cover/use is the notion of land accounting, that can be used to describe how the stock and quality of land cover and the uses associated with it change over time (Figure 6.1). Thus one may envisage a land mosaic, defined by the stock of different cover types at time 1, being transformed to a mosaic at time 2, as new stock is created or old stock is lost, as a result of the process of land cover change, such as urbanisation, reclamation, afforestation and abandonment, etc. (Figure 6.1a). Such dynamics can be documented systematically in 'land accounts' which provide a 'balance sheet' for the different land covers and uses (Figure 6.1b, c).

6.4. The impetus to develop such land accounts is now actively being promoted at the European scale by the European Environment Agency (for example, EEA, 2005; Weber et al., 2003), as part of the more general development of Standard Environmental Economic Accounts initiative being promoted by the United Nations[23]. The work of the EEA builds on earlier research undertaken

[23] SEEA2003, Integrated Environmental and Economic Accounting, Chapter 8, Section F Land and Ecosystems Accounts, §8.336 to §8.399 Publication forthcoming in the first half of 2004. Electronic version available at http://unstats.un.org/unsd/environment/seea2003.htm

Figure 6.1: The Land Cover Accounting Model used by the EEA (Source: Weber, et al., 2003)



in Europe, to which the UK made an important contribution using the results of Countryside Survey 1990 (see Haines-Young, 1999).

6.5. In the context of the present discussion of limits and thresholds, the idea of land cover accounting is useful because it poses a series of challenging questions about the nature of the transformations depicted and the 'critical points' might be crossed. For example, in the context of the goal of sustainable development, we may look at the transformation over an accounting period and ask:

a. Do the gains in cover or use compensate for the losses?

b. Is the quality of the stock carried over maintained, in the sense that retains its capacity to sustain or expand a given suite of uses or to provide a particular set of benefits?

6.6. Resolution of the question of compensation clearly requires an understanding of the benefits associated with a given land cover element and the status those benefits have in the new mosaic. Moreover, it requires some set of criteria by which the significance of the change in benefits can be judged. The decision that some 'critical point' has been reached, and that gains do not in some sense compensate for losses would represent a limit as we have defined it is this study. Such a limit defines a point where questions about weak and strong sustainability have to be resolved.

6.7. For example, in a particular area, woodland cover in general might be regarded as a constant natural asset, in the sense that while we may accept that individual woodlands can be lost and gained, it is the overall woodland cover that must be maintained. As long as woodland cover is stable or increasing, we would judge that the gains over the period compensate for the losses. However, certain types of woodland, such as ancient woodland, could be regarded as a critical asset which fundamentally cannot be replaced. Thus while woodland cover might increase over an accounting period, we may judge that compensation has not occurred if losses included a significant proportion of ancient woodland.

6.8. Clearly, questions of sustainability in relation to land cover do not only depend on the stock of cover types and the uses or benefits associated with them. In many situations land cover changes only very slowly, and much of the stock is simply carried over. Thus in addition to judgements about the implications of changes in stock, questions of sustainability also depend on whether the condition or quality of the stock carried over is maintained. As was observed from the results of the Countryside Survey 2000 (Haines-Young et al., 2003), in Great Britain the quality of many of our Broad Habitats had declined between 1990 and 1998, even though their areal extent had been maintained.

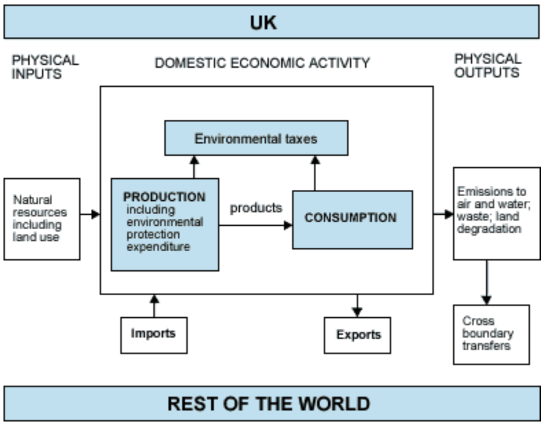
6.9. A better understanding of what constitutes quality, and in particular what limits can be set to assess changes in the quality of particular types of land cover is an urgent need. Examples of what can be achieved include:

- The site assessment criteria developed through Natura 2000 which set out the condition limits for a range of structural and functional attributes to determine conservation status.
- The types of decision support tools that are being developed in the context of sustainable forestry management. Reynolds et al. (2003) and Prabhu et al. (2001) have argued that one of the biggest challenges in this area is to identify and quantity the thresholds relevant to the suite of sustainable forest management indicators currently being used. They regard such thresholds are fundamentally norms or putative standards (i.e. limits as they are defined in this study), which can be used to judge whether management has been successful at achieving sustainability outcomes, and go on to develop a 'logic base' that can be used as a decision support tool in which such threshold notions are embedded.

6.10. **Approaches to land accounting are now developing rapidly in Europe and elsewhere. In order to develop the information base available to the UK, it would be valuable to examine how the simple land cover accounts that are presently published by National Statistics[24] (Figure 6.2), as part of our national environmental accounts, can be extended.** The work could:

- Draw upon a wider range of available data to make a more detailed analysis of changes in both land cover and land use,
- Analyse the relationship of changes in land cover and use to activity levels across the key sectors of the economy; and,
- Trace the implications for habitats and ecosystem services, particularly relation to the quality or levels of benefit.

Figure 6.2: Diagram showing how the areas covered by environmental accounts relate to the economy as described by the National Accounts




Source: http://www.statistics.gov.uk/cci/nugget.asp?id=143

[24] http://www.statistics.gov.uk/statbase/Product.asp?vlnk=3698

As Weber et al. (2003) have noted, land accounts are key platforms on which to build ecosystem accounts covering issues such as biodiversity and materials use such as water. **The extension of land cover accounting methods is likely to complement other mass-balance studies being addressed under the umbrella of the UK Sustainable Consumption and Production Strategy, and would facilitate better analysis and modelling of long term trends.** At present the only 'decoupling issue' related to land that is considered is the proportion of housing built on previously developed land (see Chapter 3, para 3.31 ff.).

### Multifunctional Landscapes

6.11. The literature on land cover and land use change, and particularly that part of it which deals with questions about the existence of limits and thresholds, is closely related to a much wider body of materials dealing with landscape. It is therefore useful to broaden the discussion at this point, because the notion of landscape can provide a way of integrating a number of important issues. In this study we have followed the definition of landscape given by the European Landscape Convention[25], and take it to be 'an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors'.

6.12. A discussion of the relationships between land cover and the multiple uses that it can support clearly has resonance with the idea of ecosystem goods and services, since land uses may depend on ecosystem functions (e.g. forest products depend on woodland productivity), and be the means through which value of those functions is realised (forestry as a source of economic well-being). However, the relationship between land use and ecosystem goods and services is problematic, since clearly there are some ecosystem functions that arise at scales beyond the individual land parcel. It is in this context that it is particularly useful to think about landscape. Landscapes, like land cover parcels can have multiple uses, the difference being that the uses identified at the landscape scale are dependent not only on the properties of the parcels themselves, but on the mix and spatial relationships between all parcels in the overall mosaic.

6.13. Many of ecosystem services are broad in scale and map more easily onto whole landscapes than they do to individual land use elements (de Groot et al., 2006). The advantages of moving to this broader scale is illustrated by considering work that has sought to reference notions about thresholds and limits to ideas about landscape structure and function.

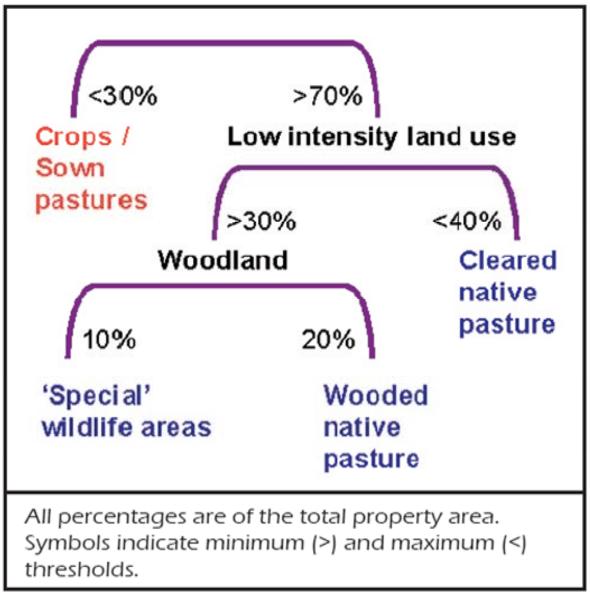
6.14. In order to resolve question about compensation relating to benefits and maintenance of quality following land cover change, many workers have sought answers in relation to properties of the land cover mosaic itself. As noted in Chapter 5 (Biodiversity), a number of studies have sought to identify biophysical limits and thresholds, and to explore their use for conservation planning and management (e.g. ELI, 2003). The latter focused on the

[25] http://www.coe.int/T/e/Cultural%5FCo%2Doperation/Environment/Landscape/

influence of habitat patch characteristics, such as size and connectivity on the persistence of individual species. Elsewhere, work has looked at issues of the structure of landscape mosaic more widely. Thus for example:

- In a recent study of three contrasting areas in Saxony, Germany, Bastian and Lütz (2006) investigated the problem of land use thresholds, specifically with the design of agri-environmental schemes in mind. They argued that depending on the study area, the minimum proportion of semi-natural biotopes that should be maintained was between 5% and 20%.
- Dale et al. (1999) have published a general set of guidelines for sustainable land use management in the North American context, which also draws heavily on threshold concepts relating to habitat patch structure and arrangement.
- Best et al. (undated) have published a set of guidelines to help balance conservation and development in Australia, based on a set of thresholds relating to land cover proportions which if exceeded will 'adversely affect ecosystem services, lead to declines in native flora and fauna and adversely affect production in the long-term' (see Figure 6.3).
- In the UK, the Woodland Trust (2003), has argued that in terms of habitat proportions, in those areas where ancient woodlands are an important feature of the landscape, then in order to sustain and improve their quality, the aim should be to achieve a mix of woodlands, semi-natural habitats and low intensity land use in the ratio 30:30:40 at the 2km x 2km scale of resolution.

Figure 6.3: Landscape thresholds suggested by CSIRO to balance conservation and development.



- A number of studies, including those based on 'model landscapes' have looked at the vulnerability of landscapes to a range of disturbances such as fire, disease spread and identified structural thresholds that determine susceptibility (Bastian and Lütz, 2006; Foley et al., 2005; Wickham et al., 2000).
- Wickham et al. (2004) have suggested some methods by which the 'geography of landscape vulnerability' can be assessed on the basis of anthropogenic threats.

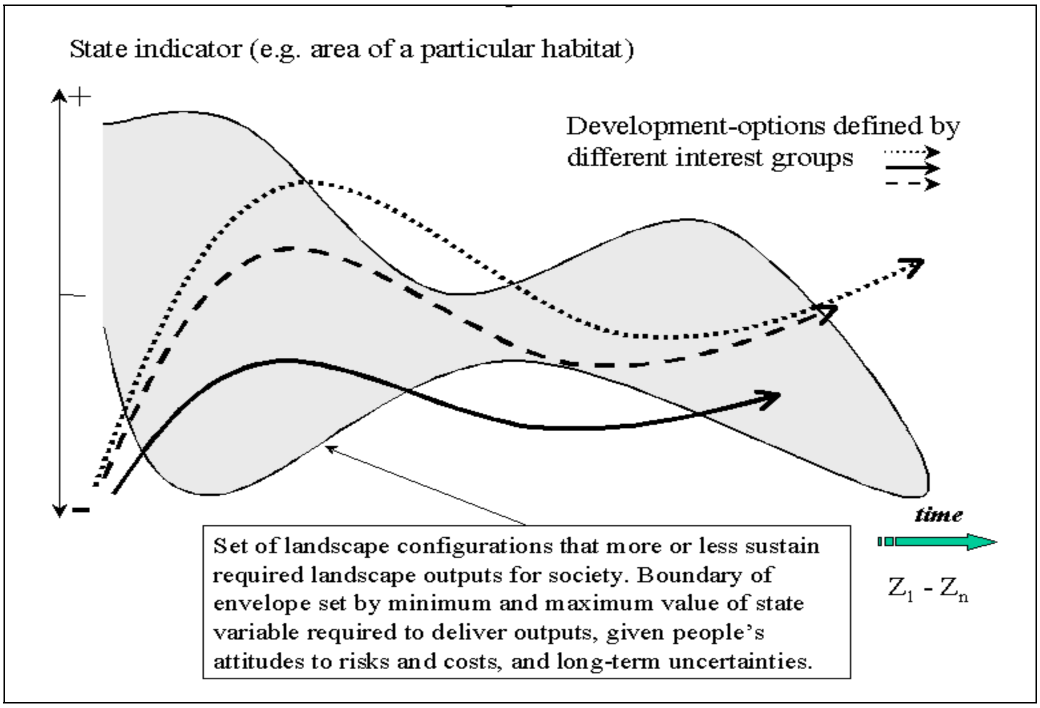
6.15. Although empirical work, such as that noted above is indicates that an understanding of landscape structure is important in terms of the factors that may limit particular ecosystem functions, there are few generalizations that can be made to assist those faced with making planning decision. Unfortunately, context is highly significant. Thus at this stage it may be wise to base judgments on a more deliberative types of approach embodied in the *Quality of Life Capital* initiative[26], which reviews potential changes in land cover or landscape by posing the following set of questions:

- What are the characteristics or attributes of this place that matter for sustainability?
- How important is each of these, to whom, and for what reasons?
- What, if anything, could act as a replacement or substitute for each of the benefits?
- Do we expect to have enough of each of these functions or services in the future?
- What kinds of management actions are needed to protect or enhance the attributes?

6.16. Using such an approach, Potschin and Haines-Young (2006) have argued that a sustainable landscape is one which is able to maintain, in the face of change, the output of landscape goods and services that people currently value or which might provide the basis of new goods and services in the future. By focusing on the outputs of good and services rather than upon land use pattern or landscape structure *per se*, the model they suggest is based on the assumption that a range of different landscape configurations might be consistent with notions of 'sustainability', and the problem is now one of understanding the boundary or set of sustainability thresholds that define this sustainability choice space (Figure 6.4). It is argued that they partly reflect the biophysical properties of the system being considered, but are finally determined by combining them with social and economic constrains, such as the views that people take of the risks and costs associated with protecting or restoring a given landscape function. In a sense, the boundary line for the sustainability choice space is somewhat equivalent to the 'safe minimum standard' that marks the transition from the marginal to non-marginal regimes discussed in Chapter 4.

[26] http://www.environment-agency.gov.uk/aboutus/512398/830672/831980/832252/?lang=_e

Fig. 6.4: Conceptualising the sustainability choice space (tongue model) (Potschin and Haines-Young, 2006)




6.17. On the basis of what we know about limits threshold responses for the individual elements of landscape (e.g. species occurrence and habitat pattern; the impact of different land covers on water quantity and quality) the task of defining these thresholds, or safe minimum standards appears to be one of combining the information about each of the components in some integrated framework or measure. Thus, for example:

- Bastian and Lütz (2006) have looked at the impact of agriculture from a multifunctional perspective, and sought to extend the AEMBAC[27] concept of *Environmental Minimum Requirement.* They developed some benchmark values for limits spanning biodiversity, landscape, soil and water. Within the landscape theme, landscape diversity, and minimum field size, the relationships between forests and open areas and linear landscape elements were considered.

- Similarly the Delbaere and Nieto Serradilla (2004) study sought to extend the approaches developed by the earlier ELISA and ENRisk[28] Projects, to identify thresholds for landscape quality. The work is based on a landscape typology of European Landscapes, created by combining information on climate, soil, parent material and land cover, and the analysis of the characteristics of these typological units in terms of their

[27] Definition of a common European analytical framework for the development of local agri-environmental programmes for biodiversity and landscape conservation (http://www.aembac.org/)
[28] Environmental Risk Assessment for European Agriculture http://europa.eu.int/comm/research/quality-of-life/ka5/en/projects/qlrt_2000_01911_en.htm

diversity, coherence and degree of openness or closure. Regions are then classified according to the vulnerability of landscape quality to agricultural change, and risk maps are then produced on the basis an analysis of various environmental pressures.

- In the UK the *Countryside Quality Counts* Project[29] led by the Countryside Agency, has developed a national indicator of how the English countryside is changing. The aim of the work, which is on-going, is to understand both where change is occurring, and most importantly, where change matters most in terms of its impact on landscape character. The notion of landscape character is central to the approach, and is used as a context against which the extent and direction of change in the individual elements that define character (woodland, boundaries, agricultural cover, settlement and development, semi-natural habitats, historic features, and river and coastal elements) can be judged.

6.18. All three studies draw heavily on expert judgement to determine what landscape thresholds exist, and what levels of change constitute their transgression. The types of threshold considered are perhaps best thought of as minimum standards, norms, or values, rather than thresholds as defined in the systems ecology literature, although they may reflect the belief or assumption that beyond such limits unstable threshold responses may be experienced. However, as yet the empirical basis of these judgements about limits and thresholds is unclear.

**Supporting decisions**

6.19. Discussion of the way in which threshold concepts might inform the development of standards, targets and management guidelines in relation to land use and landscape opens up a vast planning literature, whose analysis goes beyond the remit of this study. It is, however, important to consider how current thinking about the way in which sustainable natural resource management should be built into land use and landscape planning procedures and how policies impacting on landscapes might affect the natural resources and ecosystem goods and services associated with them.

6.20. A number of scenario planning tools and land use/landscape models are now being built to explore the implications of land use and landscape change issues. These include CLUE-S[30] and IMPEL[31], both of which can potentially be linked to the output of other sectoral models relating to climate, demographics or economic change. The aim of such work is to gain insights into the effects these drivers have on the allocation of land, soil and agriculture. Elsewhere biodiversity issues are being considered by the extension and development of the MIRABEL model, currently being undertaken as part of the BIOPRESS project[32]. This will which provides a set

[29] www.cqc.org.uk
[30] http://www.dow.wau.nl/clue/
[31] http://www.geo.ucl.ac.be/LUCC/research/endorsed/02-impel/IMPEL.html
[32] http://www.creaf.uab.es/biopress/

of tools designed for an integrated review and analysis of biodiversity in European landscapes based on the OECD DPSIR[33] framework.

6.21. In addition to these modelling initiatives, further substantial investment is being made within the EU to develop a Sustainability Impact Assessment Tool (SIAT) that will allow the assessment of policies that may drive land use change to be assessed in relation to their implications for sustainable development. The SIAT will combine the results of European-scale policy scenario analyses, and identification of regional sustainability thresholds and an understanding of stakeholder targets[34].

6.22. The development of such decision support and modelling tools is significant in the context of the present study because these initiatives will focus attention on better articulating and representing the way thresholds operate in land use and landscape systems. It is likely that such research will open up way of extending the valuation of landscape goods and services, to the analysis of risks and costs by participatory methods, although Haberl et al. (2004) have argued that material and energy flow accounting may also offer a way forward.

## Conclusions

6.23. On the basis of their review of thresholds in coupled social-ecological systems Walker and Meyers (2004) suggest that by far the most frequently citied case study deals with thresholds at the 'landscape' scale. While it is not clear from their work they take the 'landscape scale' to mean, the materials reviewed here suggest that an analysis of the relationship between land use, landscape and ecosystem services is essential for understanding how limits and threshold might generally constrain human action.

6.24. In the UK we are well placed to explore issues relating to limits further through the development of such approaches as land and ecosystem accounting. We recommend that further work is undertaken in this area. The land and ecosystem accounts potentially provides both a framework in which issues of multifunctionality can be explored, and means by which information about the status of natural resources system can systematically be assembled and communicated to decision makers.

[33] Driving-Force, Pressure- State- Impact- Response
http://org.eea.eu.int/documents/brochure/brochure_reason.html
[34] EU Integrated Project "SENSOR" http://www.sensor-ip.org/

# Chapter 7. Exploring the Evidence Base: Recreation and Access to the Natural Environment

## Introduction

7.1. The impact of tourism on the environment and natural resource systems has been given new resonance with the growth of 'sustainable tourism' and recognition of the wider benefits that the development of tourism can have for the rural economy. In this short review we explore how limits and thresholds might be identified and defined in relation to recreational use, and what impacts recreation might have on the natural resources that support it.

## Carrying capacity

7.2. In the literature relating to recreation and access to the natural environment, the term **carrying capacity**[35] has been widely used to express the idea that some limit to use might exist. In its simplest form, concept suggests that a particular place could indefinitely sustain a particular intensity of use providing that pressure does not exceed its capacity. However, beyond this limit, it is suggested that additional use would produce undesirable resource degradation. The concept has had a long history (see McCool and Lime, 2001), and over time various attempts have been made to refine and apply it. Although these efforts have often been of limited success, the concept is still discussed. The early research suggested that there are both **biophysical** and **social** carrying capacities.

7.3. Damage due to recreational use has been most easily demonstrated in relation to the **biophysical** characteristics of an area, with, for example, studies of the trampling of vegetation being common in the literature (Cole and Bayfield, 1993; Manning, 2002), along with measures of damage arising from vehicles (Collins, 1999). The results of such studies tend, however, to be locally specific to the types of environment or habitats being considered, and few generalisations have been possible. In fact, the experimental conditions often do not reflect real visitor pressure, which are usually more diffuse across a site. As a result the experimentally calculated indices are only relative indicators for species or habitat types, and cannot easily be translated into limits for setting visitor numbers more generally.

7.4. Attempts to measure the **social** carrying capacity have been equally limited. They have generally started from the assumption that such measures will depend upon the motivations of tourists during a visit, so that a range of social carrying capacities in fact exist for a given site or area (see McCool and Lime, 2001). Thus such work often began by defining a 'hierarchy of needs' and explored relationships between recreation use level and ability to achieve certain desired outcomes of the recreation experience, such as challenge, solitude, and companionship. Although empirical relationships could be established between these dimensions and visitor number, the results were often site and time specific.

[35] Sometimes 'recreational carrying capacity' or 'tourism carrying capacity'

7.5. As a result of the problems that have been encountered in attempting to conceptualise and measure biophysical and social carrying capacities, Krumpe (2000) has concluded that that there is little empirical evidence to support the way in which the term is used and promoted by politicians and resource managers. Price (1999) also argues that the concept is 'seriously flawed' and may be no more that 'a self-validating belief', and along with others (e.g. Dhondt, 1988; McLeod, 1997; Roe, 1997), casts doubt on its ability to serve as a paradigm for managing tourism development. A key issue that undermines the concept has been highlighted by Cole (2003), who points out that the fundamental limitation in the research is that carrying capacities cannot assigned objectively. From the outset the approach involves value-based decisions about what the important qualities and functions of a site are, and how they should be used to define such limits.

**Alternative Approaches**

7.6. In response the inherent limitations of the carrying capacity concept for recreation, alternative approaches to define limits of recreational use have been tried. Thus for example, in the context of wilderness management the Limits of Acceptable Change (LAC)[36] planning process was developed in order to make explicit the value judgments about appropriate types and levels of use and their management. The system explicitly recognised that all recreational use of wilderness causes some impacts, but a limit should be placed on the amount of change to be tolerated. At the core of the nine-step process are the selection of indicators of change, the development of standards, the assessment of current conditions through inventory and monitoring, and the formulation and implementation of management prescriptions to bring conditions into compliance with standards. The LAC process recognises an explicitly political component of establishing limits on the use of public resources (Krumpe, 2000).

7.7. Other approaches that have been suggested to frame ideas about levels of accept able use include a 'cautious iterative identification process with a long lead time' described by Collins (1999). This involves developing an appreciation of limits by commencing management with a substantial underestimate of the carrying capacity. The subsequent impacts on a relevant set of environmental quality indicators are then recorded, and these observations inform judgements about capacity in the subsequent period, which may involve additional levels of use if it is judged that damage has not occurred. A drawback of this approach is that it requires a major slowdown in development plans and lower financial returns on tourism-related investments. There seems to be little beyond anecdotal evidence to suggest that the approach has been widely used, although in practice this is effectively the situation that managers face as recreational pressures grow, because at some point they may need to make a judgement that resources are at risk (see below).

[36] http://www.fs.fed.us/r8/boone/lac/lac_process.shtml

7.8. Although the LAC concept has not been applied explicitly in the UK, it has resonances with attempts at to map tranquillity and the way it is changing over time, championed by CPRE in the 1990s. Although their analysis dealt with the countryside as a whole, and was not specifically directed at the relationship between tranquillity and tourism, the approach was based on the proposition that the impact of development on tranquillity undermined the benefits that a peaceful countryside would otherwise provide. As Levett (2000) has pointed out, however, there is little by way of empirical or theoretical justification for the mapping approach used, which was driven more by the technical capabilities of GIS than an understanding of how people frame tranquillity in the countryside. This approach has now been superseded by a more robust approach to tranquillity mapping, based on participatory appraisal techniques, developed by MacFarlane et al. (2004).

### Objectives and targets rather than limits

7.9. As we have seen, attempts to define carrying capacity or related concepts such as LAC have largely meant developing normative judgements about what ought to be done in a given area. These cover such questions as what recreational opportunities should be provided, what conditions should be maintained, and how recreation use should be managed (cf. Cole, 2003). Thus in turning away from notions that general limits can be defined, resource managers have become more concerned with identifying resource management *objectives,* which in turn guide management practices rather than rigorously attempting to measure anything like a maximum capacity for use (Farrell and Runyan, 1991).

7.10. At it simplest level such objectives might be to ensure that visitor pressure does not result in the loss of the characteristic species of the plant communities that typify the area of concern (Gallet and Roze, 2001). Somewhat similar objectives have arisen in the England with the implementation of the CRoW Act, which give people free access to mountain, moor, health and down, except where an particular site sensitivities exist in particular places (e.g. SSSIs) or at particular times (breeding or hunting seasons). Conflict resolution by some kind of zoning (or design of a 'recreational opportunity spectrum') is likely to be an important way of managing recreational access to environmental resources as pressure of visitor numbers grows.

7.11. More sophisticated examples of attempts to define objectives and targets rather than to specify maximum capacities for use are illustrated by the efforts to promote minimum levels of recreational provision, such as that by English Nature in relation to 'greenspace'[37]. Following such work as Harrison et al. (1995), English Nature have argued that local authorities should consider the provision levels such that there is:

- an accessible natural greenspace less than 300 metres (5 minutes walk) from home;

[37] http://www.english-nature.org.uk/special/greenspace/

- statutory Local Nature Reserves at a minimum level of one hectare per thousand population;
- at least one accessible 20 hectare site within two kilometres of home;
- one accessible 100 hectare site within five kilometres of home; and,
- one accessible 500 hectare site within ten kilometres of home.

7.12. Although an attempt was made to base these standards on empirical evidence, and to promote them in terms of public health benefits, Harrison et al. (1995) have noted that insufficient data were available to justify these standards, and recommended a more detailed and comprehensive survey to be made. As they stand therefore, the standards remain largely normative.

7.13. The extent to which targets and standards in relation to recreational provision can be anything other than normative is a moot point. Many assert that we must simply accept that they are, and develop approaches to management that take account of the values that managers bring to the problem of resource management. Thus McCool and Lime (2001) suggest that future research strategies in the area of sustainable tourism should focus on developing frameworks and approaches that would allow managers to determine which of the many plausible futures are desirable, what social, economic and environmental conditions are required for tourism development, what tradeoffs might be necessary, and how people (both tourists and residents) can be included in decision making.

7.14. Clearly the approach recommended by McCool and Lime (2001), is one that would enable researchers to show more clearly the benefits which the biophysical environment can provide for people, the way they are valued by different people in different places, and ultimately how they view the costs and risks that are associated with sustaining those benefits at different levels. Such work is therefore likely to be informed by the current work involving the valuation of environmental resources based on people's willingness to pay and willingness to travel, and by the marginal values they place on changes in the outputs of ecosystem goods and services associated with the places they visit. As the recent work for the EEA has shown (Weber et al., 2003) such an approach would also benefit by collating data on recreational use in the form of a set of environmental accounts related to land cover so that the pressures associated with it and the linkages it has with other sectors of the economy and natural environment, can be explored systematically.

## Conclusions

7.15. The materials we have reviewed in the area of recreation and access suggest that notions of limits and thresholds are perhaps of restricted value in developing management strategies for recreation, and that objective or target-based approaches are probably more appropriate. Indeed, it could be argued that in the UK, the objective- or target-led approach to managing recreational use of the countryside is well established, as a result of the various types of management plan have and are being developed for both our protected landscapes and the wider countryside. However, this is probably an over simplification.

7.16. It may well be that a consideration of limits and capacities will re-emerge to inform objective- and target-led management strategies, not by trying to develop better direct measures the physical or social capacities of a place, but rather the constraints that social, cultural and economic values imply for its use.

7.17. As the recent experience arising from the outbreak of Foot and Mouth Disease (FMD) has shown (see Thompson et al., undated), access to the countryside and the resources associated with it, is an important factor in the rural economy. Basing their estimates on data from surveys of tourism, businesses directly affected by tourist expenditure these workers estimated that FMD resulted in a loss of between £2.7 and £3.2 billion as a result of reduced numbers of people visiting the countryside. Although some of the loss in expenditure was displace to other sectors of the economy, the impact on many rural businesses was serious.

7.18. The interface between the management of recreational pressure and the understanding of limits and thresholds associated with land use and landscape is an important one. **Our review suggests that valuable way in which the evidence base could be developed in this topic area would be to build an environmental account for recreational and tourism.** A prototype approach has been developed by the European Environment Agency. Such an account can be used to identify the pressures associated with recreation and the linkages they have with other sectors of the economy and the natural environment. Such an account would have particular relevance in the context of monitoring future patterns of sustainable consumption and production, and the ‘decoupling’ of recreation and tourism from its wider environmental impacts.

7.19. In the UK, our extensive system of protected and heritage sites with their different characteristics and varying level of accessibility, we are particularly well placed to undertake research that will enable us to better understand the way people use and value recreational assets. **As we look to the future therefore, we recommend that the evidence base can best be developed by better understanding the relationship between recreation and the elements of our natural capital that support it.** Such work on the value of the natural environment for recreation and access is likely to be informed by current work involving the valuation of environmental resources based on people’s willingness to pay and willingness to travel, and by the marginal values they place on changes in the outputs of ecosystem goods and services associated with the places they visit.

# Chapter 8. Exploring the Evidence Base: The Marine Environment[38]

## Introduction

8.1. The UK Marine Stewardship Report, *Safeguarding our Seas* (D*efra*, 2002) sets out the Government's vision for the marine environment, which is broadly for a 'clean, healthy, safe, productive and biologically diverse oceans and seas, and to have made a real difference in one generation'. At the heart of the strategy is the ecosystem approach, which seeks the promotion and understanding of current ecological status and the identification of ecosystem properties that are structurally and functionally important, and the threats to which they are subject.

8.2. The approach to future policy and management that is envisaged is one based on gaining knowledge through integrated ecosystem assessment, and the use of such evidence to set ecosystem level objectives that cover the protection of the marine environment and the regulation of human activities. The refinement of these objectives will also be shaped by the requirements of the Water Framework and Habitats and Birds Directives, and the EcoQO framework currently being developed by OSPAR (OSPAR, 2003).

8.3. As Rogers et al. (2005) have noted the concept of a healthy marine ecosystem needs to be resolved across a range of sectors and policy areas. For example, it might focus on water quality issues and relate to nutrient loadings, or it might be defined from a fisheries perspective and involve considerations of the maximum sustainable level of benefits that can be achieved from a fishery. Common to all, however, is the fact that in setting objectives, there should be some understanding of the ***limits*** beyond which unacceptable harm to the marine environment will be caused, and the ***targets*** that need to be met if the overall quality of the marine environment is to be achieved.

8.4. In this short review we focus on the conceptual issues surrounding the identification of limits and their relationship to targets in the context of the ecosystem approach to the management of the marine environment, rather than focus on the specific types of pressure that may be driving systems to collapse.

## Threshold Responses and the Identification of Limits

8.5. The state of marine systems can change rapidly as a result of both natural and human pressures, and there are many examples in the research literature to support the proposition that threshold responses and regime shifts can occur. For example:

a. Ocean-atmosphere interactions, such as El Niño in the Pacific Ocean, the Pacific Decadal Oscillation or the North Atlantic Oscillation, cause large scale oceanographic changes which are often cyclical. El Niño

[38] Chapter 8 draws heavily on the position paper by Agnew, D. (2006): Marine Environment. Unpublished Position Paper for Scoping Study on "Defining and Identifying Environmental Limits for Sustainable Development, funded by D*efra*. (see Appendix A).

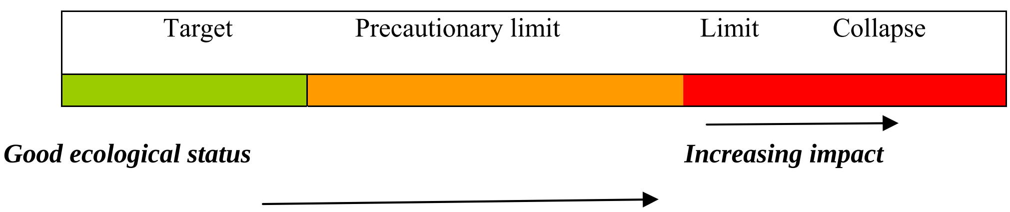
itself is most famous for its effects on Peruvian anchovy stocks, which are severely reduced during El Niño years, and for shifting the position of warm core water in the western Pacific and, with it, the distribution of skipjack tuna (Lehodey et al., 1997). As a result Pacific sardine and anchovy populations have experienced cyclical periods of abundance and collapse in response to changing climatic/oceanographic conditions have been significant, including:

b. An end of a fishery that had been maintaining Newfoundland populations since the 1800s (Baumgartner et al., 1992).

- Major regime shifts may also apparently be triggered by human activity, in particular over-exploitation of fisheries resources. A recent example is the wholesale collapse of many stocks of cod and haddock from the grand banks area off Newfoundland in 1991. This collapse does not seem to have been the result of changes in oceanography or environment, reductions in recruitment, or increased predation, but rather poor management and over fishing (Hutchings and Myers, 1994; Hutchings, 1996). The social and environmental effects of the collapse.
- Major changes in the structure of the marine ecosystem, involving increases in the populations of cod prey species such as shrimp, crab, capelin and flounder, and the decline of large demersal feeders.

8.6. Given the problem that thresholds are difficult to foresee before they are crossed many have advocated approaches to policy and management for the marine environment which are essentially precautionary, involving identification of indicators of the integrity of the marine system, and the specification of limits, or 'reference points' that might trigger different levels of policy or management response. Figure 7.1 shows the relationship between target, precautionary and limit reference points described in the guidance provided by the European Commission for the application of the ecosystem approach to the management of human activities in the marine environment (EC, 2004). This model is consistent with the general schema described in Chapter 2 of this report, except it introduces the notion of a **target**, which is some way above the precautionary limit.

Figure 7.1: Relationship between target, precautionary and limit reference points (EC, 2004)



8.7. Precautionary reference points are generally set to ensure that irreversible harm does not occur. Thus in the context of individual fish stocks, where data on actual limits of viability are unavailable, the precautionary limits may be set using the lowest biomass observed from historical records. Identification of such a limit should not, however, be taken as a justification that the systems should be managed at this level. Rather, on grounds of caution it is probably more appropriate to aim at some target condition where the status of the system is judged to be favourable or good. As Rogers et al. (2005) note, the European Marine Strategy has proposed that meeting the objectives for good ecological status will be achieved by achieving targets, rather than avoiding limits.

8.8. While the European International Council for the Exploration of the Sea (ICES) defines only precautionary and limit reference points, other management authorities have developed different approaches. For example, the National Marine Fisheries Service (NMFS) of the National Oceanographic and Atmospheric Administration in the US has developed a 6-tier system for its fisheries, based on different levels of uncertainty and knowledge about the stock (e.g. NPFMC, 2004). Lower levels of uncertainty allow more precise estimates of sustainable yield to be made; higher levels of uncertainty require more conservative, or precautionary approaches to be taken. This approach is consistent with that defined in the FAO's Code of Conduct for Responsible Fishing (FAO, 1995, 1998).

8.9. **Although the theory and application of reference points for *single species fisheries* is well established, the development of reference points for other ecosystem components is much less well advanced (Rice, 2005).** This poses a particular challenge in terms of implementing an integrated ecosystems approach to the management and protection of the marine environment. It is generally accepted that a site of indicators is required to describe the integrity of the system, examples of which Rogers et al. (2005) suggest are:

a. Indictors relating to the condition of populations in relation to disease and contaminant loads;

b. Indicators relating to the population status of individual species;

c. Indicators based on the status of community properties, such as richness, diversity; and,

d. Indicators of ecosystem function, such as tropic structure and dynamics.

Given that many marine systems are, in fact, 'coupled socio-ecological systems' it is possible that this list should be extended to include elements from the social and economic realms.

8.10. **In terms of the robustness of the evidence base available to policy customers and managers, there is currently scant information or understanding about the kinds of reference points that might be constructed around these wider indicators of ecosystem structure and function, and how these limits vary over time and space. Our review suggests that further work is required to understand how the limits and targets identified across each of the ecosystem dimensions should be**

**compared or combined, since objectives may not always mutually consistent. In addition further information is required about how those limits and targets might need to be adjusted over time, in the light of changes in external drivers such as patterns of human development or climate.**

8.11. The management of populations of species that are ecologically dependent on economically exploited populations illustrates the kinds of issue that is likely to arise with the implementation of an integrated approach to ecosystem management. A case study that illustrates the types of situation that is increasingly likely to arise is that of the sandeel fishery of the North Sea, which was closed in June 2005, partly because of concerns about the effects of low sandeel population sizes on kittiwake breeding success (RSPB, 2005).

8.12. While reference points for individual species and ecosystem components are likely to be based primarily on biophysical criteria, the problem of setting targets, and of prioritising limits and targets across different ecosystem components, will mean that questions of the values that society attaches to those properties or outputs of the marine ecosystem will come into play. Further development of the tools and concepts needed to handle questions of environmental values will therefore be necessary.

8.13. For example, as a result of seeking to apply the ecosystem approach, the concept of Monitoring of Large Marine Ecosystems (LMEs) has received considerable attention both in the US and Europe (EPA 2005; UNEP-WCMC and MRAG, 2004). In the LME approach, assessments are based around a series of five modules: productivity, fish and fisheries, pollution and ecosystem health, socioeconomic, and governance (Sherman, 2003; UNEP-WCMC and MRAG, 2004). The socio-economic and governance modules are probably least developed, although they are ultimately the operational interface of assessment (UNEP-WCMC and MRAG, 2004).

## Conclusions

8.14. Threshold responses are evident in the marine environment, and the application of limits has been attempted as one way of guarding against the risk of collapse of marine systems. However, the need to develop integrated approaches to ecosystem management poses a considerable difficulty in deciding what limits or reference points should apply and how they should be prioritised, and this poses a considerable research challenge. There is little doubt that the ecosystem approach is reshaping fisheries policy, largely as a result of the different view it imposes about environmental limits (Pope and Symes, 2002). The extent to which the objectives of fisheries-based ecosystem management will drive approaches that prioritise conservation is, however, likely to remain a contentious issue.

8.15. Our review of the marine situation is of particular interest in the context of the study of limits overall since, compared to other topic areas, it has thrown into sharper focus the important relationship that needs to be negotiated between limits-based and targets-based approaches. Both are compatible with the ecosystem approach, providing that management actions set to avoid limits do not compromise other management actions designed to achieve wider targets. The ecosystem framework is a particularly good one in which to set them, as it potentially encourages an integrated approach to indicator construction than has been apparent in the past.

8.16. There is a clear advantage of target-based approaches to management over methods based on limits, because targets focus on achieving good ecological status rather than a safe minimum standard. The identification of targets is perhaps more closely dependent on the values that society places on the different ecosystem components and the benefits associated with them, so that issues may be more difficult or contentious to resolve than questions of limits which are based more firmly on biophysical criteria. Despite this tension, our review suggests that in the real world, when faced with incomplete information, the two approaches are not really alternatives. Which ever approach is adopted it seems increasingly clear that for them to be accepted and applied they will have to meet to kinds of decision making norms envisaged by the Millennium Assessment, which involve deliberative and flexible approaches to management issues (cf. Barkley Rosser, 2002; Hughes et al., 2005). Such a conclusion is also consistent with the view developed in the recent report of the Royal Commission on Environmental Pollution, *Turing the Tide*[39].

[39] Royal Commisson on Envronmental Pollution (2004) *Turing the Tide,* http://www.rcep.org.uk/fisheries/englishsummary.pdf

# Chapter 9. Exploring the Evidence Base: Water – Supply and Demand[40]

## Introduction

9.1. The European Water Framework Directive (WFD) and the European Habitats Directive will profoundly change the way in which water resources are managed in the UK, in that they will promote and require a more integrated approach to the management than has occurred in the past. The key objectives of the WFD, for example, are to:

a. Enhance the status and prevent further deterioration of aquatic ecosystems and associated wetlands. There is a requirement for nearly all inland and coastal waters to achieve 'good status' by 2015;
b. Promote the sustainable use of water;
c. Reduce pollution of water, especially by 'priority' and 'priority hazardous' substances;
d. Lessen the effects of floods and droughts; and,
e. Rationalise and update existing water legislation and introduce a co-ordinated approach to water management based on the concept of river basin planning.

9.2. All conservation sites designated through the Habitats Directive will become 'protected areas' under the WFD, and water quality objectives developed through the WFD will be shaped by the conservation objectives and ecological quality criteria developed under the Habitats Directive. Taken together, therefore, these two Directives will ensure that the 'ecosystems approach' will be central to water resources management in the UK. In this short review we consider how thinking about limits and thresholds may shape the way forward.

9.3. Our review has identified three pressure points with implications for environmental limits that are likely to emerge at global scales different times in the future in relation to water quality, supply and demand:

- in the short (20 year) term, human impact on the reserves of freshwater that is readily available in rivers and lakes is likely to increase, and so needs to be very carefully managed;
- in the mid (20-50 year) term, improving and protecting groundwater quality will be essential for the sustainable management of the freshwater environment; and,
- in the long (50 year +) term, climate change impacts on water bound in snow and ice will have far reaching but unpredictable impacts on the water environment.

[40] Chapter 9 draws heavily on the position paper by Heathwaite, A.L. (2006): Water Quality, Supply and Demand. Unpublished Position Paper for Scoping Study on "Defining and Identifying Environmental Limits for Sustainable Development, funded by D*efra*. (see Appendix A).

9.4. Since issues of climate change are discussed elsewhere in our study, this chapter deals only with the first two sets of pressures, with particular reference to the UK. We consider first issues of water supply, with particular reference to current thinking about how use limits might be set. We then look at issues relating to water quality.

**Water Supply: the concept of 'environmental flows'**

9.5. The recent debates surrounding the ideas about integrated water management and the sustainable use of water have emphasised the importance of thinking about limits and thresholds in a wider ecosystem context. Policies relating to water supply have in fact begun to move away from simply seeking to ensure maximum extraction of available water for Society, to perspectives that emphasise the wider benefits that river and lake systems have to people. The concept of 'environmental flows' is now one actively being promoted, for example, by the IUCN (see Dyson et al., 2003) and other international bodies[41].

9.6. King et al. (2003) suggests that approaches to flow assessment have evolved over time, and have ranged from those which were more narrowly hydrological, through techniques based on hydraulic rating, habitat rating and to the more holistic methods that are currently being considered. The earlier approaches were, as their names suggests, mainly based on hydrological data and were largely insensitive to the wider consequences that flow modification might have. Although based on river specific data, they generally failed to indicate the consequences that changes physical conditions might have, for example, for the aquatic biota. These limitations led to the development first, of habitat-rating methods, and then more latterly to holistic approaches that have come to be referred to as 'environmental flows'.

9.7. According to the Dyson et al. (2003), an environmental flow is the water regime provided within a river, wetland or coastal zone that is sufficient to maintain ecosystems and their benefits, where there are competing water uses and where flows are regulated. In a policy context, the need to understand and to maintain such flows, is often presented as the key step in ensuring the overall health of, say, an entire river system[42].

9.8. Decisions about what constitutes an environmental flow are often iterative in character, since the methods suggests attempt to avoid the pit-falls of the earlier formulaic approaches. The intention is generally initiate a more deliberative approach, through which the consequences and risks of different management policy options can be explored. To illustrate the idea, the IUCN Report (Dyson et al., 2003), uses a case study from the River Wylye Catchment in England, where there are four major pumped groundwater sources. In order to set acceptable abstraction levels, the Environment Agency considered a set of scenarios ranging from no abstraction to full abstraction from all sources, with different combinations of pumping rates. Each scenario

[41] http://iucn.org/themes/wani/pub/FLOW.pdf; and
[42] http://www.deh.gov.au/water/rivers/flows.html#flows

was then assessed according to the impact on habitat for target fish species and the water supply for the public and industry, and the results used as a framework for discussions with stakeholders, such as fisherman and the representatives of water companies[43].

9.9. The importance of the environmental flow concept is that it sets up a framework in which the delivery of ecosystem-related goods and services can be considered, and the relative values that people associate with them brought into sharper focus. They are therefore particularly relevant in the context of debates about sustainable consumption and production, because they show how notions of sustainability might need to be redrawn once the wide consequences of maintaining particular levels of consumption are considered. With the scenario approaches that discussions of environmental flows foster, the marginal costs and benefits of different management options can potentially be considered and communicated more effectively.

**Diffuse Pollution: land use pressures, sediment transport and their impacts on aquatic ecosystems.**

9.10. Unlike the fisheries of the marine environment, and with the exception of lentic water bodies, freshwater systems do not generally experience threshold type dynamics, with rapid regime shifts changes in water quality. Rather, changes are thought to be a gradual process[44]. The limited evidence for regime shifts in the freshwater environment may be a consequence of the large bulk of the freshwater stock – groundwater – being subterraneous and consequently difficult to monitor. This does not mean that thresholds are not crossed; just that they are much more difficult to detect.

9.11. In the short term, human impact on the freshwater that is readily available for exploitation in rivers and lakes requires careful management if the quality and quantity of the resource is to be sustained. Human activities have increased the availability of nutrients such as nitrogen and phosphorus in freshwater and coastal environments. Although it is known that changes to nutrient loadings to ecosystems affect carbon and nutrient transformations, the literature suggest that predicting the responses of ecosystems to nutrient loading is difficult because multiple factors regulate biogeochemical transformations in freshwater and coastal ecosystems. The sources of elevated nutrient loadings are relatively well-understood, and much work has focused on how they might be limited through regulation.

9.12. Reduction in point source nutrient loadings from, for example, sewage treatment works, has shifted the emphasis to agricultural diffuse pollution as a significant threat to the long term sustainability of freshwater ecosystems. Diffuse pollution is a critical issue because the cost of tackling only the tangible aspects of diffuse pollution from agriculture in the UK has been estimated by be around £300 million per year (Pretty et al., 2003). However, approaches to policy have largely been target-led rather than driven by the

[43] See Acreman, M.C. Adams, B. (1998) Low flow, groundwater and wetland interactions. Report to Environment Agency (W6-013), UKWIR (98/WR/09/1) and NERC (BGS WD/98/11)
[44] www.apis.ac.uk

identification of limits. Reducing diffuse pollution is, for example, a central aim of the UK Government's Sustainable Food and Farming Strategy (D*efra*, 2002) and is critical if Public Service Agreement targets to bring 95% of SSSIs into 'favourable' condition by 2010 are to be met.

9.13. The environmental consequences of land management decisions include the degradation of freshwater ecosystems, increased water treatment costs and reduced aesthetic value. The main physical drivers of these processes have been identified (e.g. for water quality degradation they include sediment-associated contaminants, livestock waste disposal, and pesticide and veterinary medicines). However, from a social and economic perspective, the impacts of these drivers are largely external to the agricultural system and are not factored into decisions. Consequently, limits for freshwater ecosystems are not linked to the land management decisions that may be causing their deterioration. Only recently has this status quo started to change towards more risk-based evaluation of land-water causality. The source of this change is primarily legislative in the form of the WFD but also in terms of the reform of the Common Agricultural Policy (CAP) away from headage payments and towards environmental stewardship via the Entry Level Scheme (ELS) and Higher Level Scheme. Risk-based management is a relatively new science involving uncertain decisions and thresholds are as yet difficult to discern. Much risk-based science follows the DPSIR (drivers, pressures, states, impacts, and responses) modelling framework for risk forecasting[45] .

9.14. While the control of diffuse pollution is a major theme in the literature, issues arising out of sediment transport are also important. Sediment plays a major role in the transport and fate of pollutants and is of critical concern in water quality management. Toxic chemicals can become attached, or adsorbed, to sediment particles and then transported to and deposited in receiving waters. Unlike water, sediments can be long-term or permanent sinks for contaminants in rivers and lakes, posing a risk to ecosystem function, water resources and human health. River beds are transitional environments between groundwater and surface water, and are known to be both a sink and source of fine organic and inorganic sediment and associated pollutants, including phosphorus. Stream borne sediment directly affects fish populations through reduced light penetration and increases susceptibility to disease through irritation of the gills, scales and mucous covering the eyes.

9.15. Our review suggests that, traditionally, environmental research has been compartmentalised in different sectors (e.g. air, land, water) and has been integrated across the different compartments (Harris and Heathwaite, 2005). The holistic approach to river basin management required under the Water Framework Directive has recently pinpointed the strategic importance of understanding sediment sources, pathways and sinks as a controlling 'switch' on the state of aquatic ecosystems.

9.16. Figure 9.1 illustrates the controls and potential limits for the impacts of fine sediments in rivers. It shows the complexity of the links from sediment deposition to ecological impacts and begs the question as to whether

[45] www.org.eea.eu.int

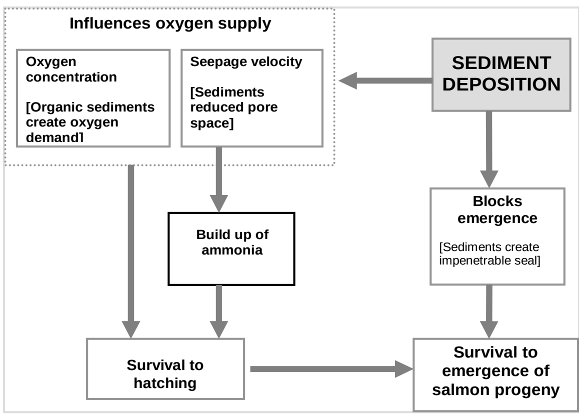
ecologically acceptable levels of fine sediments can be set in rivers for e.g. salmon. Current research (Graig et al., 2005) suggests that limits cannot be defined at the river reach scale, and probably not at river scale, because salmon spawning depends on a combination of factors and these factors vary in time and space. The causes of low pre-emergent survival of salmon appear to be river-specific, which means that it is difficult to set ecologically acceptable levels of fine sediments in rivers. Preliminary research suggests, however, that oxygen flux is a critical factor in spawning success. Elevated nutrient loads generate increased organic matter detritus which in turn increases the sediment oxygen demand; the latter appears to be an important control on spawning success but to date there is no research to indicate appropriate levels for fine sediments in rivers. **The evidence base needs to be developed in this area.**

### Sustaining Groundwater Quality

9.17. In the mid term, improving and protecting groundwater quality will be essential for the sustainable management of the freshwater environment. The challenges are already been felt in the context of water abstraction, saltwater intrusion into groundwater bodies, wetland sustainability, and water treatment to maintain the quality of water supplies.

9.18. The quality of groundwater in UK aquifers has deteriorated significantly over the last few decades. The UK Groundwater forum[46] estimate that around 2450 Ml per day, almost 50% of the groundwater used for public supply is affected by quality problems. Research funded by UK Water Industry Research Limited (UKWIR) and the Environment Agency found that deteriorating groundwater quality in the UK has cost the water industry c. £754 million since 1975 – over 60% was spent on treatment schemes, 17% on blending, and 24% on replacement water to compensate for source closures. The costs reflect a combination of deterioration in groundwater quality and more stringent regulatory standards for drinking water. The capital and operating costs of groundwater treatment for the water utilities are passed on to the

Figure 9.1.: Potential limits for the impacts of fine sediments in rivers (modified from Sear et al., 2003)




[46] www.nwl.ac.uk/gwf

consumer through water charges.

9.19. Groundwater contaminants come from two categories of sources: point sources and diffuse sources. Landfills, leaking gasoline storage tanks, leaking septic tanks, and accidental spills are examples of point sources. Infiltration from farm land treated with pesticides and fertilizers is an example of diffuse sources. Clearly there are links here between diffuse pollution of rivers and lakes, as described in the section above, and the contamination of groundwater resources. To date, much of the concern has focussed on nitrate contamination. However, recent evidence suggests that phosphorus in groundwater may be a potential future problem. Phosphorus contamination of groundwater may occur were there are high densities of septic systems. Problems with septic systems worsen when communities that rely on subsurface disposal systems also depend on private wells for drinking water.

**Developing the evidence base**

9.20. The use of environmental indicators or thresholds for freshwater systems has been developed to describe the state of the ecosystem, and to indicate the risks that it might move to a less-favourable status. Such systems have only recently been incorporated into land management schemes, largely in response to the Water Framework Directive (WFD) that is requiring an holistic approach to the management of aquatic ecosystems. The concept of environmental flows (Dyson et al., 2003) illustrates particularly well, how a more integrated approach to the management of water supply might be developed. Such ideas could clearly be applied to other topic areas where decisions are needed about what levels of resource consumption are consistent with the broader goals of sustainability.

9.21. Most uncertainties relate to the quality of the available data and the scale at which is it collected, however. Integrated treatment of water quality and water supply and demand issues require data from many disciplines to be brought together. Often such data and conceptual models are built around research that spans large spatial and temporal scales. **Future research is needed to identify limits in the context of new approaches to integrated catchment management, sediment transport and fate, groundwater quality evaluation and measures, and diffuse pollution modelling.** The AMP4 Process, involving the identification of pollution control measures required to ensure good water status of SSSIs, illustrates how to achieve this, despite uncertainties.

9.22. It should also be noted that many of the approaches to river basin and sustainable water management that are in use today were not designed to deal with indeterminacy in decision making, particularly about new investments to meet the requirements of, for example, legislation like the Water Framework Directive (WFD). **Thus as in the other topic areas covered by this study, the recent literature suggests that deliberative styles of decision making are likely to become increasingly important in the context of managing issues related to water quality, supply and demand.**

# Chapter 10. Exploring the Evidence Base: Climate Change[47]

## Introduction

10.1. The issue of climate change, and the implications that it may have for the integrity of natural resource systems and for human societies dominates current research and policy agendas. The topic area is a vast and complex one, and so in this part of our study we focus only on the position that the concepts of limits and thresholds have in current debates. We conclude by highlighting some of the implications for policy that emerge from recent literature.

## Gradual vs. Abrupt Change

10.2. The work of the IPCC[48] has resulted in a broad consensus across the science and policy communities, that there is a high probability that as a result of human action, climate is changing. In the context of this study the key questions that arise concern what types of change are likely to occur, and whether we are faced with the situation that, while rates of change are higher than in the pre-industrial period, are those changes essentially gradual and continuous, rather than discontinuities and potentially catastrophic. In recent years the position taken by the science community of the issue of gradualism vs. discontinuity has changed.

10.3. Early work, such as the pioneering study by Rijsberman and Swart (1990) report for the Stockholm Environment Institute (SEI), was built on the assumption of gradual change, and for them the issue was the rate at which it occurred and the implications if it were too rapid. The SEI approach based its judgment of climate change targets on what they felt was the most sensitive parts of the system (the migration rate of trees) and suggested that the limiting rate for global mean average surface temperatures was a maximum rate of change of 0.1°C/decade and 1-2°C temperature increase above the pre-industrial level. Another classic study was that of Krause et al. (1992) who also based their estimates of rate limits on the capabilities of the capabilities of ecosystems to adapt. They arrived at the same rate per decade as the SEI study, but settled for an increase of 2-2.5°C as the limit for the next centuries.

10.4. In recent years, however, it has been increasingly recognised that the Earth's climate system is highly nonlinear (cf. Severinghaus and Brook, 1999; Rahmstorf, 2002; Alley et al., 2003; Alley, 2004; Rial et al. 2004; NRC, 2002). Climatic records suggest that large, widespread abrupt climate changes have occurred repeatedly throughout the geological period (Augustin et al., 2004). The variability of the climate has been underlined in the recent study of Moberg et al. (2005) who looked at temperatures in the northern

[47] Chapter 10 draws heavily on the position paper by Olsson, L. and J. Stripple (2006): Environmental thresholds, the case of climate change. Unpublished Position Paper for Scoping Study on "Defining and Identifying Environmental Limits for Sustainable Development, funded by D*efra*. (see Appendix A).

[48] http://www.unep.ch/ipcc/

hemisphere over the last 2000 years, and showed that natural multi-centennial climate variability may be larger than commonly thought.

10.5. Definitions of what constitutes an abrupt climate change can (on the crudest level) be categorized in two groups:

a. ***Mechanistic definitions*** that focus on transitions of the climate system into a different state (of temperature, rainfall etc.) on a time scale that is faster than that of the drivers of change. Frequently cited examples in this category include rapid shifts in thermohaline circulation (Rahmstorf 2002) and a possible disintegration of the West Antarctic Ice Sheet (Oppenheimer and Alley, 2005).

b. ***Impacts-based*** definitions that focus on changes in the climate system that is faster than the adaptation of social and ecological systems.

A variant of this simple dichotomy is also to be found in Schneider and Lane (2005), who in the context of Article 2 of the UNFCCC suggest a differentiation between systemic (natural) thresholds, normative (social) impact thresholds, and legal limits.

10.6. Despite an increasing awareness of non-linear features of the climate system, the scientific community are only at the beginning of formulating and testing hypothesis in climate models and against proxy data. The extent to which these non-linearities involve points of no return or thresholds defining alternative stable states with hysterisis effects is also unknown. Thus his review article entitled "*Does the Trigger for Abrupt Climate Change Reside in the Ocean or in the Atmosphere?*" Broecker (2003) argues that much work is left to be done:

> *We are still a long way from understanding how our climate system accomplished the large and abrupt changes so richly recorded in ice and sediment. However, despite this ignorance, it is clear that Earths climate system has proven itself to be an angry beast. When nudged, it is capable of a violent response (Broecker, 2003).*

## Understanding the significance of change

10.7. Whether climate change is gradual or abrupt, the key issue that arises in terms of judging is whether those changes constitute a 'danger' of some kind is whether some threshold or limit has been crossed. A number of issues combine to make this issue a difficult issue to resolve.

10.8. The *rate of climate change* is, for example, only 'dangerous' when the response rate in society (i.e. the capacity for adaptation) or other ecological systems, is insufficient to avoid harmful consequences. Because science is only partly capable of grasping the sensitivities of many human and ecological systems to changes in climate and climate related parameters, it cannot easily assess dangerous levels for different activities. Moreover, even if all the social impacts of climate change were known, we would not be able to decide what constituted a danger simply on biophysical grounds alone, because the question of whether or not a certain impact is significant is a value-based issue that ultimately can only be resolved in the political arena (cf. Azar and Rodhe, 1997; Dessai et al., 2004).

10.9. The same arguments about what constitutes a 'danger' apply whether we are dealing with gradual or abrupt change, although clearly with non-linear responses, systems are less likely to be able to accommodate those changes. However, at present there is little consensus in the literature on how to approach the assessment of these sudden changes, although Hulme (2003) has recently provided an interesting elaboration of how we can organise the issue.

10.10. Hulme (2003) regards the IPCC (2001) scenarios as default scenarios of 'non abrupt climate change', and argues that the assessment of 'abrupt climate change' must involve the dimensions of rate, severity and direction. Hence, he suggests that abrupt climate change occurs if:

a. The *rate* of warming is greater than 0.55°C/decade, or if the rate of global sea-level rise is greater than about 10cm/century.

b. Contrary to the projections of the IPCC scenarios, which are typically uni-directional curves of climate change, we observe a *direction* of climate change that differs in a sustained manner from these projections, for example, we observe a substantial cooling or warming for several decades.

c. The *severity* of change exceeds certain thresholds, for example those that triggers a collapse of the thermohaline circulation (THC), or the occurrence of more extreme weather/climatic events.

10.11. In terms of what types of occurrence that could be triggered by climate change, the work of Keller et al. (2005) is useful because it summarises many of the climate limits (including limits for their initiation) that have been discussed in the wider literature. Their summary includes the melting of the Greenland Ice sheet, coral bleaching, changes in the El-Niño Southern Oscillation, a weakening or collapse of the THC and a disintegration of the West Antarctic Ice Sheet. Table 10.1 draws upon this an other materials such as the materials presented at the 2005 D*efra*-sponsored symposium *Avoiding Dangerous Climate Change* to summarise the range of events that change be triggered if some critical level were exceeded in GHG concentrations and rates and levels of warming.

10.12. One of the most cited examples of abrupt climate change noted in Table 10.1 is the possible collapse of the Thermohaline Ciculation (THC) (or the, Meridional Overturning Circulation, MOC). A major disruption of the THC can have significant impacts on the global and especially regional climate (cf. Broecker, 1987; Ganapolski and Rahmsdorf, 2001; Vellinga and Wood, 2002). Current thinking on the issue has been reviewed by Kerr (2005) who concluded that 'the threat from an abrupt circulation switch in the North Atlantic and resultant climatic chaos seems to be receding, but researchers still worried'. It seems that none of the model simulations of a warming world (using standard IPCC emission scenarios) have been able to drive the MOC to collapse. The prognosis is a weakening of up to 15-20 percent.

Table 10.1: Potential Change Limits (see Olsson and Stripple, 2006 for references)

| Vulnerability | Critical limits for Initiation | References |
|---|---|---|
| Shutdown of thermohaline ciculation | 3°C in 100 yr<br>700ppm $CO_2$ | O'Neill and Oppenheimer (2002)<br>Keller et al. (2004) |
| Weakening of thermohaline circulation | Very low | Higgins and Vellinga (2004)<br>Gregory et al (2005) |
| Disintegration of West Antarctica Ice Sheet | 2°C, 450ppm $CO_2$<br>2-4°C,<br><550ppm $CO_2$ | O'Neill and Oppenheimer (2002) Oppenheimer and Alley (2004, 2005) |
| Disintegration of Greenland Ice Sheet | 1-1.5°C | Hansen (2004) Gregory et al. (2004) |
| Complete melting of the Greenland Ice Sheet, starting at: | 3°C | Johannessen, Khvorostovsky et al. (2005) |
| Widespread bleaching of coral reefs | >1°C | Smith et al. (2001)<br>O'Neill and Oppenheimer (2002) |
| Broad ecosystem impacts with limited adaptive capacity | 1-2°C | Leemans and Eickhout (2004), Hare (2003), Smith et al. (2001) |
| Large increase of persons-at risk of water shortage in vulnerable regions | 450-650ppm $CO_2$ | Parry et al. (2001) |
| Increasingly adverse impacts, most economic sectors | >3-4°C | Hitz and Smith (2004) |
| El-Niño Southern Oscillation Changes | Deeply uncertain | Philander and Fedorov (2003)<br>Timmerman et al (2004) |
| The table builds on Schneider and Lane (2005) and Keller et al. (2005) but modified and extended by the Olsson and Stripple (2006). | | |

10.13. Table 10.1 also includes two cases of rapid deglaciation: the disintegration of the West Antarctica Ice Sheet (WAIS), and the Greenland Ice Sheet (GIS). A complete disintegration of the GIS would raise sea levels by 7m. While the GIS is much more stable than WAIS (since it is grounded above sea level), Gregory et al. (2004) claim that a warming of 3°C above 1990s temperatures would eliminate it (see also Oppenheimer and Alley, 2005; and Hansen 2004). However, as Schneider and Lane (2005) caution: 'Due to large uncertainties in models and in interpretation of paleoclimatic evidence, a critical issue … is whether the values selected correspond to actual geophysical or biological thresholds or simply represent convenient and subjective judgments about levels or risk'.

10.14. The problem of uncertainty pervades all the issues summarised in Table 10.1. A review of the literature suggests that there are, in general, very few attempts to estimate the probabilities of rapid or abrupt climate change. For example, Arnell et al. (2005) have argued that there are 'no scientifically robust estimates of the likelihood of thermohaline collapse'. Oppenheimer and Petsonk (2005) note that probability distributions have not been presented for these particular limits and assumptions about non-$CO_2$ gases vary from one study to another.

10.15. There are, in principle, three ways of estimating the likelihoods of abrupt climate change: analysis of past records, computer simulations and expert judgement. Arnell et al. (2005) regards the first two as problematic in the climate case, and opts for the third one. **However, much more work is required to develop the evidence base, particularly in terms of making a judgement about the consequences of the abrupt changes, highlighted in Table 10.1 for ecological and social systems more generally.**

10.16. Hulme (2003), for example, notes that there are few credible scenarios of abrupt climate change associated with THC collapse, so that ‘virtually none have explored what the implications of such an anticipated abrupt climate change would be for current decision-making for adaptation policy’. Assessments of consequences must also take account of the fact that thresholds are not static and can be modified by adaptation, for example, by increasing the performance and extent of drought tolerant crops. The influence of adaptability was also noted by Arnell (2000) for the water sector: “thresholds in the water management system are not necessarily fixed, especially when they are imposed by human demands…. flexible water management implies the ability to move thresholds”.

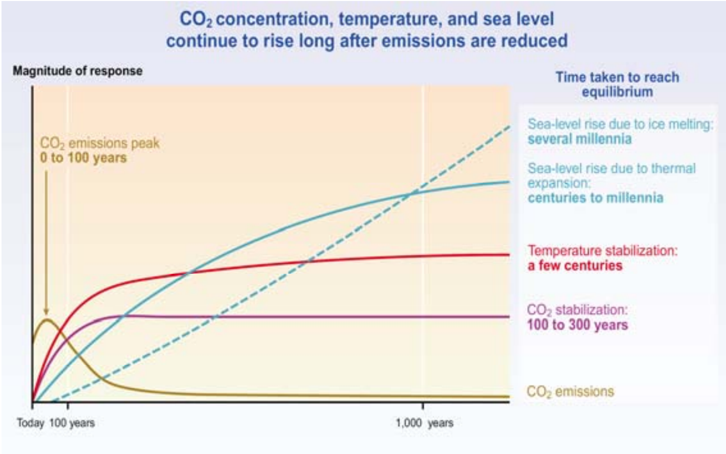
10.17. Johannesson (2000) has argued that while the risks of a climate change have been widely considered, the risk of ‘worst-case scenarios and surprises have been given scant attention’. As Hume (2003) and Johannesson (1998) have pointed out, this is partly a consequence of the IPCC not engaging in the analysis of ‘worst-case’ scenarios, since they have not taken them to be ‘within their mandate’.

**Developing the Evidence Base**

10.18. This brief review of some of the debates within the climate change literature suggests that thinking about limits and non-linearity is a fundamental part of the discussion, particularly in terms of how we might assess the significant implications of future changes. It is especially interesting to note, however, that in thinking about such limits the focus rapidly shifts from the discussion of biophysical factors to the evaluation of social and economic consequences. **As a result, if we consider how the evidence base that is needed to support decisions about climate change must be developed it is clear that while we need to improve the general circulation and Earth system models, we also need to be able understand what those changes will mean for human societies.** Indeed, Dessai et al. (2004) have argued that ‘radical new methods of participatory research are necessary to truly elicit what level of climate change might be regarded as dangerous by different cultures, communities and constituencies’.

10.19. The difficulties of framing both research and policy agendas can be highlighted by reference to the conceptual model suggested by the IPCC for the coupled climate - ocean - land system (Figure 10.1). The key point this model illustrates is the fact that the time lags between mitigation actions and a system response in the biophysical systems are likely to be very long and varied.

Figure 10.1: Conceptual model showing the inertia of the coupled atmosphere–ocean–land system (source: IPCC, 2001)




10.20. The IPCC model (Figure 10.1) suggests that if society is able to reduce drastically the emissions of greenhouse gases (GHG) by 2050 (the brown curve), by making the transition to carbon neutral energy sources, the effect on the GHG levels in the atmosphere will follow the purple curve, i.e. a stabilisation of levels after some 150 – 200 years. It is important to note that the emission reduction in 2050 will lead to a stabilisation, not a reduction of the level. There is no technology known by which a significant reduction of the atmospheric GHG level can be achieved – we have to live with whatever level we have reached.

10.21. If the stabilisation envisaged in Figure 10.1 is achieved, then this will result in a gradual levelling off of the temperature increase (red curve), with a stabilisation after an additional time lag of 50 – 100 years. The temperature increase before this levelling off will cause a rise of sea levels by thermal expansion of water that will continue for many centuries after the stabilisation of GHG and temperature (blue solid curve). If we also consider the effect on the polar ice caps of the temperature increase, the sea level rise is likely to continue over millennia (blue dashed curve).

10.22. Thus decisions about limits and targets to mitigate GHG emissions and slow the rate of temperature increase, are only part of the problem that we have to resolve. The consequences of the changes that have been initiated go much wider. Since they will have different effects in different places, the judgements societies will try to make about them are likely to be contentious.

10.23. The EU has adopted a temperature target for its climate policy of maximum 2°C above the pre-industrial level (den Elzen and Meinshausen, 2005). This threshold, however, does not really represent a level below which no severe climate impacts are believed to occur, but rather a pragmatic level that might be realistic to achieve from both a technological and a political point of view. The countries that make up the Alliance of Small Island States (AOSIS) have a completely different perception of what might be a dangerous interference compared with an industrial European country. A comprehensive review and analysis of fairness related climate change mitigation and adaptation is found in Toth (1999). **Further work is required at global, European and national scales on the issues of equity and fairness arising out of the implementation of climate change mitigation and adaptation measures.**

10.24. Similar value-based issues arise in designing targets. For example, many studies have used the doubling of pre-industrial levels of atmospheric $CO_2$[49] as a starting point, when reasoning about climate change. The doubling of pre-industrial levels is somewhat ambiguous, however, and depends on whether only $CO_2$ is considered or also other GHG are included as well. If all the six GHGs that are covered by the Kyoto Protocol are considered, we may argue that we have almost reached a doubling already. The use of the $2xCO_2$ target is also ambiguous in terms of setting targets for temperature regulation because of the unknown sensitivities of climate to GHG levels.

10.25. Finally, in planning sustainable development strategies for the future, societies have to explore what kinds of risks to the different elements of our physical infrastructure can be tolerated? The assessment of risks is usually based on the analysis of past events with for example, dams constructed to withstand water levels experienced once in 1000 years, or building prevented in areas where floods are likely to occur more often than once in 100 years. How are such risks likely to change in the future as a result of climate change? **At present the evidence base that can help us to resolve such questions is limited.**

10.26. The process of shaping a post-2012 climate change agenda is now under way, both internationally and within the EU. As the discussions of the UNFCC go forward an important question is likely to be whether Article 2 of the UNFCC should be operationalised and in what way. In addition, at some point the word ‘dangerous’ might be replaced by a definite level of either a certain $CO_2$ ppm level (such as 450 ppm), a temperature level (such as 2°C), a sea level rise level (such as 0.5 m) or perhaps a rate of temperature change level (such as 0.1° per century). Such a discussion must of course be based on a scientific understanding of potential risks of damage, but it also needs to be informed by understandings abut the costs and opportunities that exist to avoid the worse aspects of the damage that climate change might bring. **A better understanding of the potential impacts of climate change is therefore a high priority for future research in the UK.**

[49] Usually taken as the average level during 1000-1750, approximately 280 ppm

# Chapter 11. Exploring the Evidence Base: Pollution Loads[50]

## Introduction

11.1. Our review of pollution loads on environmental systems considered two principle areas, namely the literature relating to the definition and use of the critical loads concept for soils and ecosystems more generally, and current developments in the literature relating to environmental quality standards for soils in relation to levels of potentially toxic substances.

## Critical Loads[51]

11.2. Since the beginning of the 19th century, industrial emissions of nitrogen and sulphur have led to the atmospheric deposition of nitrogen and acidifying substances throughout Europe. This has caused acidification of soils and surface waters, as well as in a net accumulation of nitrogen over large areas. The effects on natural resources systems have been profound. They include:

a. Soil acidification which has interfered with nutrient uptake in plants, the cycling of N, increase the leaching of base cations from the forest soils;
b. Soil acidification can lead to elevated concentrations of $Al^{3+}$ in the soil solution, which can affect plant root vitality and impede the uptake of essential nutrients; and,
c. Acid water leaching from soils thereby increasing the acidity of lakes and rivers, thereby impacting on the integrity of these ecosystems.

11.3. By 1980, the problem of acidification was so widespread in Europe and other parts of the industrial world, that it was recognized as a major threat to ecosystem function. The critical load concept was proposed as a principle around which future mitigation and management strategies could be built. Cresser (2000) provides a useful insight in to the development of the concept, and has described how it came to be defined as:

> *….a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge.* (Nilsson and Grennfelt, 1988).

11.4. The concept was adopted by the UNECE Convention on Long Range Transboundary Air Pollution in 1988, which committed signatories to integrate the concept of critical loads and critical levels into their national regulations and standards. Initially the Convention covered sulphur, nitrogen,

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[50] Chapter 11 draws heavily on three unpublished ‘Position Papers’ for Scoping Study on “Defining and Identifying Environmental Limits for Sustainable Development, funded by D*efra,* See Appendix A of this report. By:
Emberson, L. (2006): Environmental thresholds and their application for ground level ozone air quality management in relation to vegetation.
Shaw, G. (2006): Levels of dispersal of toxic substances and the disposal of solid waste
Sverdrup, H. et al. (2006): Critical loads for acidity to ecosystems How environmental limits came to set the policy.

[51] For ozone ideas about limits are usually discussed with reference to critical levels, since it involves a critical concentration in ambient air rather than a deposited pollutant (e.g. via wet deposition).

ozone, and volatile organic compounds (VOC), and this was subsequently extended to the heavy metals lead, cadmium and mercury. It is likely that persistent organic compounds will be included in the future, and that other, such as for radiocaesium might be proposed. European Union (EU) is also now using the critical load or level concept to develop strategies for the control of acidification and ozone. The European Parliament has called for the objective of no critical load exceedance for acidification to be achieved by 2015[52].

11.5. The proposition of a critical load as the level of deposition of pollutant that will not cause chemical changes leading to long-term harmful to ecosystem structure and function, means that it is essentially an 'effects-based' assessment. It depends on the understanding of a causal chain, which runs from the selection of an ecosystem of interest and the components within it, through to the analysis of the **critical values** that mark the point at which damage to the component of interest occurs, and the critical loads that would cause the critical value to be exceeded. Thus for forest ecosystem in which the root growth is the parameter of interest, and for which the ratio of (Ca +Mg+K)/Al is the critical parameter determining root vitality, the causative chain would be:

- Ecosystem (e.g. forest)
- Ecosystem indicator component (e.g. Norway spruce)
- Indicator function (e.g. root growth)
- Causative parameter (e.g. ratio of (Ca+Mg+K)/Al)
- Critical limit value for causative parameter (1.2)
- Calculation Critical Load (e.g. pollution load that would maintain. ratio of (Ca+Mg+K)/Al above 1.2)
- Analysis of exceedance (e.g. is actual load>critical load?)

11.6. When this logic is applied in the policy context, the argument is then reversed:

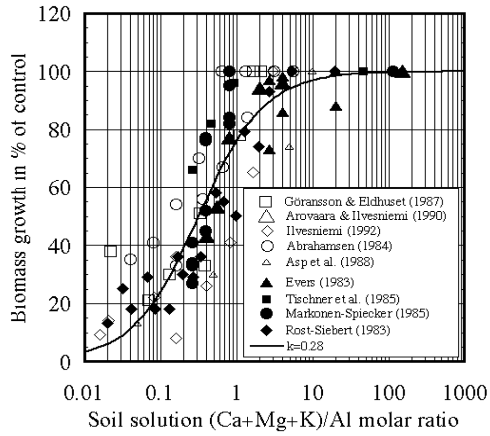
- Goal of non-exceedance
- Specify state parameter (e.g. root growth)
- Specify functionality of stock (e.g. timber production)
- Specify maximum pollution input (e.g. critical load)
- Identify emitter to receptor transmission path (e.g. atmosphere)
- Specify technology generating emissions (e.g. power stations)
- Policy design (e.g. regulation)

11.7. The calculation of the critical value is made using diagrams such as that shown in Figure 11.1, which plots the parameter representing the factor potentially causing damage against a measure of the damage caused. Thus, for a forest, we may wish to protect its potential for timber production. The growth rate of the grown tree is the ecological function we want to protect, and this depends on the roots and their capacity to take up nutrients. Root

[52] *Official J. Eur. Commun.* **1998** *C167*, 86-170

vitality has been shown to be dependent on Aluminium concentration in the soil solution (the 'causative parameter') which is best described by a function based on the ratio (Ca+Mg+K)/Al. The plot shown in Figure 11.1 suggests that it is around a value of 1.2 that the recorded biomass of seedlings expressed as a % of a control plot begins to decline.

Figure 11.1: Relationship between a chemical parameter and the response of Norway spruce seedlings and smaller plants. (Source: Sverdrup et al., see Appendix for references)




The limit value is read from the diagram by setting a maximum impact level.

11.8. We have spent some time explaining how the critical value, and the load that would cause it to be exceeded, is calculated, because this exposes the assumptions on which the approach is based, the types of evidence that is used and the potential gaps in the evidence base that remain. The key points are as follows.

11.9. At the outset, judgements have to be made about the feature of the ecosystem we want to protect. For example, in a forest ecosystem, the goal of preventing impacts of pollution loads on growth will lead to one critical value, while preventing die-off would lead to another limit being set. Thus while the calculation of particular critical loads might be a robust process, the decision about what critical load calculations should be used for policy is a more open ended issue.

11.10. Moving on, to calculate the critical value there is then the judgment that has to be made about how we use the relationship between the independent factor that we think is causing damage and the measure of damage itself. For example, we may:

a. Adopt a precautionary approach, and set a limit *before* any detectable damage is occurred; or alternatively,
b. Use the concept of maximum allowable damage (MAD), which sets the limit where a measurable damage can be shown; thus no action before damage can be proven.

11.11. Furthermore, we are constrained by the fact that calculation of the critical value or limit depends on the interpretation of response data. The approach adopted for calculating critical loads is pragmatic, in that it uses the best data available, even though it may be incomplete. The difficulty this poses can be seen in Figure 11.1, for Norway spruce. The response line is only an average, and there is a good deal of spread of data points around it. The calculation of the critical value will be different depending on whether we apply the precautionary principle or MAD. Thus using the precautionary approach for a forest ecosystem using Norway spruce as the indicator organism, with the impact of acidification on stem growth through root vitality, as the relationship we will use to assess damage, the critical value would be set at a Base Concentration (BC) to Aluminium ratio of 10-20 or pH=5.2. By contrast, application of MAD would set it at BC/Al=1.2 or pH=4.

11.12. Finally there is the issue of how critical loads are mapped. The general approach used to map critical loads and to identify where they are being exceeded is to use grid-based methods. The approach uses values for pollution loads, calculate from atmospheric models, and critical load functions for cells weighted by the area of sensitive ecosystems within them, which are ranked to form a set of cumulative distribution functions at various percentiles.

11.13. Much national critical loads information (including the UK) is mapped at the 1km, 5km and 10km scales, while European Monitoring and Evaluation Programme (EMEP)[53] uses a grid of approximately 150 x 150 km for pollutant dispersion modelling. Such mapping also carries with it a number of key assumptions, and as several commentators have argued, these may crucially affect the conclusions that might be drawn from them. For example, as Bak (2001) has shown, if uncertainties and information on spatial variation in exceedance calculations are taken into account when mapping, in general higher resolution national data gives larger exceeded area for the critical load of acidity compared to the EMEP estimates. Hall et al. (2004)[54] have reported similar effects.

11.14. **Thus, although the approach to the calculation of critical values and loads is scientifically credible, it cannot eliminate the judgements about what it is we wish to protect and what level of precaution we wish to apply. These are precisely the ones on which policy decisions depend.** Such issues led Skeffington (1999) to argue that:

> *Critical loads are best viewed as highly uncertain estimates of relative risk, which themselves incorporate political choices, rather than precise damage thresholds determined by an objective, scientific process. Pollution-control science should go beyond critical loads to the prediction and communication of pollution control policies' effects on organisms and ecosystems* (Skeffington, 1999, p.245).

**Developing the Evidence Base for Critical Loads**

11.15. To a large extent, the development of the critical loads concept has been driven by the availability of response data. Initial work in Europe was built around spruce and salmon, but since then the range of species and ecosystem characteristics has been expanded and the approach has grown in its sophistication. Our review has identified limit values for a range of soil and ecosystem parameters that have been proposed in the literature (see Appendix A, Sverdrup et al.).

[53] http://www.emep.int/
[54] http://www.airquality.co.uk/archive/reports/reports.php?report_id=270

11.16. The review shows that in terms of developing the evidence base, a pragmatic approach is possible, with initial decisions being based on the best available data, and progressive refinement as further work is completed. The work also shows that despite the fact that the calculation of critical loads and their exceedance is scientifically sound, decisions about what actual limits should be upheld for particular systems is a matter of judgement, the science can only inform the wider discussions that society must have, and not replace them. The discussion of critical loads also throws in to sharp focus the issue of whether we should aim to sustain systems at the level of 'maximum allowable damage' or adopt higher targets related to favourable ecological status.

11.17. We suggest that in terms of developing the evidence base the current work concerned with mapping and monitoring exceedance to be more strongly linked to issues covered in the sustainable consumption and production framework, to make the link between economy and the environment more transparent. The marginal values associated with managing pollution loads so that ecological targets are achieved, rather than that minimum standards are met, needs to be better understood. An important *caveat* which should be applied to the interpretation of critical loads is that exceedance does not imply sudden and catastrophic ecological collapse. In truth, the exact response of an ecosystem exposed to chronic accumulation of any pollutant or contaminant is difficult to predict, which is why ongoing monitoring and research into pollutant effects are essential.

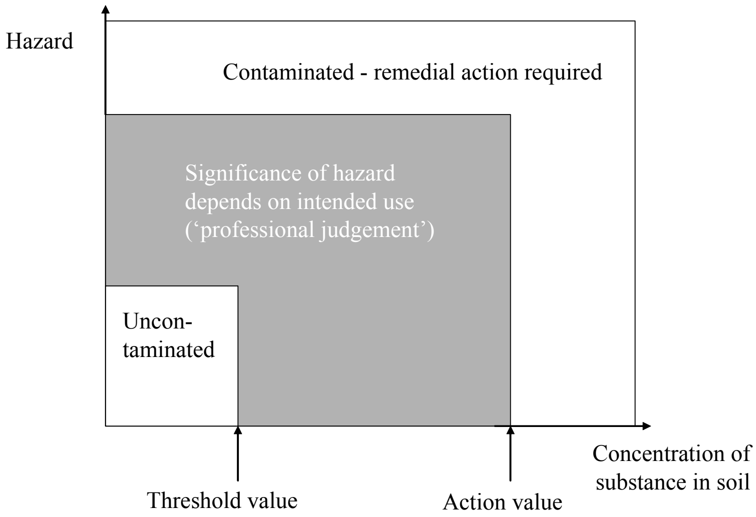
**Environmental Quality Standards for Soils**

11.18. The review of Environmental Quality Standards (EQS) for soils provided an interesting contrast to the materials on critical loads, because while the latter tended to emphasise criteria such as 'maximum allowable damage', EQS is more precautionary in its outlook. Here the goal is setting limits to ensure that no harm to human health occurs; thus limits are set above the level where any damage might occur.

11.19. Despite this contrast between the two approaches, this topic area, like that relating to critical loads, is of general interest because it demonstrates once again how a robust evidence base has been built up to inform the discussion of limits. Our review traces the development of Soil Quality Standards (SQS) through the ICRCL system, with its definition of limits as 'trigger' and 'action' points at which different responses to a potential hazard might be initiated (Figure 11.2), though to the introduction of Quantitative Risk Assessment (QRA) in the 1990s.

11.20. QRA is a formalised, quantitative and defensible methodology in the assessment of chronic risks associated with many environmental hazards and liabilities (Figure 11.3). The basis of QRA is the use of predictive models which are capable of forecasting risk(s) in the form of probability

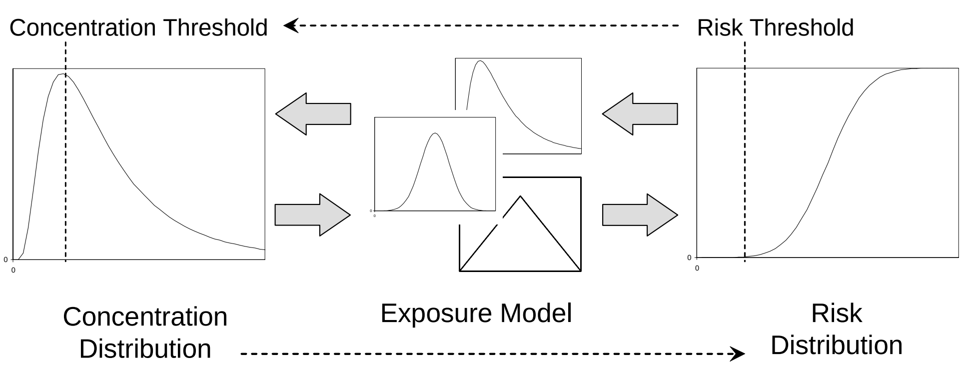
Figure 11.2 Interpretation of ICRCL trigger concentrations (redrawn from ICRCL, 1987)




distributions. In the case of contaminated land assessments, such forecasts are focussed on the probability of adverse outcomes associated with individual contaminated sites, such as exposure of individuals to harmful doses of substances at the site, or the impact the site may have on a sensitive 'receptor' such as a controlled water body (surface or groundwater) or ecosystem. Our review also looked at the way the approach can be used to assess risk associated with radioactive materials in soils, waters and other environmental media.

11.21. Implicit in the construction of models for QRA is the 'Source → Pathway → Receptor' linkage, which can be traced to the 'pollution pathway' concept. This is one that is also emphasised in the critical loads literature, although the probabilistic modelling of exposures is not one that has been developed here so strongly.

Figure 11.3: Schematic QRA modelling procedures.




*In practice, probabilistic exposure models can be used to calculate distributions of risk associated with distributions of environmental (e.g. soil) contaminants, or they can back-calculate concentration thresholds from pre-determined risk thresholds.*

11.22. Our review emphasised that despite the progress that has been made with QRA, much uncertainty applies to our understanding of the effects on human health of 'undesirable' levels of potentially toxic contaminants in the environment. This is addressed by ensuring that Generalised Derived Limits (GDLs) and Soil Guidance values (SGVs) are calculated using deliberately pessimistic assumptions. The nature of threshold values for potentially toxic environmental contaminants is, in general, precautionary, so that the monitoring of outcomes is essential.

11.23. A major area of uncertainty that should be considered in future efforts to develop the evidence base concerns to possibility of the 'chemical time bomb' (Stigliani et al., 1991). This envisages a situation in which a trigger mechanism may suddenly render potentially toxic contaminants already present in an environmental system to become suddenly more harmful, either because their physical location is altered or because their chemical state is altered. Trigger mechanisms may involve natural physio-chemical changes or human induced land-use changes. **Current threshold values such as SGVs, GDLs and CLs may be adequate under steady state conditions, but may be irrelevant under conditions in which rapid environmental change occurs.**

# Part IV: Conclusions and Recommendations

## Chapter 12. Respecting Environmental Limits

12.1. In its paper *Think Twice,* English Nature argues that, from a nature conservation perspective, consideration of environmental limits is an important principle. Our review suggests that it is important for sustainable development more generally (Burney, 2004).

12.2. There is a broad consensus in the scientific literature that the goals of sustainable development will not be achieved unless we are better able to identify and define what environmental limits are. Thus the aims set by D*efra* for this study are particularly relevant to current debates. In this final part of the report is now appropriate to review what can be concluded from our study.

**How are environmental limits identified and defined?**

12.3. Our review suggests that while at times the terms ‘limit’ and ‘threshold’ have been used interchangeably, it is useful to distinguish between them because they highlight important features of natural resource systems that must be considered in policy and management.

12.4. Natural resource systems are important to people because of the benefits they actually or potentially deliver to people and the contribution they make to human well being. However, external pressures may progressively undermine the capacity of natural resource systems to continue to deliver these benefits at the level required. As a result, society may judge that a ‘critical point’ has been reached, beyond which further change is unacceptable. This critical point is a limit.

12.5. Our review suggests that despite the diversity of materials in the different subject areas, and the different scientific methodologies used to identify these critical points, the notion of a limit is a useful one which can be applied across most fields. Limits can be identified for all types of system, whether they exhibit a progressive linear decline in the face of external pressures, whether that change is progressive but non-linear, or whether there may ultimately be some collapse if the system experiences a regime shift.

12.6. In terms of the relative importance that limits and thresholds have, it seems clear that while threshold responses with alternative stable states can be found in some natural resource systems, the extent to which such dynamics are widespread is unclear. Thus, the notion of a limit is generally considered to be more useful. In addition to highlighting the dangers of collapse, thinking about limits also focuses attention on the consequences of the chronic or gradual loss of the functionality of natural resource systems that results from increasing environmental pressures.

12.7. Although our definition of a limit seems straightforward there is, however, a hidden complexity which must be discussed. The identification of a limit hinges on the judgment made by individuals or groups 'that a critical point has been reached'. How is that judgment made and justified? Our review suggests that it is mainly in terms of the consequences or implications of exceeding a given limit that those judgments are made.

12.8. It is interesting to note that across all of the science areas considered, once the advantages of the different ways of characterizing the system response was resolved, the need to apply that knowledge took us into realms where questions of value had to be resolved. For example, in the area of critical loads, we saw that while the scientific rationale for their calculation was sound, judgments ultimately had to be made about what ecosystem function was to be protected, and what level of protection it was to be afforded. Should the critical load be calculated to protect forest productivity or biodiversity? Is there a maximum level of damage that can be accepted or should the limit be before any damage could be detected? Similarly, in the area of climate change, the question of what constituted a 'dangerous' or 'abrupt' change depended on the how people valued the losses resulting from the event.

12.9. Our review suggests that while the definition of a limit may be grounded on biophysical criteria it also depends fundamentally on the value systems being applied. If we view natural resource systems in terms of the stream of benefits they deliver, then judgments about the where a particular limit is set can be based on changes in the marginal value of those benefits, or the assessment of those benefits relative to others that people identify. Additionally, depending on the circumstances, it can be based on the application of ecological or social values. For example, if the underlying science suggests that the relationship between the pressure and system output is non-linear, or may involve threshold dynamics with regime shifts and possible points of no-return, then we may choose to justify a limit using criteria based on social justice and equity, rather than on economic grounds alone.

12.10. In other words, in a policy or management context, decisions about limits cannot hide behind the science. Not only are we forced to make value-based judgments about how limits associated with particular systems are identified, but in the real 'multifunctional' world we have to deal with the problem of potentially conflicting limits and therefore the trade-offs that might need to be considered. Such issues are particularly acute where cumulative impacts might occur. Since the problem of valuation cannot be avoided, the implication is that we have to find ways of ensuring that such issues are properly included in discussions of limits. The recognition that judgments ultimately had to be set in some kind of 'deliberative' decision-making framework was apparent in a number of the topic areas considered, and is consistent with the view taken by the Royal Commission on Environmental Pollution in their work on environmental standards and public values[55.]

12.11. The problem of how to assess and prioritize the different types of limit that can be identified when the range of benefits provide that natural resource

[55] Royal Commission on Environmental Pollution, Environmental Standards and Public Values, A summary of the 21st report on *Setting Environmental Standards.* http://www.rcep.org.uk/pdf/standardssummary.pdf

systems are considered alongside each other, is one that urgently needs to be resolved. We suggest that D*efra* could make a significant contribution in this area by initiating future work to look at the way people value the benefits associated with natural resource systems for a set of contrasting 'multifunctional landscapes' or regions in England, and how future decision making can best be supported by the provision of information about the status natural resource systems at different geographical scales. Such work would also help to clarify the way in which the concept of ecosystem goods and services can be implemented in situations where landscapes also have significant cultural, social and economic value.

**How robust is the evidence base that underpins the identification of limits, what gaps exist in current understandings, and how can the evidence base be developed?**

12.12. Any discussion of limits has to be grounded on a good understanding of the relationship between the functioning of the natural resource system, the way it supports the stream of outputs that benefit people, and the way it is impacted by external drivers. Much of the material we covered in our review of the different thematic area covers just these topics. As we have seen progress in the different fields has been variable. It is, for example, fairly well developed in the area of critical loads and the setting of environmental quality limits for toxic substances in soils. Thinking is much less well advanced in areas such as recreation and access.

12.13. However, it is probable that no simple answer can be given to the question how robust is the evidence base? In fact, there is a sense that this is probably the wrong question to be asking. As the development of the critical loads approach has illustrated, decisions and judgments have to be made on the basis of the best evidence available at the time. We cannot wait for science to deliver some 'final answer'. The act of making and testing those judgments in the public arena is the only sure way of assessing the robustness of the evidence base, and understanding how it should be developed. The review of BAP Species and Habitat Targets illustrates the type of work that is necessary. The evidence base is best developed by using it. Such a proposition is central to the notion of adaptive ecosystem management.

12.14. On the basis of our review we therefore suggest that, while the evidence base probably needs developing in all areas, in most there is a sufficiently well articulated body of materials that would allow a start to be made, in terms of discussing what kinds of limits might apply. Therefore, future work in the area of environmental limits should focus on both scientific issues related to the structure and dynamics of natural resource systems, and the institutional frameworks in which judgements about the consequences of exceeding environmental limits are made.

12.15. There are two key areas where it would be particularly useful to direct resources if work in this area is taken forward at the institutional level:

- In developing a better understanding of the ways in which the goods and services associated with ecosystems and landscapes are linked to biophysical processes at local, regional and national scales. This kind of information would provide a useful body of evidence for regional and local planning bodies. **Thus Defra should consider initiating a 'Millennium Assessment' for the UK that can serve as a strategic framework for discussion about environmental limits and as a stimulus to developing the evidence base that underpins policy**.

- We need a much better understanding of the economic, social and ecological values of our ecosystem and landscape goods and services. This kind of information would be useful to help us understand how their values are potentially affected by external pressures, and what positive benefits arise through their protection and enhancement. **Thus Defra should consider initiating a series of pilot studies which demonstrate how questions of the value can be resolved in relation to assessing the consequences of exceeding an environmental limit.**

***How can the evidence base used to identify limits be better collated?***

12.16. Given our suggestion that there is a sufficiently well developed body of materials in the topic areas covered by this study to initiate a discussion about limits, the question arises about how this material is best collated and communicated. A number of approaches can be identified.

12.17. We are aware, for example, of the preliminary findings from the parallel study sponsored by D*efra* on environmental pressures, and the suggestion that 'topic maps' and 'causal chains' be constructed for the different natural resource systems that fall within the Department's remit. In the short-term, the work on topic maps could be developed to include identification of limits, both with respect to the pressures themselves and the outputs from the natural resource systems themselves. Such an approach could provide a framework in which questions of the marginal value of benefits and potential costs of protection and management might also be explored. These causal chains might also be a way of identifying potential thresholds, where the integrity of systems might be jeopardised.

12.18. Topic maps are useful as a framework for discussion, but they are limited in that they do not yet deal with issues of geographical scale and temporal scale, nor do they take spatial heterogeneity of the resources systems into account. Thus other ways of collating information and communicating it also need to be considered.

12.19. If the goal of ensuring that development occurs within environmental limits is to be achieved, then in the short to medium term Defra needs to give clear guidance on how thi**s might be accomplished**. Thus the Department's website could provide:

- Examples of 'best practice' and reviews of the current thinking about limits in the main topic areas; and
- A checklist describing the types of question that need to be asked so that thinking about limits is included in decisions affecting natural resource systems at regional and local levels. These materials should also set out

how discussions about limits can be built into the existing approaches to Strategic Environmental Assessment and Sustainability Impact Assessment, and how it can be included in cost-benefit studies.

12.20. **Finally, in the medium term, Defra should make a much stronger link between** the issues covered in the areas of sustainable consumption and production (SCP) and natural resource protection. In section 3.39 of this Report we posed a number of questions concerning the UK SCP framework. In terms of the materials reviewed here, it is clear that:

a. The range of issues covered by the existing SCP framework is narrow compared to the issues that need to be considered, given Defra's remit to protect our natural resources.

b. Moreover, the casual connections between the themes that are included and the natural resources that Defra seeks to protect and the existing SCP framework are also unclear. The decoupling of air quality and the economy is judged by the emission of sulphur dioxide, nitrogen oxides, ammonia and particulates, and not, for example, by the extent to which resulting pollution levels exceed the critical loads for key habitats and soils. Similarly, the only aspect of land use considered is the proportion of new housing on previously developed land, and not the effects which land use patterns have on resource consumption and quality more generally.

c. It is clearly the case that the existing SCP indicators need to have limits associated with them, if the effects of policies for decoupling are to be assessed. However, given the need to develop holistic, ecosystem-based approaches to environmental management then it becomes difficult to identify limits for particular resources, such as water flows or forest yield, without considering them in the context the multiple benefits that people derive from the systems with which they associated.

d. Deliberative processes, designed to look at the way people ascribe values to the changing outputs of resources, and the risks to which they are exposed, provides one way in which issues of limits and multifunctionality can be explored.

12.21. Clearly the development of the suite of SCP indicators to include a wider range of natural resource protection issues many be hindered by lack of easily accessible information. In order to overcome this problem we suggest that a scoping study is initiated to determine the feasibility of extending the existing national environmental accounts to resolve some of these deficiencies. Such accounts can provide an integrated framework in which questions of multifunctionality and values can be explored.

12.22. The extended accounts could include more detailed information about the consumption, quality and protection of natural resources and their changes over time. They could also include national and regional ecosystem accounts linked through a refined land cover/land use account to key economic sectors. Such an accounting framework would underpin the development of indicators with a secure evidence base, and provide a model on which issues of limits and the costs of environmental protection and incentives could be calculated. **Such work would also provide a coherent framework for maintaining an**

**inventory of our natural resources.** In order to retain flexibility during development, these accounts should be treated as a set of 'satellite' accounts that supplement the national accounts, rather than being fully integrated with them.

### How can current thinking on environmental limits be used in policy-making and what further research is necessary?

12.23. The major implication of our study is that the identification and definition of limits can only be achieved through deliberative decision-making processes, so that the value-based judgements on which decisions depend can be made clear. Thus further research is needed into the concepts, tools and institutional arrangements that are needed to support these more inclusive styles of decision making.

12.24. The advice of the Millennium Ecosystem Assessment on how to evaluate ecosystem assessments is particularly useful in understanding what has to be achieved by any socially robust process which tries to identify and define an environmental limit. For example, we might ask of judgement about a given limit:

- Did it bring the best available information to bear?
- Did the decision function transparently, use locally grounded knowledge, and involve all those with an interest in a decision?
- Did it pay special attention to equity and to the most vulnerable populations?
- Did it use decision analytical frameworks that take account of the strengths and limits of individual, group, and organizational information processing and action?
- Did it consider whether an intervention or its outcome is irreversible and incorporate procedures to evaluate the outcomes of actions and learn from them?
- Did it ensure that those making the decisions are accountable?
- Did it strive for efficiency in choosing among interventions?

To these we would add:

- Did the judgment take account of the consequences for natural resource systems and human well-being that might arise if a given limit is exceeded?

12.25. Our review of the current literature suggests that there are examples of the types of concept and tool that are needed already available. For example, the Quality of Life Capital Approach (QoLC)[56] could be adapted to providing guidelines for people to develop their thinking about environmental limits when faced with some new development or policy. They might, for example be encouraged to ask[57]:

[56] http://www.environment-agency.gov.uk/aboutus/512398/830672/831980/832252/?lang=_e
[57] We have freely adapted the 'core' questions that make up the QoLC framework for present purposes.

- What are the factors likely to limit the benefits obtained from the natural resource systems associated with the area affected?
- How important are these benefits, to whom, and for what reasons?
- What, if anything, could replace or substitute for these benefits?
- Do we expect to have enough of each of these benefits natural resource services in the future?
- What kinds of management actions are needed to protect or enhance the benefits?

12.26. These questions provide a framework around which the evidence base relating a particular issue can be assembled, and thus the basis for making judgements about limits. They also provide an approach to decision making whose robustness could be tested using the criteria proposed by the Millennium Assessment (section 3, paras 3.18-3.30). We suggest that by addressing such questions the consequences of exceeding a given limit might better be identified, alongside the implications of potential conflicts between different types of limit that might arise in relation to a multi-functional ecosystem or landscape.

12.27. The Millennium Ecosystem Assessment has attempted to identify the types of deliberative tools that are currently available for assessing the status of ecosystem goods and services; they include cost benefit analysis, multi-criteria and vulnerability analysis. By using such tools it is suggested assessments will be based on public participation, gather appropriate information, and evaluate different planning options in a transparent way. We suggest that Defra could usefully take such work forward, by building on the recommendations of this study and the parallel work combining environmental values, to develop a set of best-practice guidelines that show how these deliberative approaches can most effectively be used to identify and assess limits at a range of different spatial and temporal scales.

## Joined-up thinking

12.28. Our review of environmental limits and thresholds suggests that while they are valuable concepts, identification of such ‘critical points’ is not by itself going to solve all natural resource protection problems. The ideas have to be used in the context of the other tools that we currently have.

12.29. For example, our review of the way in which limits have been defined and used suggests that there are clear dangers in using them to set management parameters. As the literature review for the marine environment illustrated, identification of limits is useful in understanding the way pressures impact upon systems, but the goals of managing the system should be that it is sustained in ‘good’ or ‘favourable’ condition, not in a state where a level of damage is judged ‘acceptable’. Discussions of environmental limits therefore have to be seen as part of target- or objective-led approaches to environmental policy and management. Although the thinking about limits in relation to recreation is much less sophisticated than in many of the other topic areas considered, the importance of setting objectives, rather than limits also emerged as a key message from current debates.

12.30. It is wise in management terms to know the limits to which any system can be pushed. However, quite apart from the dangers of managing to the minimum, the attempt to enforce those safe minimum standards can be contentious and difficult. Given the history of debates, such as those surrounding ‘Limits to Growth’, it often seems to people that talking about limits is a way of suggesting that all development should be halted. Our literature review suggests that this is clearly not the case. In fact, the recognition of limits can be a positive and constructive step if they are used to demonstrate, not just the losses in benefit that might occur of they are crossed, but what additional marginal value is of managing at a higher target level. If we are to take the calls for more ‘deliberative’ approaches to policy seriously, then these discussions need to be informed by an understanding of the consequences of different actions and decisions. A clear articulation of the costs and benefits of sustaining the system at the limits or in ‘favourable condition’ would greatly assist in such matters. In taking such work forward, the notion of ecosystem goods and services is clearly a very helpful one, since it places discussion of human well-being at the centre. If sustainable development is about ensuring that future development is qualitatively different from the forms it has taken in the past, then an understanding of environmental limits, and the consequences of exceeding them, is a vital part of the scientific and institutional framework that needs to be put in place for such goals to be achieved.

12.31. The problem with deliberative approaches to the formulation of environmental management and policy is that even though they may achieve transparent and fair outcomes no decision can be final, because constraints are always changing. Climate change, the development of new technologies and the emergence of new values and aspirations will mean that any assessment of limits and targets will probably have to be revised. Such a requirement means that the acquisition of long-term monitoring data is essential.

12.32. Efficient monitoring systems require an understanding of what indicators are needed to track the status of a given resource system, the ability to collecting the appropriate information and the commitment to maintain the collection of those data. It is in this context that approaches represented by the sustainable consumption and production framework in the UK are so important. The challenge that we now face is to ensure that they include the range of issues that have to be considered if the sustainability of our natural resource base is to be assured, and that we are able to use this information to make a case for managing societal impacts above the minimum level that is acceptable.

12.33. In paragraphs 3.31 ff. of this report we posed a number of questions about the SCP framework. To resolve them all would go far beyond the remit of this study. However, from the materials we have presented here, it does seem clear that a closer linkage between the consumption and production issues covered and the costs and benefits of better protection of natural resources and the ecosystem goods and services associated with them, would be an appropriate way forward. Better integration into systems of environmental accounting would also ensure that the work is underpinned by a clear body of evidence.

12.34. The discussion of environmental limits seems to have taken us to the boundaries of what traditional science has been expected to provide. In many of the areas reviewed, for example, scientists acknowledge that, while their work can map out what consequences might follow if certain limits are crossed, the significance of limits has to be determined by society at large. These tensions between science and values are not confined to the discussions of environmental limits. They are part of much larger set of issues concerning the way we view traditional science in the context of sustainability. The discussion of limits can, nevertheless, make a very real contribution to such debates, because it requires us to think about their implications in ways that transcend traditional disciplinary boundaries.

12.35. In order to help chart the next steps, an overview of the key recommendations arising from this study are provided in Table 12.1.

## Table 12.1: Overview of Key findings and Recommendations

| Key Findings and Recommendations | Reference (Full Technical Report) |
|---|---|
| **Overall**<br>• *Although the evidence base for environmental limits needs developing across all the thematic areas considered, in most cases there is sufficient understanding to begin discussing of what kinds of limits might apply for the protection of natural resources. We recommend that work should be initiated to develop guidelines for decision makers at national, regional and local scales to help ensure that development occurs within environmental limits.* | Executive summary |
| **Definitions**<br>• *The term limit is used to refer to the level of some environmental pressure, or level of benefit derived from the natural resource system, beyond which conditions which are deemed to be unacceptable in some way. The term can be applied irrespective of the type of dynamic exhibited by the system (linear response, simple non-linear response, threshold response).*<br><br>• *The term threshold is reserved to describe situations in which a distinct regime shift between alternative equilibrium states exists, which may or may not be reversible.* | Para 2.22 |
| **Key findings from review of concepts:**<br>• *We conclude that presently the concept of ecosystem health has little to offer in terms of understanding where the environmental limits or thresholds might lie.*<br><br>• *The literature suggest that we are still a long way from any clear generalisations about what makes one system more resilient than another, or where the limits of resilience in a given system may lie.* | Para 3.9<br><br>Para 3.25 |
| *The logic of ecosystem goods and services that underlies the Millennium Assessment has much to recommend it in terms of communicating to people what is important in the context of natural resource protection and ultimately what environmental limits might exist.* | Para 3.27 |

| Key Findings and Recommendations | Reference (Full Technical Report) |
|---|---|
| **Exploring the Evidence Base: Biodiversity** | |
| • *When published the materials of the UK BAP Targets review should be used to identify the robustness of the evidence base about the targets, and to identify what knowledge gaps are apparent in terms of the factors that limit species or habitat abundance and distribution. This work could provide a platform for developing a similar body of information for the more common species and habitats found in the wider countryside.* | Paras 5.9.a, and 5.21 |
| • *As part of the reporting process, Defra should ensure that the information on limiting factors for species and habitat viability that are contained in the target descriptions, are summarised, and linked to the types of information contained in the species and habitat action plans which document the pressure upon them.* | Para 5.9.b |
| • *Given the nature of the BAP Process, information about limits will mainly be determined using ecological criteria. Thus it would be valuable to initiate a study to identify what the contribution individual species or species groups make to the generation of ecosystem goods and services, so that the benefits of achieving and exceeding the targets identified can be communicated. The costs of recovery can also to be looked at in relation to the benefits that might be realised.* | Para 5.9.d |
| **Exploring the Evidence Base: Land Use and Landscape** | |
| • *In the UK we are well placed to explore issues relating to limits further through the development of such approaches as land and ecosystem accounting. We recommend that further work is undertaken in this area. The land and ecosystem accounts potentially provides both a framework in which issues of multifunctionality can be explored, and means by which information about the status of natural resources system can systematically be assembled and communicated to decision makers.* | Para 6.24 |
| • *The extension of land cover accounting methods is likely to complement other mass-balance studies being addressed under the umbrella of the UK Sustainable Consumption and Production Strategy, and would facilitate better analysis and modelling of long term trends.* | Para 6.10 |
| **Exploring the Evidence Base: Recreation and Access** | |
| • *The literature suggest that notions of limits and thresholds are perhaps of restricted value in developing management strategies for recreation, and that objective or target-based approaches are probably more appropriate.* | Para 7.15 |
| • *We recommend that the evidence base can best be developed by better understanding the relationship between recreation and the elements of our natural capital that support it. Such work on the value of the natural environment for recreation and access is likely to be informed by current work involving the valuation of environmental resources based on people's willingness to pay and willingness to travel, and by the marginal values they place on changes in the outputs of ecosystem goods and services associated with the places they visit.* | Para 7.19 |

| Key Findings and Recommendations | Reference (Full Technical Report) |
|---|---|
| **Exploring the Evidence Base: The Marine Environment** | |
| • *There is currently scant information or understanding about the kinds of reference points that might be constructed around the wider indicators of marine ecosystem structure and function, and how these limits vary over time and space. Our review suggests that further work is required to understand how the limits and targets identified across each of the ecosystem dimensions should be compared or combined, since objectives may not always mutually consistent..* | Para 8.10 |
| • *Deliberative styles of decision making are likely to become increasingly important in the context of managing issues related to water quality, supply and demand* | Para 9.17 |
| **Exploring the Evidence Base: Climate Change** | |
| • *More work is required to develop the evidence base, particularly in terms of making a judgement about the consequences of the abrupt changes for ecological and social systems more generally* | Para 10.15 |
| • *While we need to improve the general circulation and Earth system models, we also need to be able understand what those changes will mean for human societies* | Para 10.18 |
| • *Further work is required at global, European and national scales on the issues of equity and fairness arising out of the implementation of climate change mitigation and adaptation measures* | Para 10.24 |
| **Exploring the Evidence Base: Pollution Loads** | |
| • *In terms of developing the evidence base, the current work concerned with mapping and monitoring exceedance should be more strongly linked to issues covered in the sustainable consumption and production framework, to make the link between economy and the environment more transparent.* | Para 11.17 |
| • *Current threshold values (i.e. Soil Guideline Values, Generalised Derived Limits, and Critical Loads) may be adequate under steady state conditions, but may be irrelevant under conditions in which rapid environmental change occurs.* | Para 11.23 |
| **Respecting Environmental Limits** | |
| • *Our review suggests that despite the diversity of materials in the different subject areas, and the different scientific methodologies used the notion of a limit is a useful one which can be applied across most fields.* | Para 12.5 |
| • *In terms of the relative importance that limits and thresholds have, it seems clear that while threshold responses with alternative stable states can be found in some natural resource systems, the extent to which such dynamics are widespread is unclear. Thus, the notion of a limit is generally considered to be more useful* | Para 12.6 |
| • *Our review suggests that while the definition of a limit may be grounded on biophysical criteria it also depends fundamentally on the value systems being applied to assess the consequences of a limit being crossed* | Para 12.9 |
| • *The problem of how to assess and prioritize the different types of limit that can be identified when the range of benefits provide that natural resource systems are considered alongside each other, is one that urgently needs to be resolved.* | Para 12.11 |

| Key Findings and Recommendations | Reference (Full Technical Report) |
|---|---|
| **Next Steps**<br>• *Defra should consider initiating a 'Millennium Assessment' for the UK that can serve as a strategic framework for discussion about environmental limits and as a stimulus to developing the evidence base that underpins policy.* | Para 12.15 |
| • *Defra should consider initiating a series of pilot studies which demonstrate how questions of the value can be resolved in relation to assessing the consequences of exceeding an environmental limit.* | Para 12.15 |
| • *Defra needs to give clear guidance on how development within limits might be accomplished. Thus the Department's website could provide:*<br>o *Examples of 'best practice' and reviews of the current thinking about limits in the main natural resource protection areas.*<br>o *A checklist describing the types of question that need to be asked so that thinking about limits is included in decisions affecting natural resource systems at regional and local levels. These materials should also set out how discussions about limits can be built into the existing approaches to Strategic Environmental Assessment and Sustainability Impact Assessment, and how it can be included in cost-benefit studies.* | Paras 12.19-12.20 |
| • *In the medium term, Defra should make a much stronger link between the issues covered in the areas of sustainable consumption and production (SCP) and natural resource protection. Closer linkage between the consumption and production issues covered and the costs and benefits of better protection of natural resources and the ecosystem goods and services associated with them, would be an appropriate way forward* | Para 12.33 |

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# Appendix A:

# Position Papers

## A1. Briefing letter to experts

## A2: Original Position Papers by external experts

- **David J. Agnew** (Imperial College, London/UK) on "Marine Environment"
- **Lisa Emberson** (University of York/UK) on "Environmental thresholds and their application for ground level ozone air quality management in relation to vegetation"
- **A. Louise Heathwaite** (Lancaster University, UK) on "Water Quality, Supply and Demand"
- **Lennart Olsson and Johannes Stripple** (Lund University/ Sweden) on "Environmental thresholds, the case of climate change"
- **George Shaw** (University of Nottingham/UK) on "Levels of dispersal of toxic substances and the disposal of solid waste"
- **Harald Sverdrup et al.** (Lund University/Sweden) on "Critical loads for acidity to ecosystems How environmental limits came to set the policy"
- **Paul Upham** (University of Manchester/UK) on "Renewable and Non-Renewable Resource Use: environmental thresholds and UK policy applications".

# Environmental Thresholds Review: Position Paper Briefing Document

## Background

1. **The aim of the project, to which this invited review will contribute, is to collate and assess existing knowledge on environmental limits/thresholds and their application in policy-making within the UK.**

2. Despite the UK focus, however, the project seeks to explore wider international experience and perspectives in order to:

   a. Examine how environmental limits are identified and defined elsewhere, in terms of a range of scientific and social/cultural criteria;
   b. Assess the robustness of the evidence used to define environmental limits and how that evidence might be collated and used;
   c. Identify gaps in our present understandings of environmental limits and where further research may be needed.

3. The work was prompted by the commitment made in the UK Sustainable Development Strategy[58] to collate existing research and identify shortfalls in understanding about where environmental limits exist, and where they are being exceeded. This study will contribute to fulfilling this commitment and will form part of the evidence-base for Defra's work on Natural Resource Protection and Sustainable Consumption and Production.

## Scope

4. **For the purposes of this review, a threshold is understood to represent some kind of "regime shift" in an environmental system, separating alternative, qualitatively different states.** Given such a definition, any review of environmental thresholds could obviously be very wide ranging. Thus as a way of scoping the review it has been decided that the focus of should primarily be on thresholds that involve understanding the physical or biological thresholds associated with environmental systems that have relevance to people, in terms of their economic or social value and consequences that might arise of a threshold or limit is approached or crossed.

5. The definition thresholds according to their biophysical, social and economic dimensions is close to the position expressed by other organisations such as the EU[59], which has argued that environmental sustainability thresholds must be seen

[58] www.sustainable-development.gov.uk
[59] European Commission Directorate General for Research (2002): *Thresholds of environmental sustainability: the case of nutrients.* EUR20170.

"as a physical value reflecting the extreme state of the environment ***and*** as an economic value reflecting the damage on monetary valuation or the restoration costs". The view is also consistent with recent attempts to explore society-nature relationships through the concept of 'ecosystem goods and services', which argues that ecosystems and the biological diversity associated with them provides a stream of goods and services to people and communities, the maintenance of which is essential to their economic prosperity and other quality of life[60].

**Structure of the Invited Position Paper**

6. In order to assist us in making our review of environmental thresholds or limits you are asked to provide a short briefing paper, in which you explore the concept as it relates to your area of expertise. While we would like you to share any insights that you have in relation to the 'state-of-the-art', the specific questions that we would like you also to address are as follows:

    a. To what extent have 'threshold concepts' or similar ideas been developed or explored in you subject area?
    b. Are you aware of any physical or biological limits that been identified or conjectured in your subject area, that have a consequence for people or communities? If so how have they been defined?
    c. What kinds of evidence or data have been used to test the idea that such thresholds or limits exist?
    d. What kinds of factor are thought likely to drive the environmental system towards or beyond such thresholds or limits?
    e. Have any of these thresholds been embodied in standards or targets that have then be used in regulations or management policies?
    f. Do these thresholds vary over time or space, and if so, how is that variation represented?
    g. What kinds of uncertainty are associated with defining or identifying the thresholds or limits?
    h. What kind of future research is needed in relation to identifying or operationalising the threshold concept for policy or management?
    i. How useful do you think the threshold idea is in taking forward our general thinking about sustainable development?

    In making you response, you are asked mainly to provide an overview, with links to case studies and what you consider to be the relevant literature in the topic.

Roy Haines-Young
Marion Potschin
CEM, School of Geography, University of Nottingham

[60] Daily, G.C. (1997) "Nature's Services: Societal Dependence on Natural Ecosystems", Island Press, Washington, D.C.

## Environmental Thresholds Review:
## Marine Environment

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### Introduction – regime shifts in marine ecosystems

Human interaction with marine ecosystems is diverse, including relatively small scale but concentrated recreational use, including marine tourism; major habitat modification associated with industrial extraction (for instance of oil or gravel); environmental change associated with human-induced global warming; pollution-induced environmental and ecosystem change; and ecosystem changes associated with fishing. Ospar (2000) identified the 6 top human pressures on the marine environment as follows:

1. Fisheries: removal of target species
2. Input from land: organic micro-pollutants
3. Fisheries: seabed disturbances
4. Inputs from land: nutrient
5. Fisheries: effects on non-target species
6. Shipping: inputs from anti-fouling substances

Marine environments often appear to experience regime shifts of the type envisaged in this review series, and their cause is often thought to be environmentally driven. Ocean-atmosphere interactions, for instance El Niño in the Pacific Ocean, the Pacific Decadal Oscillation or the North Atlantic Oscillation, cause large scale oceanographic changes which are often cyclical. El Niño itself is most famous for its effects on Peruvian anchovy stocks, which are severely reduced during El Niño years, and for shifting the position of warm core water in the western Pacific and, with it, the distribution of skipjack tuna (Lehodey et al 1997)[61]. Pacific sardine and anchovy populations have experienced cyclical periods of abundance and collapse in response to changing climatic/oceanographic conditions (Baumgartner et al. 1992).

Major regime shifts may also, however, be triggered by human activity, in particular over-exploitation of fisheries resources. The most recent example of this type of shift is the wholesale collapse of many stocks of cod and haddock from the grand banks area off Newfoundland in 1991. This collapse does not seem to have been the result of changes in oceanography or environment, reductions in recruitment, or increased predation, and can be squarely laid at the door of poor management and overfishing

[61] El Niño of course also has significant affects on global land-based weather patterns, including drought/flood cycles in South America and Australia.

(Hutchings and Myers, 1994; Hutchings, 1996). Signals of the decline were present at the time, but were ignored in favour of optimistic interpretations of the data (Caddy & Agnew, 2004). The social and environmental effects of the collapse have been significant, a virtual overnight end of a fishery that had been maintaining Newfoundland populations since the 1800s. The consequence for the marine ecosystem to the east of Newfoundland has been profound, because even now 15 years after the event there has been only a partial recovery of cod stocks. As a consequence of the removal of cod, populations of its prey (shrimp, crab, capelin and flounder) increased, whereas other large demersal feeders declined. The population of harp seals increased slightly and some analyses suggest that they may be slowing the recovery of cod (Bundy 2001).

It is beguiling to attribute regime shifts simply to environmental changes beyond our control. Very often it seems that subsequent detailed analysis reveals that fishing contributed to, or in some way exacerbated, environmental changes. The Pacific Decadal Oscillation created a major climatic shift, from an Arctic climate to a warmer subarctic maritime climate, in the Bering Sea around 1977 (Livingston et al 2004). Starting at this time, and culminating in the early 1980s there was a major ecosystem reorganisation in the Bering Sea, with increases in some species such as walleye pollock, Pacific cod, skates and non-crab benthic invertebrates, and decreases in crabs (Conners et al 2002). Although these changes were coincident with the PDO changes, they were also coincident with a major shift in fisheries management policy (the 1976 US Magnuson-Stevens Fishery Conservation and Management Act), and it is appears that they resulted from a combination of fishing and ecosystem changes (Otto 1986, NAS 1996, Dew & McConnaughey 2005).

The recent collapse of cod in the North Sea appears to be primarily a consequence of a regime shift in about 1988 (Reid et al 2001), which created unfavourable conditions for larval and juvenile cod. Rising temperatures, linked to warming of the North Sea and to the North Atlantic Oscillation, appear to have induced major changes in copepod community structure and a reduction in the size and abundance of copepods and euphausids available to larval cod in their critical growing period March – July (Beaugrand et al 2003). The subsequent decline in the north sea cod stock was exacerbated by high fishing pressure which did not decline fast enough in line with the environmentally-induced decline in recruitment to avoid a collapse of the stock (Caddy & Agnew 2004).

By contrast with fishery-induced environmental changes, pollution events appear to be capable of effecting significant changes on marine environments only when those environments are relatively contained such as enclosed seas (eg the Baltic or Black seas) or large embayments. Major marine pollution incidents, such as the Exxon Valdez in Prince William Sound in 1989, cause local environmental damage and costs, and may create long-term local environmental perturbations even if superficial recovery of ecosystems and large mammals and birds occurs in a relatively short time (Peterson 2003). But they do not generally affect the wider large marine ecosystem (LME: see below) within which they occur.

## Thresholds in marine ecosystem management

Clearly there is great potential for unrestrained harvesting in fisheries to cause regime shifts that have catastrophic consequences for the harvested species, the marine ecosystem and human economic and societal values associated with that ecosystem. It is therefore not surprising that there is a long history of analysis of single species exploitation dynamics and the development of thresholds for single species management (Ricker 1975; Hilborn & Walters 1992). Three thresholds are usually acknowledged and termed management reference points. In order of increasing fishing pressure these are termed

Target reference point- a target for management that may be at or lower than the precautionary reference point

Precautionary reference point – a reference point which, given the undertainty in the system and in the assessment (i.e. both process and observation error), provides a high probability of being below the limit reference point

Limit reference point – a reference point beyond which the sustainability of the stock is likely to be impaired.

The European International Council for the Exploration of the Sea (ICES) defines only precautionary and limit reference points, but it does so both in terms of stock biomass and fishing effort. The limit reference point for spawning stock biomass, $\mathbf{B_{lim}}$ is set on the basis of historical data, and chosen such that below it, there is a high risk that recruitment will 'be impaired' (seriously decline) and on average be significantly lower than at higher SSB. $\mathbf{F_{lim}}$ is the fishing mortality that, if maintained, will drive the stock to the biomass limit. $\mathbf{B_{pa}}$ is the reference point at which there is a high probability, given process and observation error, that the true level of spawning stock biomass is above Blim. $B_{PA}$ plays a key role in ICES advice, as a risk control tool for $B_{LIM}$. Maintaining the biomass at or above $\mathbf{B_{pa}}$, and the fishing mortality at or below **Fpa**, is unlikely to create a situation where recruitment is seriously impaired and stock sustainability compromised (ICES, 2004a).

Other management authorities have developed different approaches. The National Marine Fisheries Service (NMFS) of the National Oceanographic and Atmospheric Administration in the US has developed a 6-tier system for its fisheries, based on different levels of uncertainty and knowledge about the stock (eg NPFMC 2004). Lower levels of uncertainty allow more precise estimates of sustainable yield to be made; higher levels of uncertainty require more conservative, or precautionary, approaches to be taken. This is consistent with the precautionary approach as defined in the FAO's Code of Conduct for Responsible Fishing (FAO 1995, 1998).

In single species terms, harvesting reference points are usually understood to be between 30% and 50% of unexploited biomass. For instance, NMFS sets a limit reference point of 35% SPR (SPR is the spawning biomass arising from one recruit; 35% SPR is the biomass level at which SPR is 35% of the unexploited population

SPR) and a target reference point of 40% SPR. In the Antarctic, the Commission for the Conservation of Antarctic Marine Living Resources, which has a much larger remit for ecosystem conservation than many other fisheries management bodies, adopts a more conservative target of 50% of unexploited spawning biomass for its major finfish species (Constable et al. 2000).

Although the theory and application of reference points for *single species fisheries* is well established, the development of reference points for other ecosystem components is much less well developed (Rice, 2005). Studies in this area are extensive and of growing importance to the development and general acceptance of the need for an *ecosystem approach*[62] to fisheries (FAO 2003). Several modelling approaches have been developed to enable the understanding of marine ecosystem functioning, the most widely used being mass balance approaches such as ECOPATH/ECOSIM/ECOSPACE family (Walters et al 1998, Christensen et al 2000) and biogeochemical ecosystem models (Fulton & Smith, 2004).

Problems arise in quantitative understanding of the functional links between ecosystem components, and understanding the critical points at which ecosystems will change or undergo regime shifts. In consequence, absolute thresholds for ecosystems have not yet been set or incorporated into management reference points except in a precautionary way. Rice (2005) consider that simple good management of single species is unlikely alone to guarantee good ecosystem based management, although even this result would be a considerable achievement for many over-exploited fisheries. Additional precaution in setting ecosystem based reference points is almost certain to be required, but is very sparingly applied. One example is the Antarctic krill fishery, for which CCAMLR has set a limit reference point of spawning biomass at 75% of unexploited biomass because krill is a key ecosystem component and food species for a large number of squid, fish, bird and mammal species.

Reference points for ecologically dependent species (species that are tightly linked ecologically to the target species) or species that are directly impacted by fishing for the target species are easier to define. Some single, critically threatened dependent species have their own reference points which if exceeded will close a fishery: for instance there is an allowable take of only 2 short-tailed albatross per year in the Bering sea fishery (USFWS 2003); a rationale for using a three-year depression in breeding success of kittiwakes (*Rissa tridactyla*) as a reference point corresponding to

[62] Various terms are used to describe ecosystem approaches: The terms *ecosystem approach*, *ecosystem based fisheries management*, and the *ecosystem approach to fisheries* are all modern encapsulations of the general purpose to *plan, develop and manage fisheries in a manner that addresses the multiplicity of societal needs and desires, without jeopardizing the options for future generations to benefit from a full range of goods and services provided by marine ecosystems"* (FAO 2003; Garcia et al. 2003) and replaces the older term *ecosystem management*, which implied direct manipulation of ecosystems rather than manipulation of fishery impacts on ecosystems. OSPAR and the North Sea Conference of Ministers consider the implementation of an ecosystem approach in fisheries management as an important step for the integration of fisheries and environmental issues.

local depletion of sandeels has been made (ICES, 1999), and the sandeel fishery was closed in June 2005 because of concerns about the effects of low sandeel population sizes on kittiwake breeding success (RSPB, 2005).

As an initial approach, many marine management bodies have been exploring the development of monitoring and indicators (Agnew 1997; Jennings, 2005). The indicators are most useful in describing the state of the ecosystem, and can be used to present qualitative "traffic light" systems indicating to managers where there are problems (Caddy 1995, 2004) but have rarely been incorporated into management reference points. They are, however, increasingly included in advice provided by scientific organisations for fisheries managers (eg Boldt et al. 2004; ICES 2004b).

Monitoring of Large Marine Ecosystems (LMEs) has received considerable attention both in the US and Europe (EPA 2005; UNEP-WCMC & MRAG 2004) and the concept arises out of the development of the ecosystem approach (Sherman & Duda 1999) and the statutory obligations of marine environmental management organisations such as OSPAR (Commission for the Protection of the Marine Environment of the Northeast Atlantic). In the LME approach assessments are based around a series of five modules: productivity, fish and fisheries, pollution and ecosystem health, socioeconomic, and governance (Sherman 2003; UNEP-WCMC & MRAG 2004). The EPA uses a slightly different set of modules: water quality, sediment quality, benthic, coastal habitat and fish tissue (EPA 2005). A comparative matrix of LME assessments has been compiled by GIWA (Daler et al. 2001; GIWA 2005).

With few exceptions, these assessments have not been incorporated into explicit reference points and operational management strategies for the marine environment as a whole. However, with the exception of enclosed water bodies such as the Black sea and the Baltic sea, where environmental pollution or eutrophication become very important (ICES 2004), the major impact on marine environments is likely to come from fishing. The relatively advanced state of consideration of monitoring the marine environment with respect to fish and fisheries, and of consideration for incorporation of ecosystem approaches into fisheries management reference points (Rice, 2005) means that this aspect is the most likely to lead to operational management strategies in the future. The socioeconomic and governance modules are probably least developed, although they are ultimately the operational interface of assessment (UNEP-WCMC & MRAG 2004).

**Conclusion – the use of thresholds and reference points to avoid anthropogenic regime change in the marine environment.**

Taking the above discussion into account, the following answers to the questions are relevant.

j. To what extent have ‘threshold concepts’ or similar ideas been developed or explored in you subject area?
k. Are you aware of any physical or biological limits that been identified or conjectured in your subject area, that have a consequence for people or communities? If so how have they been defined?

*In terms of single species models, thresholds are defined, set and used regularly to manage marine fisheries. In terms of dependent and related species, thresholds are used occasionally, and usually only when the species concerned are threatened. In terms of the ecosystem, thresholds have not yet been defined in quantitative ways, although qualitative thresholds are understood and may be used to influence management.*

l. What kinds of evidence or data have been used to test the idea that such thresholds or limits exist?
m. What kinds of factor are thought likely to drive the environmental system towards or beyond such thresholds or limits?

*There are many historical examples of regime shift, which have been analysed using models or historical data. Regime shifts may be triggered anthropogenically, usually through unrestrained fishing or un-anticipated ecosystem effects of fishing, or as a result of climatic changes (often cyclical). In the latter case fishing or other human activities can exacerbate the environmental effect.*

n. Have any of these thresholds been embodied in standards or targets that have then be used in regulations or management policies?
o. Do these thresholds vary over time or space, and if so, how is that variation represented?
p. What kinds of uncertainty are associated with defining or identifying the thresholds or limits?

*In terms of thresholds that may send whole ecosystems into regime shift, very few have been identified or incorporated into quantitative management policies. However, qualitatively most management authorities are now attempting to implement the ecosystem approach to marine management, and fisheries management in particular, and there are numerous examples of them doing this in a precautionary way even if explicit reference points are not available.*

q. What kind of future research is needed in relation to identifying or operationalising the threshold concept for policy or management?
r. How useful do you think the threshold idea is in taking forward our general thinking about sustainable development?

*The topic of ecosystem approaches to management is receiving considerable attention world-wide, and in Europe particularly in work by ICES (Rice, 2005), work on* *indices funded by the European Commission (IEEP 2005), and in terms of ecosystems that by the European Environment Agency. However, it is also true that there have been attempts for the last two decades to get to grips with operationalising the ecosystem approach within fisheries. Part of the problem has been defining what is required. Initially it was thought that there would be a single management strategy that would optimise all ecosystem management objectives, but it is now realised that this is unrealistic. Ecosystem based management therefore now tries to minimise the effects of, for instance, fishing, on critical components of the ecosystem, monitored with indices (Sainsbury & Sumaila 2003; Jennings 2005; WCMC & MRAG 2005) and expressed through reference points for target species, non-target species, habitat change or genetic health (Rice, 2005). In this new paradigm, it is precisely the thresholds that are being discussed, particularly in the context of key dependent and related species, rather than the general concept of an ideally or optimally managed ecosystem.*

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# Environmental Thresholds Review:
# Position Paper

Environmental thresholds and their application for ground level ozone air quality management in relation to vegetation


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Tropospheric or ground level ozone is an extremely phyto-toxic pollutant causing serious damage to agricultural productivity, forest health and semi-natural ecosystems (e.g. Fuhrer & Booker, 2003; Matyssek & Sandermann, 2003; Davison & Barnes, 1998). The extensive body of evidence, both observational and experimental, that has been collated since the first observations of ozone injury (e.g. Middleton et al., 1950) has provided the impetus to develop air quality management strategies and formulate emission reduction policies to limit the negative effects of this pollutant. This paper will focus on the development and application of thresholds (critical levels) as an air quality management tool in Europe.

Tropospheric ozone occurs naturally in the atmosphere at background concentrations. Since pre-industrial times, background ozone levels have risen about 36% (IPCC, 2001) and are projected to continue to increase in the future as emissions of ozone precursors (nitrogen oxides and volatile organic compounds) continue to rise (Vingarzan, 2004). As such, the use of a "threshold for effects" concept lends itself particularly well to ground level ozone and related impacts since plants have evolved under natural background concentrations and would be expected to show effects once some critical threshold is exceeded.

At the plant level, the threshold concept is supported theoretically on the understanding that plants can cope with some level of ozone stress by mechanisms of avoidance and defence (Wieser et al., 2002). As such, it is evident that not all ozone exposures will contribute to plant damage. Since the external plant cuticle provides an effective barrier to internally damaging ozone uptake (Kerstiens, 1995) *avoidance* can be conferred by stomatal narrowing (e.g. Grünhage & Jäger, 1994). *Defence*, in terms of the absorbed ozone dose, may occur due to detoxification by biochemical reactions (Long & Naidu, 2002).

Identification of effect thresholds based on ambient ozone concentrations combined these two stress determinants into one single, concentration based ozone characterization index. More recently, methods have been developed to estimate stomatal ozone flux, thereby allowing the potential for thresholds to become more physiologically based (Ashmore et al., 2004). The use of such thresholds as a policy tool within Europe has been a driving force behind the development of a threshold methodology applicable for air quality management.

The transboundary nature of ground level ozone pollution requires international agreements for co-ordinated emission control. In Europe, the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution (UNECE CLRTAP) was established in 1979 to develop protocols for emission control (Working Group on Effects, 2004). Initially, signatories were required to reduce their national emissions or transboundary fluxes by at least 30%. This equal percentage of reduction for every country was both unpopular and difficult to justify on scientific grounds (Kuylenstierna et al., 2002). In response to this, the "effects-based approach" was developed whereby reductions of emissions would be negotiated on the basis of pollution effects. This resulted in the development of "critical loads and critical levels" for wet/occult and dry (gaseous) deposition respectively. The approach uses air quality guidelines formulated from the definition that they represent:

> 'the concentrations of pollutants in the atmosphere above which direct adverse effects on receptors, such as plants, ecosystems or materials, may occur according to present knowledge' (UNECE 1988)

Critical levels for ozone are designed to protect vegetation (categorised as forests, agricultural crops or semi-natural) and can be used to identify areas which are potentially at risk from air pollutant damage. Identifying these exceedance areas, both for current day and future pollutant concentrations, enables the derivation of optimised emission abatement policies through their application in integrated assessment models.

Observations of visible injury and damage to vegetation led to attempts to understand both the threshold at which effects might be observed, and the magnitude of effects with increasing exposure over and above a threshold level. As such, research efforts were targeted towards the development of exposure-response relationships, relating ozone concentrations to plant damage, using experimental apparatus (Open Top Chambers) specifically designed for these purposes (e.g. Heagle et al., 1979). OTCs allowed controlled ozone fumigations under near "field" conditions and experimental design using replicated randomised blocks with different treatments (e.g. ambient-open, charcoal-filtered chamber, non-filtered chamber, 1x $O_3$, 2x $O_3$) allowed statistical interpretation of results.

Two major programmes employed these new techniques during the 1980s. Firstly, the National Crop Loss Assessment Network (NCLAN) that applied standardised protocols at locations across the United States (EPA, 1996) and secondly, the European Open Top Chamber (EOTC) Programme. In Europe, the EOTC study led to the development of an ozone characterisation index capable of summarising the cumulative seasonal ozone exposure, termed the AOT40 (Accumulated exposure Over a Threshold concentration of 40ppb) index (Fuhrer et al. 1997).

**The use of this index allowed linear relationships to be established with yield or biomass reductions from a pooled data-set of different experiments, performed in different countries. From such dose-response relationships it is possible to derive the critical level or threshold for plant response using statistical analysis to determine the level of yield reduction that could be discerned with 99% confidence (Pleijel, 1996). As such, these methods aim to identify the concentration representing a 'no-significant-effect' level. However, it is clear that there are difficulties in defining thresholds, partly because a large volume of data is required to determine 'no-significant-effect' levels, partly due to difficulties in interpretation of the data and the influences of different biotic and abiotic factors (such as climate), and partly due to the lack of experimental data close to the proposed threshold (Emberson et al., 2003).**

Some of the problems in identifying thresholds listed above are related to the use of a concentration rather than flux based ozone characterisation index. Relating damage to flux rather than concentration would provide information and a means of quantifying the avoidance component of the “effects threshold”. As such, it has been hypothesised that flux should give more statistically robust relationships with damage than AOT40. Re-analysis of existing OTC data by Pleijel et al. (2004) for wheat and potato confirmed this hypothesis with stronger correlations with relative yield being observed for flux compared to concentration indices. Pleijel et al. (2004) also found that optimum correlations were obtained on using a “flux threshold” representing a constant detoxification capacity although it was acknowledged that this represents a simplification of the biological detoxification capacity.

To better understand detoxification thresholds conceptual models have also been under development. Massman et al. (2000) differentiate between ozone induced plant injury and damage according to the definitions of Guderian (1977) where injury is any biological response, such as changes in metabolism, photosynthesis, leaf necrosis; and damage is the reduction in the intended use or value of the plant, such as economic value, ecological structure or function, biological or genetic diversity. In general plant injury precedes plant damage. They argue that passive defences (related to normal levels of antioxidants within the plant tissue) will likely vary with time according to e.g. plant developmental stage, plant health. In contrast, active defences result from specific stress-induced responses, for example those caused by ozone contact with internal plant tissues. As such the detoxification capacity, and hence effective dose threshold, will not be a constant but will vary over time dependent upon innate and stress induced detoxification potentials.

Although conceptually these ideas seem plausible, the difficulty in their application lies in the paucity of data available to quantify, even for key species, the impact these innate and external drivers may have on detoxification potentials. Attempts at modelling detoxification processes (e.g. Plochl et al., 2000) have concentrated on the importance of the reactions of $O_3$, and its derivatives, with apoplast ascorbate (vitamin C) having been identified as a key cellular component mediating ozone response (Barnes et al., 2002). However, it is clear from other studies, that additional cellular constituents comprise important, if not vital, forward-defensive barriers protecting cell components from $O_3$ attack (Moldau, 1998).

Since ozone effects are determined both by the avoidance and defence mechanisms, any variation in these as a function of time and space will alter the thresholds. Growing season and daylight ozone characterisation indices were introduced to account for such avoidance although there is still debate within the community as to the role of night-time stomatal conductance in allowing effective ozone doses, especially as evidence suggests that anti-oxidant levels are also reduced during the nocturnal period (Wieser & Havranek, 1995; Frederiksen et al., 1995). In addition to growth period, stomatal conductance and hence the potential to absorb ozone is also determined by the prevailing environmental conditions and in particular temperature and atmospheric and soil water deficits. The use of a flux based concept, that determines ozone dose on estimation of stomatal conductance (e.g. Emberson et al., 2000, Grünhage et al., 2000) is useful to integrate the avoidance aspects related to injury and damage. Similarly, the magnitude, frequency, and distribution of the ozone pollution episodes will also determine dose as well as the rate at which detoxification thresholds are exceeded (Musselman et al., 2006).

Uncertainties associated with the threshold concept for ground level ozone can be considered either in terms of the experimental/observational uncertainty in defining the biological threshold or the identification of the threshold exceedance across geographical regions, as is necessary for policy formulation.

Considering experimental/observational uncertainty first, it is evident that only a certain number of species have been screened for ozone sensitivity and further tested to derive exposure or flux-response relationships, with even fewer cultivars/ genotypes having been assessed. As such, the exposure or dose-response relationships that do exist for different species vary in their robustness since regressions will be based on variable numbers of experiments, performed in different climate regions, during different years and on a variety of different cultivars/genotypes (Mills et al., 2000).

In addition, exposure-response relationships are commonly derived from experiments using OTCs, which are often characterised by conditions of constant turbulence, higher-than-ambient temperature, altered hydrology, higher humidity and vapour pressure deficit, and reduced irradiance (e.g. McLeod & Long, 1999). For forest trees chambers are commonly only capable of accommodating potted seedlings or saplings, leading to problems in extrapolation of responses observed in juvenile to mature trees due to variations in canopy stomatal dynamics, carbon allocation, crown and root architecture and response to biotic and abiotic stresses such nutrient and soil water availability (e.g. Matyssek & Innes, 1999). One answer to these issues of experimental uncertainty may be the use of open-air fumigation systems (e.g. Dickson et al., 2000) which as well as removing problems associated with chamber artifacts, also allow larger plot sizes and hence examination of effects such as intraspecific and interspecific competition, ozone fluxes to soil and pest epidemiology. For example, trophic interactions are facilitated by the unencumbered movement of insects into and out of the free air fumigation rings (Karnosky et al., 2005).

There are also uncertainties associated with identifying threshold exceedance across geographical regions so as to formulate policy to mitigate (reduce such exceedances) or adapt to impacts that might be expected to occur in the exceedance areas. In order to use critical levels for regional assessments various data are required, each adding an additional level of uncertainty to the identification of threshold exceedance.

The UNECE CLRTAP employs the chemical transport model of the European Modelling and Evaluation Programme (EMEP) to inform pollution abatement strategies and legislation work (Simpson et al., 2003). Such modelling of ozone concentrations requires a detailed emission inventory and meteorological data. To reduce these uncertainties the EMEP model is constantly evaluated against concentration measurements (e.g. Tarrasón et al., 2005). However, the inclusion of any type of threshold in the pollution characterisation index has a tendency to magnify errors in the modelling of that index. For example, Tuovinen (2000) found that a 5% overestimation of the mean ozone concentration resulted in a 10 to 50% overestimation in AOT40 on analysis of data from measurement sites located across Europe.

**Once ozone concentrations have been characterised, receptor information is required to describe species location. Uncertainties exist in accurately mapping receptor distribution, especially as land use is constantly changing over time, in addition, any associated physical characteristics and production statistics necessary to understand the import of threshold exceedance will also vary temporally and be subject to uncertainty (e.g. de Smet & Hettelingh, 2001).**

The critical level approach was designed specifically for policy evaluation to manage air quality and as such, has already been instrumental in driving policy and targeting emission abatement strategies across Europe. Although it could be argued that a well established framework exists for applying threshold concepts in relation to air quality management there are still a number of rather serious limitations in the approach, partly attributable to a lack of data and partly attributable to a lack of validation that the areas in exceedance of the thresholds are actually suffering damage.

Assessments using dose-response relationships provide “bottom up” estimates of damage which ideally would be complemented with “top down” assessments. A variety of such methods have been developed and applied for different vegetation types and include passive and active bio-monitoring (e.g. as employed by two of the UNECE International Co-operative Programmes (ICP) to assess effects of air pollutants on forests and natural vegetation and crops), dendrochronological assessments (using tree ring cores to assess past years’ growth), transect studies (assessing growth across a gradient of pollutant exposure) and epidemiological style studies employing regression methods (e.g. McLaughlin & Downing, 1995; Braun et al., 1999, Shankar & Neeliah, 2005). Such methods could prove extremely valuable in validating threshold based risk assessments and ensuring emission reductions are targeted to those areas of Europe where they will be of most benefit.

Data resources could be improved by establishing more robust dose-response relationships for a wider range of species and cultivars/genotypes; the use of experimental techniques such as “Free Air Ozone Experiments” (FAOE) should be encouraged since these reduce experimental uncertainties. In addition, transferability of the methods to geographical regions away from where they have been developed (and more importantly experimentally parameterised) will be key in ensuring wider geographical/global application of threshold assessment tools. Finally, a better understanding of the processes of ozone impact will reduce the reliance on empirical data to identify thresholds. Such information will be crucial to our understanding of threshold dynamics under altered environmental conditions. For ozone this can be exemplified on consideration of the increasing background concentration which will lead to chronic ozone exposures, as opposed to the acute exposures employed in experimental studies. How plants will respond to such different ozone exposure dynamics is currently extremely uncertain.

However, to fully understand the social and economic costs of pollution and the associated benefits in reducing emissions, it is useful to be able to quantify effects rather than merely identify where they are likely to occur. The dose-response relationships from which the critical thresholds are statistically derived provide the opportunity to perform such quantifications, though extreme care has to be taken in interpretation of the results. Once again, the use of complementary “top down” assessment tools will be essential to ensuring appropriate interpretation of damage estimates.

The selection of the threshold index should also be careful to consider the influence of additional stresses which are likely to change over time, ideally the index would be able to integrate key factors that may affect the threshold level. A case in point is the different opportunities afforded to risk assessment by the concentration- and flux-based indices under climate change. The concentration-based index assumes both a static avoidance and defence mechanism. The flux concept at least goes some way towards allowing for a more dynamic approach to risk assessment by accounting for variations in “avoidance”, as well as offering a mechanistic based methodology that could be further modified to incorporate defence. The approach integrates species specific characteristics such as maximum stomatal conductance and environmental conditions. As such, the influence of elevated $CO_2$ and changes in temperature, precipitation and atmospheric water status on stomatal aperture can be incorporated, which will be especially important on consideration of future climate conditions (IPCC, 2001).

The selection of the response parameter is also rather crucial. Currently critical levels are established only for visible injury, or yield and biomass losses (UNECE, 2004). Ground level ozone can impact on plants in a variety of different ways from sub-cellular alterations in biochemistry to shifts in ecosystem composition. The most appropriate response to drive environmental management may well change with time as new environmental issues become important, for example, understanding the role of ozone in affecting carbon sequestration (e.g. Loya et al., 2003) may become more important under future climate change conditions.

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# *Environmental Thresholds Review:* WATER QUALITY, SUPPLY AND DEMAND

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## CONTEXT

This position paper forms part of a wider critical review of environmental thresholds. The intention is that this review helps frame policies for the protection of natural resources in the UK. This position paper seeks to apply the concept of thresholds to the general area of water quality, supply and demand. A 'threshold' is understood to represent a regime shift in an environmental system, separating alternative, qualitatively different states. The focus is on physical or biological thresholds associated with environmental systems and their relevance to people, in terms of their economic or social value and consequences that might arise of a threshold or limit is approached or crossed. Such thresholds are difficult to quantify, partly because our understanding of the functional links between different elements of freshwater ecosystems remains partial. In particular, for water quality and water resource supply and demand issues, there is necessarily a close link in terms of the ecological health of the freshwater system to the terrestrial environment. This creates an added complexity in trying to understand the impacts of changes in terrestrial ecosystems on the quality and quantity of receiving waters (Harris and Heathwaite, 2005). Consequently, where thresholds have been set e.g. in relation to water quality standards, these thresholds often have limited quantitative scientific understanding and usually follow a precautionary principle that may be over protective in some instances. Nitrate is a good example here because the WHO standard of 50 mg $NO_3^-$ $l^{-1}$ was set according to the perceived risks from cancer and 'blue baby syndrome'. However, evidence now suggests that nitrate is not toxic to infants at the threshold of 50 mg $NO_3^-$ $l^{-1}$ (Wilson et al., 1999).

## INTRODUCTION – REGIME SHIFTS IN THE WATER ENVIRONMENT

Water is a 'landscape agent' in terms of its erosive capacity, it capacity as a mobile solvent, and in its provision of habitats for aquatic biota. Because water provides 'environmental services' it is a heavily exploited and highly managed natural resource. Consequently, sustainable solutions to water management must address both social and natural science objectives.

Of the total estimated water volume on Earth (1,385,984 $km^3$) only approximately 35,029 $km^3$ or 2.53% forms the freshwater stock (Gleick, 2000). Of this total freshwater stock, over 99% is not readily accessible: nearly 70% is bound in glaciers, permanent snow cover or permafrost; the remaining 30% is groundwater. These figures highlight three pressure points that are likely to emerge at different times in the future, but which will be of critical significance for water quality, supply and demand: (1) in the short (20 year) term, human impact on the 1% of freshwater that is readily available in rivers and lakes is likely to increase and so needs to be very carefully managed; (2) in the mid (20-50 year) term, improving and protecting groundwater quality will be essential for the sustainable management of the freshwater environment; and (3) in the long (50 year +) term, climate change impacts on water bound in snow and ice will have far reaching but unpredictable impacts on the water environment.

The scope of this position paper as it relates to *water quality, supply and demand* is potentially very wide. Consequently, this position paper will focus on the first two pressure points identified above in order to meet the objectives of the review to examine how environmental limits in relation to freshwater systems may be defined and to assess the robustness of the evidence used to define environmental limits for freshwater systems. At present, climate change impacts seriously challenge our understanding of environmental limits in the freshwater environment but better predictive understanding may be gained by addressing the pressure points under (1) and (2) with respect to advancing our process understanding of the freshwater environment. Climate change is likely to generate long-term risks for the sustainability of water resources in terms of more extreme floods and droughts but the immediate scientific challenge is that of water quality. Key problem areas are associated with diffuse sources of agricultural nutrients and biocides; human- and livestock-derived microbial contaminants such as *E. coli* and *Cryptosporidium*; the problems posed by waste disposal and contaminated land; and the impacts of urban storm water overflows. These are difficult problems in respect of both obtaining adequate measurements to characterise the sources of water quality problems and in making predictions about the impact of investments in improvements. Those predictions will be inevitably uncertain. Added to this, many of the approaches for river basin management and sustainable water management in use today were not designed to deal with indeterminacy in decision making, particularly about new investments to meet the requirements of, for example, legislation like the Water Framework Directive (WFD).

Unlike the fisheries of the marine environment, and with the exception of lentic water bodies, freshwater systems do not generally experience rapid regime shifts of the type envisaged in this review series. Lakes and reservoirs are the exception because regime shifts are known to occur (e.g. Schindler, 1977) in response to, for example, nutrient pressures and the consequent impact on the trophic status of the water body. However, these changes are thought to be a gradual process (www.apis.ac.uk). Eutrophication may be recorded in response to phosphorus (P) concentrations as low as 10 to 100 μg P $l^{-1}$ of water, which amounts to only a few kg of P loss per hectare from agricultural land per year. As with the enclosed seas of marine environment (e.g. the Baltic or Black seas), the impact of pollution on lakes and reservoirs has been widely recognised as capable of effecting significant changes on freshwater environments. The limited evidence for regime shifts in the freshwater environment may of course be a consequence of the large bulk of the freshwater stock – groundwater – being subterraneous and consequently difficult to monitor. This does not mean that thresholds are not crossed; just that they are much more difficult to detect.

PRESSURE POINT 1: ***Diffuse Pollution: land use pressures, sediment transport and aquatic ecosystem health***

In the short term, human impact on the 1% of freshwater that is readily available for exploitation in rivers and lakes requires careful management if the quality and quantity of the resource is to be sustained. Human activities have increased the availability of nutrients such as nitrogen (N) and phosphorus (P) in freshwater and coastal environments. Although it is known that changes to nutrient loadings to ecosystems affect carbon and nutrient transformations, predicting the responses to of ecosystems to nutrient loading is difficult because multiple factors regulate biogeochemical transformations in freshwater and coastal ecosystems (Seitzinger et al., 1983; Sundareshwar et al., 2005). Although predicting thresholds for ecosystem response is difficult, establishing the sources of elevated nutrient loadings is relatively well-understood. Reduction in point source nutrient loadings from, for example, sewage treatment works, has shifted the emphasis to agricultural diffuse pollution as a significant threat to the long term sustainability of freshwater ecosystems (Heathwaite et al., 2005). Diffuse pollution is a critical issue because the cost of tackling only the tangible aspects of diffuses pollution from agriculture in the UK has been estimated by be around £300 million per year (Pretty et al., 2003). Reducing diffuse pollution is also a central aim of the UK Government's Sustainable Food and Farming Strategy (Defra 2002) and is critical if Public Service Agreement targets to bring 95% of SSSIs into 'favourable' condition by 2010 are to be met.

Diffuse pollution may arise where low or medium intensity activities on the land surface (e.g. spreading manures; surface compaction through overgrazing or cultivation) occur over a large geographic area, creating problems at particular places and times (*e.g.* exacerbated flood risk (Defra, 2004), water quality degradation (e.g. Heathwaite, 1999), biodiversity loss). Diffuse pollution is increasingly subject to national and supranational legislation (*e.g.* Habitats Directive 92/43/EEC, Water Framework Directive 2000/60/EC). The environmental consequences of land management decisions include the degradation of freshwater ecosystems, increased water treatment costs and reduced aesthetic value. The main physical drivers of these processes have been identified (*e.g.* for water quality degradation they include sediment-associated contaminants, livestock waste disposal, and pesticide and veterinary medicines). However, from a social and economic perspective, the impacts of these drivers are largely *external* to the agricultural system and are not factored into decisions. Consequently, thresholds for freshwater ecosystems are not linked to the land management decisions that may be causing their deterioration. Only recently has this *status quo* started to change towards more risk-based evaluation of land-water causality. The source of this change is primarily legislative in the form of the WFD but also in terms of the reform of the Common Agricultural Policy (CAP) away from headage payments and towards environmental stewardship via the Entry Level Scheme (ELS) and Higher Level Scheme (www.defra.gov.uk/erdp/schemes). Risk-based management is a relatively new science involving uncertain decisions (e.g. Beven et al., 2005; Lane et al., in press) and thresholds are as yet difficult to discern. Much risk-based science follows the DPSIR (drivers, pressures, states, impacts, and responses) modelling framework for risk forecasting (see: www.org.eea.eu.int).

The most significant outcome of diffuse pollution for freshwaters is eutrophication. Phosphorus is traditionally regarded as the limiting nutrient in freshwaters (Schindler, 1977). Recent work by Maberly et al., 2003) suggest there may be temporally dynamic co-limitation by N and P in lentic waters. Eutrophication effects on phytoplankton and thresholds of environmental sustainability are dependent on nutrient concentrations and nutrient composition. Increases in suspended phytoplankton are traditionally described as blooms. A bloom depends on critical nutrient concentrations, but when blooms become dense and algae sticky, critical thresholds exist where they aggregate and sink into deeper water. Consequently, eutrophication can result in increased vertical export, food supply to benthic organisms and increased oxygen consumption in bottom waters, which may result in anoxia (Wassmann and Olli, 2004). Attempts have been made to define thresholds for phytoplankton blooms, primary production and vertical export in terms of retention lines, export loops and balance points. However, phytoplankton blooms are not only a function of nutrient supply and nutrient concentration, but also via top-down regulation by key zooplankton species. Consequently, different regions can have the same nutrient supply but different phytoplankton concentrations. This shows how difficult it is to elucidate specific thresholds within the aquatic environment where multiple factors drive the measured response.

Land management and diffuse pollution has consequences beyond the immediate freshwater environment: the Baltic Sea, for example, is a hypoxia hotspot (alongside the Gulf of Mexico and the Yangse River); it receives around 1 million tonnes of N per year and round 50,000 tonnes of P per year. The Baltic has been hypoxic for over 30 years but the North Sea is now becoming hypoxic. The solutions lie in sustainable land management and careful nutrient budgeting.

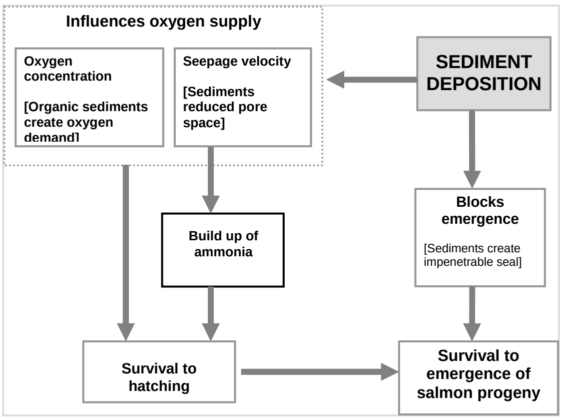
CASE STUDY: SEDIMENTS AND ECOSYSTEM HEALTH

The following case study illustrates the critical controls and environmental thresholds in relation to diffuse pollution.

Sediment plays a major role in the transport and fate of pollutants and is of critical concern in water quality management. Toxic chemicals can become attached, or adsorbed, to sediment particles and then transported to and deposited in receiving waters. Unlike water, sediments can be long-term or permanent sinks for contaminants in rivers and lakes, posing a risk to ecosystem function, water resources and human health. River beds are transitional environments between groundwater and surface water, and are known to be both a sink and source of fine organic and inorganic sediment and associated pollutants including P. Stream borne sediment directly affects fish populations through reduced light penetration and increases susceptibility to disease through e.g. irritation of the gills, scales and mucous covering the eyes.

Traditionally, environmental research has been compartmentalised in different sectors (e.g. air, land, water) and has been integrated across the different compartments (Harris and Heathwaite, 2005). The holistic approach to river basin management required under the WFD has recently pinpointed the strategic importance of understanding sediment sources, pathways and sinks as a controlling 'switch' on aquatic ecosystem health.

The figure below (modified from Sear et al. 2003) illustrates the controls and potential thresholds for the impacts of fine sediments in rivers. The figure shows the complexity of the links from sediment deposition to ecological impacts and begs the question as to whether ecologically acceptable levels of fine sediments can be set in rivers for e.g. salmon. Research by Greig et al. (2005) suggests that thresholds cannot be defined at the river reach scale and probably not at river scale because salmon spawning depends on a combination of factors and these factors vary in time and space. The causes of low pre-emergent survival of salmon appear to be river-specific, which means that it is difficult to set ecologically acceptable levels of fine sediments in rivers. Preliminary research suggests, however, that oxygen flux is a critical factor in spawning success. Elevated nutrient loads generate increased organic matter detritus which in turn increases the sediment oxygen demand; the latter appears to be an important control on spawning success but to date there is no research to indicate appropriate levels for fine sediments in rivers.




**Pressure Point 2:** ***Sustaining Groundwater Quality***

In the mid term, improving and protecting groundwater quality will be essential for the sustainable management of the freshwater environment. The challenges are already been felt in the context of water abstraction; saltwater intrusion into groundwater bodies; wetland sustainability; and water treatment to maintain the quality of water supplies.

The quality of groundwater in UK aquifers has deteriorated significantly over the last few decades. The UK Groundwater forum (www.nwl.ac.uk/gwf) estimate that around 2450 Ml per day, almost 50% of the groundwater used for public supply is affected by quality problems. Research funded by UK Water Industry Research Limited (UKWIR) and the Environment Agency (UKWIR Report 04/WR/09/8) found that deteriorating groundwater quality in the UK has cost the water industry c. £754 million since 1975 – over 60% was spent on treatment schemes, 17% on blending and 24% on replacement water to compensate for source closures. The costs reflect a combination of deterioration in groundwater quality and more stringent regulatory standards for drinking water. The capital and operating costs of groundwater treatment for the water utilities are passed on to the consumer through water charges. Groundwater contaminants come from two categories of sources: point sources and diffuse sources. Landfills, leaking gasoline storage tanks, leaking septic tanks, and accidental spills are examples of point sources. Infiltration from farm land treated with pesticides and fertilizers is an example of diffuse sources. Clearly there are links here between diffuse pollution of rivers and lakes as described in the section above and the contamination of groundwater resources. To date, much of the concern has focussed on nitrate contamination. However, recent evidence suggests that P in groundwater may be a potential future problem. Phosphorus contamination of groundwater may occur were there are high densities of septic systems (Carvalho et al. 2004). Problems with septic systems worsen when communities that rely on subsurface disposal systems also depend on private wells for drinking water. Most expenditure in the UK has been in response to diffuse contaminants, in particular the presence of nitrate, pesticides, Cryptosporidium; critical point source contaminants include hydrocarbons and solvents.

Conclusion – the use of thresholds and reference points to avoid anthropogenic regime change in the freshwater environment.

Taking the above discussion into account, the following answers to the questions are relevant.

a. *To what extent have 'threshold concepts' or similar ideas been developed or explored in you subject area?*

The use of environmental indicators or thresholds for freshwater systems has been developed to describe the state of the ecosystem, and to indicate the risks that it might move to a less-favourable status (e.g. Heathwaite et al., 2003; 2005 for phosphorus export from land to water). Such systems have only recently been incorporated into land management schemes, largely in response to the Water Framework Directive (WFD) that is requiring a more holistic approach to the management of ecosystem health.

b. *Are you aware of any physical or biological limits that been identified or conjectured in your subject area, that have a consequence for people or communities? If so how have they been defined?*

Nutrient pressures are critical in water quality and sustainable water management. With the exception of potential risks for human health from nitrite, nutrients have only indirect impact on people and communities in the form of e.g. increased water treatment costs, loss of recreational value. Direct risks include those from pathogenic organisms.

c. *What kinds of evidence or data have been used to test the idea that such thresholds or limits exist?*

Both empirical data and predictive modelling are used. It is widely accepted that the quality of the available data at scales beyond specific research catchments is limited and consequently the predictive power of process-based models is compromised.

d. *What kinds of factor are thought likely to drive the environmental system towards or beyond such thresholds or limits?*

Nutrient pressures are critical in defining the trophic status of lentic water bodies; our understanding of lotic water bodies is more limited owing to their dynamic nature. Other factors include sediment (especially fine sediment) and sediment associated contaminants.

e. *Have any of these thresholds been embodied in standards or targets that have then be used in regulations or management policies?*

Nutrient concentrations feature in standards in e.g. nitrate concentrations in drinking water with knock on consequences in terms of policy e.g. Nitrate Vulnerable Zones.

f. *Do these thresholds vary over time or space, and if so, how is that variation represented?*

The ratio between N and P in freshwaters is important (e.g. Maberly et al., 2003); this ratio is highly dynamic. Critical controls relate to the capacity of rainfall events to transport nutrients from land to water (e.g. Heatwaite, 2003)

g. *What kinds of uncertainty are associated with defining or identifying the thresholds or limits?*

Most uncertainties relate to the quality of the available data and the scale at which is it collected. Integrated treatment of water quality and water supply and demand issues require data from many disciplines to be brought together. Often such data and conceptual models are built around research that ranges in spatial scale from a few millimetres to whole catchments. It is difficult to integrate such information successfully. Furthermore, the timeframes of the available data vary widely from seconds to annual timesteps. An analysis of these issues with respect to 'riverscapes' is given in Harris and Heathwaite (2005).

h. What kind of future research is needed in relation to identifying or operationalising the threshold concept for policy or management?

Integrated catchment science; sediment transport and fate; groundwater quality evaluation and measures; diffuse pollution modelling.

i. How useful do you think the threshold idea is in taking forward our general thinking about sustainable development?

The concept is valuable as long as the uncertainties are carefully examined.

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Environmental thresholds, the case of climate change

Input to DEFRA report on environmental thresholds

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The chapter is intended to answer the following questions:

a) To what extent have 'threshold concepts' or similar ideas been developed or explored in the area of climate change?
b) Are you aware of any physical or biological limits that been identified or conjectured in the area of climate change, that have a consequence for people or communities? If so how have they been defined?
c) What kinds of evidence or data have been used to test the idea that such thresholds or limits exist?
d) What kinds of factor are thought likely to drive the environmental system towards or beyond such thresholds or limits?
e) Have any of these thresholds been embodied in standards or targets that have then be used in regulations or management policies?
f) Do these thresholds vary over time or space, and if so, how is that variation represented?
g) What kinds of uncertainty are associated with defining or identifying the thresholds or limits?
h) What kind of future research is needed in relation to identifying or operationalising the threshold concept for policy or management?
i) How useful do you think the threshold idea is in taking forward our general thinking about sustainable development?

#### A note on the history of climate change thresholds thinking

Already in 1824, the French physicist and mathematician Joseph Fourier established the radiation balance of the Earth where he stated that gases in the atmosphere trap outgoing long-wave radiation but it was not until 1896 that the role of carbon dioxide ($CO_2$) was described by the Swedish physicist Svante Arrhenius. In the 1930s, there was much public discussion about winters becoming warmer and meteorologists confirmed the trend, but without worrying about causes nor implications (Waert 2003). But there were other important scientific ideas put forward in the 1930s. The Serbian engineer Milutin Milankovitch, presented his theory that cyclical changes in the Earth's orbit around the Sun could explain the repeated ice ages. The idea that $CO_2$ could be the main reason for the warming trend was first proposed by G.S. Callendar (Callendar 1938). The signs of a warming climate were by most people seen as beneficial to humanity.

In Arrhenius (1896) classic paper "on the influence of carbon acid in the air.." there was not a concern about global warming, such questions did not emerged until the 1970s. Two publications of the early 1970s express various ways of conceiving of climate change. The *Report of the Study of Mans impact on Climate* (SMIC 1971) from 1971 emphasized the dangers of rising global average temperatures, while a CIA report from 1974 interpreted available evidence as supporting a trend towards decreasing global average temperatures and envisioned a shortage of food for the poor and the powerless (CIA 1974). However, despite the two reports' contradictory assessments (warming vs. cooling) *change* itself is perceived as the complication (Wiman and Chong 2000).

An early reflection regarding the potential for thresholds of climate change is found in the NRC report *Energy and Climate* from 1977 where meteorologist J. Murray Mitchell, Jr. asked, "Can man establish which, if any, alternative scenarios would lead to 'unacceptable' climatic consequences and are therefore to be avoided?" (Oppenheimer and Alley 2005). A pioneering study that consciously developed a thresholds based methodology was the Rijsberman and Swart (1990) report for the Stockholm Environment Institute (SEI). In contrast to cost-benefit approaches (which compare the benefits and costs of abatement strategies) in setting climate change targets, the SEI approach bases its judgment of climate change targets on the most sensitive part of the system. It is the most vulnerable group of people or the most vulnerable ecosystem that defines what constitutes 'overall' dangerous climate change (Azar, 2000: 81-82). The well cited SEI target for global mean average surface temperatures were set to a maximum rate of change of 0.1°C/decade and 1-2°C temperature increase above the pre-industrial level. SEI derived their target from the migration rate of trees. Another classic study is Krause et al. (1992) who too based their study on the capabilities of the expected capabilities of ecosystems to adapt and arrived at the same rate per decade but settled for an increase of 2-2.5°C as the limit for the next centuries.

**Thresholds related to the climate change issue**
(questions: b,c,f,g)

## *Non-linearity and the climate system*

How should we generally conceive of change and stability in environmental systems? In the history of environmental-change line of thought, two traditions can be distinguished (Wiman 1991). The first goes back to Aristotle, Linneaus and Eugene P. Odum and is well represented in classical ecology. It holds that natural systems change very gradually and continuously towards stability and diversity. The other tradition, contrariwise, revolves around discontinuity and while it also has ancient roots, its main influences are the science of fluid mechanics and chaos theory (Mason et al. 1986). The continuity tradition implicates that as natural systems mature into more complex systems they become less sensitive to anthropogenic disturbances. When natural systems are put under stress, for instance when the climate becomes subject to increasing emissions, they will, according to this line of thought, respond in a linear and predictable way. Over the years, this has been the predominant view of the climate system, but in the 1990s the idea that the climate system might better be understood in discontinuous terms has gained ground.

The discontinuity tradition in environmental systems thinking focuses on non-linear responses and acknowledges that "surprises" constitute a normal feature of a natural system's response to perturbations. The hypothesis that the climate system can change rapidly, even abruptly, when certain thresholds are crossed was early proposed by Lorenz (1963), Broecker (1987) and Dansgaard (1969). One of the best known recent additions this literature is the US National Research Councils' *Committee on Abrupt Climate Change* (NRC 2002; See also Alley et al. 2003) which states that abrupt change is a common feature of the global climate system and has reached up to 10°C in a decade in some regions due to the warming since the last ice age.

The insight the climate is inherently variable does not bode well in world dependent of fossil fuels. Broecker puts it succinctly in a paper almost ten years ago, "Through the record kept in Greenland ice, a disturbing characteristic of the Earth's climate system has been revealed, that is, its capability to undergo abrupt switches to very different states of operation. I say 'disturbing' because there is surely a possibility that the ongoing buildup of greenhouse gases might trigger yet another of these ocean reorganizations and thereby the associated large atmospheric changes" (Broecker 1997).

The idea of rapid climate change has also been articulated in modern cultural and political circles. Examples here include the BBC horizon documentary *The Big Chill* that was first broadcasted in November 2003, a report commissioned by the Pentagon (Schwartz and Randall 2003) has received a lot of debate and, not least, the Hollywood movie *The Day After Tomorrow* released the UK in May 2004. However, the non-linearity argument cuts both ways in the climate debate. Hulme (2003) views the possibility of abrupt climate change as a wild card, suggested both by those who propose strong and early mitigative action and by those who argue that the unknowns are too large to justify early action.

## Defining abrupt climate change

The general difficulties that the emerging literature on abrupt climate change is experiencing is similar to the "dangerous levels of climate change" debate. Scientists have many times been asked to assess the "dangerous level" of concentrations of GHGs in the atmosphere (Leggett 1990), but they have been reluctant. There are two main reasons for this. First, it is not clear how sensitive the climate system is to increasing concentrations of GHGs. The IPCC SAR (1995) projected that a doubling of the concentration of GHGs (compared to pre-industrial levels) in the atmosphere would result in a temperature increase of 1.5° to 4.5°C. Secondly, the rate of change in climate is only dangerous when the response rate in society (i.e. the capacity for adaptation) is insufficient to avoid dangerous consequences. Because science is only partly capable of grasping the sensitivities of many human and ecological systems to changes in climate and climate related parameters, it cannot assess dangerous levels for different activities. The uncertainty that arises from the second reason cannot solely be solved by further natural scientific research. Even if all the social impacts of climate change were known, scientists would not be able to decide on what should be considered 'dangerous'. Whether or not a certain impact is to be considered dangerous is a value issue that has to be settled in the political arena (cf. Azar and Rodhe 1997; Dessai et al. 2004).

Definitions of abrupt climate change can (on the crudest level) be categorized in two groups. First there are "mechanistic" definitions that focus on transitions of the climate system into a different state (of temperature, rainfall etc.) on a time scale that is faster than the responsible forcing. Frequently cited examples in this category include rapid shifts in thermohaline circulation (Rahmstorf 2002) and a possible disintegration of the West Antarctic Ice Sheet (Oppenheimer and Alley 2005). Second, there are "impacts-based" definitions that focus on changes in the climate system that is faster than the adaptation of social and ecological systems. A variant of this simple dichotomy is also to be found in Schneider and Lane (2005) which was presented at a recent seminar. In the context of Article 2 in the UNFCCC Schneider and Lane differentiate between systemic (natural) thresholds, normative (social) impact thresholds, and legal limits.

Despite an increasing awareness of non-linear features of the climate system, the scientific community are only at the beginning of formulating and testing hypothesis in climate models and against proxy data. In the review article *Does the Trigger for Abrupt Climate Change Reside in the Ocean or in the Atmosphere*, Broecker argues that much work is left to be done: "we are still a long way from understanding how our climate system accomplished the large and abrupt changes so richly recorded in ice and sediment. However, despite this ignorance, it is clear that Earths climate system has proven itself to be an angry beast. When nudged, it is capable of a violent response" (Broecker 2003).

## Climate Change, low probabilities and the risk society

Across social science, the German sociologis Ulrich Beck has been influential with his theory about the "risk society". His theory concerns the inability of risk management strategies to mitigate the risks of late modernity. In Beck's words: "the entry into risk society occurs at the moment when the hazards which are now decided and consequently produced by society undermine and/or cancel the established safety systems of the provident state's existing risk calculation" (Beck 1996). The point that Beck is making is that the standard techniques of risk management (actuarial and probabilistic approaches) fail to comprehend the new risks. The "downside" is that this particular uncertainty (about where the climate thresholds are) is used a reason for inaction. In his speech on the 11th of June, 2001, the U.S. President George W. Bush said that "finally, no one can say with any certainty what constitutes a dangerous level of warming, and therefore what level must be avoided".

The "failure" to account for the climate' "non-probabilistic" dimensions has recently been noted. According to Johannesson (2000), "even though the risks of a climate change have been analyzed and discussed in depth, the risk of worst-case scenarios and surprises has been given scant attention". Schneider (2004) writes that "unfortunately, most climate change assessments rarely consider low-probability, but high-consequence extreme events." The forum for debates about abrupt climate change has been the media and popular literature, while the main international body for providing coherent assessments of climate change, the IPCC, does not engage "worst-case" scenarios, or scenarios of abrupt climate change (Hulme 2003).

Johannesson additionally argues that the reason for this is that the IPCC has not understood “worst-case” scenarios to be within their “mandate” (Johannesson 1998).

In a recent article, Dessai et al (2004) reiterate the important argument that science can not decide on what constitutes dangerous thresholds of climate change and that there are no universally established methodology or process for deciding on what constitutes a dangerous level and for whom. They argue that expert led approaches to dangerous climate change must be combined with assessments of experienced or perceived perceptions of what constitutes dangerous climate change. Therefore, the vulnerability of human activities to climate change thresholds (such as the potential for negative outcomes or consequences) is influenced by a human judgment of value. Ideally, the data and the projections of climate change thresholds should be open to a wide range of stakeholders, such as indigenous people, youth, women, business, academia, local governments, and environmental non-governmental organizations. Many scholars have identified that this puts scientific knowledge in a new perspective, i.e. the borders between the scientific and the political is not particularly clear-cut and that the science/policy interface can be seen as a mixed zone that runs from the realm of “truth” (science) to the realm of “power” (politics). This zone has been called, for example, trans-science (Weinberg 1972), regulatory science (Jasanoff 1990), postnormal science (Funtowicz and Ravetz 1992), and hybrid science (Schackley and Wynne 1995). We believe that many future assessments of climate change thresholds will emerge from this zone.

It is therefore important, when approaching and thinking about climate change thresholds, not to solely focus on “objective” physical and social measures but to advance knowledge about various methodologies (such as participatory integrated assessments, participatory policy appraisal frameworks) that can account for “subjective” dimensions of danger. Hence, we do not just need to improve the general circulation models (GCMs) to be able to account for abrupt climate change but “radical new methods of participatory research are necessary to truly elicit what level of climate change might be regarded as dangerous by different cultures, communities and constituencies” (Dessai et al. 2004).

**Thresholds in climate**

It seems more and more clear that the Earths climate system is highly nonlinear (cf. Severinghaus and Brook 1999; Rahmstorf 2002; Alley 2004; Rial et al. 2004). As it was put in a recent article in the journal Science: ”Climatic records show that large, widespread abrupt climate changes have occurred repeatedly throughout the geological period” (Alley et al. 2003). Systematic measurements of the climate (temperature, rainfall etc.) has produced a record of the last 150 years, but scientists have been able through the use of proxy data (tree rings, ice cores, corals etc.) to reconstruct past variations of the climate systems much further back in time. With the latest deep ice core from Dome C, Antarctica, the paleoclimatic community has recently been able to provide a record of climate variabilities for the past 740.000 years (Augustin et al. 2004). The variability of the climate is further underlined in the Moberg et al. (2005) study on temperatures in the northern hemisphere for the past 2000 years which shows that natural multicentennial climate variability may be larger than commonly thought. Much research has been devoted to depict the change from a glacial (cold) to an interglacial (warm) state that took place 11500 years ago. At that moment, the Younger Dryas era ended with temperatures increasing by up to 10°C in a very short time period (cf. Correge et al. 2004).

There is no consensus in the literature regarding how to approach abrupt climate change. Hulme (2003) has recently provided an interesting elaboration of how we can organize the issue. He regards the IPCC (2001) scenarios as default scenarios of ”non abrupt climate change” and argues that ”abrupt climate change” must involve the dimensions of rate, severity and direction. Hence, abrupt climate change occur if the *rate* of warming is greater than 0.55°C/decade, or if the rate of global sea-level rise is greater than about 10cm/century. Note that these thresholds are much higher than what would be acceptable according to the SEI or the Krause et al. report mentioned earlier. Further, IPCC scenarios are typically uni-directional curves of climate change. A non standard abrupt scenario would therefore be when the *direction* of climate change alters in a sustained manner, for example, substantial cooling or warming for several decades. Hulme's last category refers to *severity* and implies exceeding certain thresholds, for example those that triggers a collapse of the thermohaline circulation (THC), or the occurrence of more extreme weather/climatic events. These three categories can all included events that has already happened or events that might happen.

Much of the current thinking climate thresholds was aired at a recent meeting in Aspen, Colorado.[63] Keller et at (2005) summarizes many of the climate thresholds (including thresholds for their initiation) that has been mentioned over the years. Their summary include the melting of the Greenland Ice sheet, coral bleaching, changes in El-Nino Southern Oscillation, a weakening or collapse of the THC and a disintegration of the West Antarctic Ice Sheet. Another recent important venue was the "Avoiding Dangerous Climate Change" symposium sponsored by the UK Department for Environment, Food and Rural Affairs and held in Exeter, 1-3 Feb 2005.[64] At this event, Schneider (2004) made a useful overview (based on Chapter 19 in the upcoming IPCC Fourth Assessment Report) of climate thresholds including numerical values for the thresholds. We have put together a table (see below) that combines both Keller et al. and Schneider. The table could be read as a summary of contemporary discussions on climate change thresholds.

Table 1. Change thresholds

| **Vulnerability** | **Threshold for Initiation** | References |
|---|---|---|
| Shutdown of thermohaline ciculation | 3°C in 100 yr<br>700ppm CO2 | O'Neill and Oppenheimer (2002)<br>Keller et al. (2004) |
| Weakening of thermohaline circulation | Very low | Higgins and Vellinga (2004)<br>Gregory et al (2005) |
| Disintegration of West | 2°C, 450ppm CO2 | O'Neill and Oppenheimer |

[63] The meeting ”Abrupt climate change: Mechanisms, Early Warning Signs, Impacts, and Economic Analyses" was held 9-15 July in Aspen, Colorado, and organised by the Aspen global change institute.
[64] For more information visit http://www.stabilisation2005.com/ where the presentations are downloadable.

| | | |
|---|---|---|
| Antarctica Ice Sheet | 2-4° C, <550ppm CO2 | (2002) Oppenheimer and Alley (2004, 2005) |
| Disintegration of Greenland Ice Sheet | 1-1.5°C | Hansen (2004) Gregory et al. (2004) |
| Complete melting of the Greenland Ice Sheet, starting at: | 3°C | (Johannessen et al. 2005) |
| Widespread bleaching of coral reefs | >1°C | Smith et al. (2001) O'Neill and Oppenheimer (2002) |
| Broad ecosystem impacts with limited adaptive capacity | 1-2°C | Leemans and Eickhout (2004), Hare (2003), Smith et al. (2001) |
| Large increase of persons-at risk of water shortage in vulnerable regions | 450-650ppm | Parry et al. (2001) |
| Increasingly adverse impacts, most economic sectors | >3-4°C | Hitz and Smith (2004) |
| El-Nino Southern Oscillation Changes | Deeply uncertain | Philander and Fedorov (2003) Timmerman et al (2004) |
| The table builds on Schneider (2005) and Keller et al (2005) but modified and extended by the authors. | | |

Probably the most cited example of abrupt climate change is the possible collapse of the THC (or the MOC, meridional overturning circulation, as it also is called). A major disruption of the THC can have significant impacts on the global and especially regional climate (cf. Vellinga and Wood 2002). Broecker (1987) was an early article identifying the possibility of rapid changes in the behaviour of the thermohaline circulation and Ganapolski and Rahmsdorf (2001) has shown how anthropogenic greenhouse gas emissions might contribute to the instability of the THC. Current thinking on the THC was summarized in the October issue of Science where Kerr (2005) commented on the issue that ”the threat from an abrupt circulation switch in the North Atlantic and resultant climatic chaos seems to be receding, but researchers still worried". It seems that none of the model simulations of a warming world (using standard IPCC emission scenarios) have been able to drive the MOC to collapse, but mostly only to a reduction of up to 15-20 percent.

The table also includes two cases of rapid deglaciation, the disintegration of the West Antarctica Ice Sheet (WAIS) and the Greenland Ice Sheet (GIS). A complete disintegration of the GIS would raise sea levels by 7m. While the GIS is much more stable than WAIS (since it is grounded above sea level), Gregory et al (2004) claims that a warming of 3°C above 1990s temperatures would eliminate it. Even though Oppenheimer and Alley (2004) and Hansen (2004) propose threshold values, there are reasons to be cautious: "Due to large uncertainties in models and in interpretation of paleoclimatic evidence, a critical issue in all of the above studies is whether the values selected correspond to actual geophysical or biological thresholds or simply represent convenient and subjective judgments about levels or risk" (Schneider and Lane 2005).

There are, in general, very few attempts of estimating the probabilities of rapid or abrupt climate change. For example, Arnell et al. argues that there are "no scientifically robust estimates of the likelihood of thermohaline collapse" (Arnell et al. 2005) and Oppenheimer and Petsonk (2005) notes that probability distributions have not been presented for these particular limits and assumptions about non-$CO_2$ gases vary from one study to another. There are, in principle, three ways of estimating the likelihoods of abrupt climate change: analysis of past records, computer simulations and expert judgement. Arnell et al. (2005) regards the first two as problematic in the climate case and opt for the third one.

What do these often mentioned examples of climate change thresholds imply for society, what is their relevance? Actually, there are no credible scenarios of abrupt climate change associated with THC collapse and hence, "virtually none have explored what the implications of such an anticipated abrupt climate change would be for current decision-making for adaptation policy" (Hulme 2003). Further, we need also to be reminded that impacts based thresholds are not static, adaptation can raise thresholds of tolerance that need to be avoided (for example, by increasing drought tolerance of crops) (Parry et al. 2001). The same point is also expressed by Arnell regarding the water sector: "thresholds in the water management system are not necessarily fixed, especially when they are imposed by human demands, and flexible water management implies the ability to move thresholds" (Arnell 2000). Another example is Barnett and Adger (2003) who, in relation to climate dangers and atoll countries, make the claim that critical thresholds may be both behaviourally driven as well as ecologically driven.

**Biophysical thresholds translated into climate policy**

(questions: a)

Based on the rich evidence of non-linearity and emergent properties of the climate system reviewed in the section above, the question is to what extent such biophysical thresholds can be translated into climate policy, both in terms of thresholds for mitigation and for adaptation.

We argue that the concept of thresholds, which is very prominent in the biophysical domain of climate change, cannot easily be translated into policies for responding to the challenge of climate change. This is particularly valid for climate change mitigation policies and less so for adaptation policies. The main reason for this problem emanates from the inertia of the coupled climate – ocean – land system. The time lags between mitigative actions and a response in the biophysical systems are very long and varied. One way of describing this inertia is through the conceptual diagram from IPCC TAR.

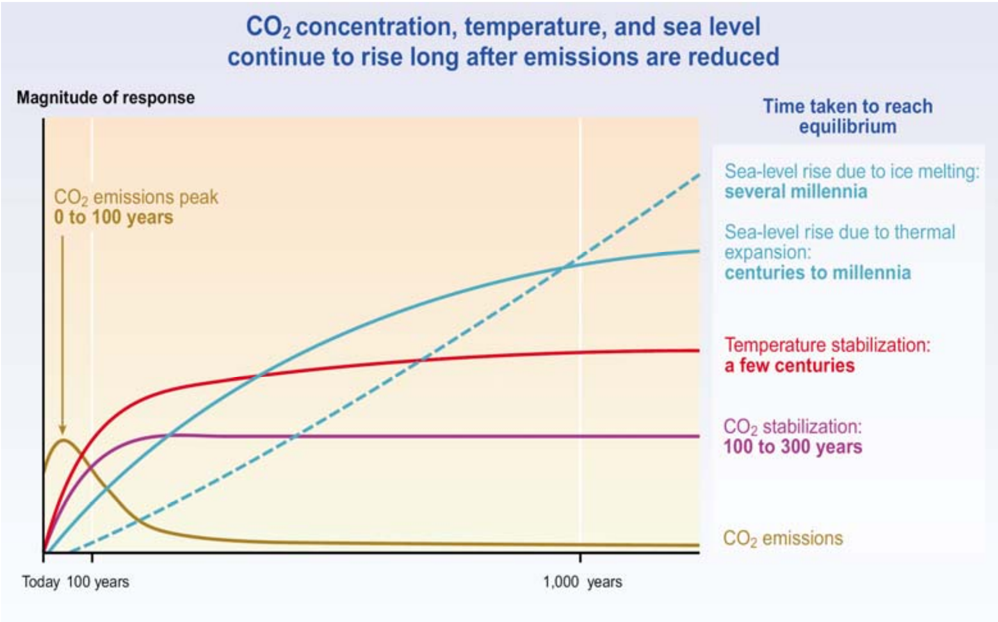


Figure 1. Conceptual graph showing the inertia of the coupled atmosphere – ocean – land system. Reproduced from (IPCC 2001).

The diagram should be interpreted in the following way: If we are able to reduce drastically the emissions of GHG in 2050 (the brown curve), implying a transition to carbon neutral energy sources, the effect on the GHG levels in the atmosphere will follow the purple curve, i.e. a stabilisation of levels after some 150 – 200 years. It is important to note that the emission reduction in 2050 will lead to a stabilisation, not a reduction of the level. There is no technology known by which a significant reduction of the atmospheric GHG level can be achieved – we have to live with whatever level we have reached. This stabilisation will then cause a gradual levelling off of the temperature increase (red curve), with a stabilisation after an additional time lag of 50 – 100 years. The temperature increase before this levelling off will cause a rise of sea levels by thermal expansion of water that will continue for many centuries after the stabilisation of GHG and temperature (blue solid curve). If we also consider the effect on the polar ice caps of the temperature increase, the sea level rise is likely to continue over millennia (blue dashed curve).

The implication of this conceptual view of climate change for mitigation thresholds is that the biophysical thresholds cannot easily be translated into policies. Nevertheless, thresholds as a policy instrument might be an effective way towards mitigation actions.

From an adaptation point of view, biophysical thresholds might be much easier to translate into policy instruments, but very little has been done in this field.

In the climate change policy discourse we can identify a number of commonly used values or concepts that we may refer to thresholds. We will here discuss the origin of these thresholds and to what extent they provide a viable approach for responding to the challenge of climate change.

1/ The notion of "dangerous" interference with the climate system from the UNFCC

The lack of a more tangible expression of the goal of the UNFCC (e.g. a temperature or a GHG level) is often seen as a serious shortcoming of the convention. It is easy to see that what is a dangerous interference differs enormously between different actors. The AOSIS[65] countries, for example, have a completely different perception of what might be a dangerous interference compared with an industrial European country. A comprehensive review and analysis of fairness related climate change mitigation and adaptation is found in (Toth 1999). On the other hand, the vague expression might very well be an important reason why the convention was accepted in the first place. The kind of constructive vagueness we find in many places of the UNFCC probably contributed to get all the countries on board. Several countries would probably have objected to a more firm writing.

2/ the EU target of 2°C

The EU has adopted a temperature target for its climate policy of maximum 2°C above the pre-industrial level (den Elzen and Meinshausen 2005). This threshold, however, does not really represent a level below which no severe climate impacts are believed to occur. The extreme European heat wave of August 2003 is one such example of a climate impact. Other such examples worldwide were recently reviewed in (Patz et al. 2005). The 2°C target rather represents a pragmatic level that might be realistic to achieve from both a technological and a political point of view. It is a bold target that will require substantial emission cuts worldwide within the next decade.

3/ the commonly used $2xCO_2$ target for stabilisation of GHG levels

Many studies have used the double pre-industrial level of atmospheric $CO_2$ when reasoning about climate change. The double pre-industrial level[66] is somewhat ambiguous and depends on whether only $CO_2$ is considered or if also other GHG are considered. If all the six GHG that are covered by the Kyoto Protocol are considered, we may argue that we have almost reached a doubling already. The use of the $2xCO_2$ target is also ambiguous from a temperature increase point of view, which is dependant on the climate sensitivity.

4/ Constructed thresholds based on experience and statistics of the past:

Another kind of thresholds, much more concrete, is the one we often find within physical planning and construction of buildings and infrastructure. Such thresholds are usually based on previously experienced extreme events. This might be expressed as dams constructed to withstand water levels experienced once in 1000 years or buildings are not allowed in areas where floods are likely to occur more often than

[65] Allicance of Small Island States
[66] Usually taken as the average level during 1000-1750, approximately 280 ppm

once in 100 years. When such historical thresholds are used it is important to consider the risk of future changes due to climate change.

#### Fossil fuels, security and the modern state

The societal decision stakes surrounding the climate issue are very high. There is (or at least there has been) a close relationship between energy production and economic prosperity. Energy production through the consumption of fossil fuels is a companion of the industrial project and lies at the heart of the modern state. The Kyoto protocol, which aims at lowering the emissions of carbon dioxide within industrialised countries, can be seen to challenge a fundamental feature of the modern state. Given that wealth production can not be de-coupled from economic production (or at least that the causal connection is understood in that way) the Kyoto protocol can be understood as undermining the state's ability to function as a guarantor of wealth production.

George W. Bush took office in January 2001. Two months later, in March 2001, Bush announced that the United States would withdraw from the Kyoto protocol. His argumentation echoed the security discourse: "we will not do anything that harms our economy, because first things first are the people who live in America". Later on in June 2001, Bush claimed that "for America, complying with these mandates (the Kyoto protocol) would have a negative economic impact, with layoffs of workers and price increases for consumers" (Bush, June 11 2001). On the European scene, these issues have played out a little bit differently. Of course, the economic costs of emission reductions are heavily debated also in Europe, but in Europe the discourse is not so much one about ”danger” but one on ”opportunity” in terms of the possibilities for so-called ecological modernization. Climate policy becomes an opportunity for the ”competitive state” (Paterson 2001; Barry and Paterson 2004).

Because mitigating climate change touch a core value of the modern state, there has been attempts to link climate change to another core value, i.e. the security of the state (cf. Stripple 2002). The waning of the Cold War opened up for a major controversy (in both academic and policy making circles) about what is and what should be the focus and content of security policy (Ullman 1983; Buzan 1984; Enloe 1989; Kratochwil 1989; Mathews 1989; Booth 1991; Lipschutz 1995; Smith 1999; Wyn Jones 1999). Military threats to the security of the state are no longer predetermined as answers to the questions of "what should be secured" and "what phenomena should the security discourse view as potentially threatening". Attempts to broaden the traditional conception of security include analysis of a wider range of threats stemming from non-military realms such as the economy, society or the environment. One pervasive theme has been the focus on environmental scarcity as a contributor to (violent) conflict. Homer-Dixon has presented several hypotheses on the probable linkages between environmental change and acute conflict. He emphasizes the role of the scarcity of renewable resources that places stress on socio-political systems and that, when given other variables (conditions), will erupt into sub-national violence and strife (Homer-Dixon 1991; 1994; 1999). While a salient theme in this Malthusian tradition is the focus on water scarcity (Gleick 1993; Lowi 1993), very few studies make climate change as its focus (However see Carius et al. 1997; Edwards 1999;

Barnett 2003; 2003). It is difficult to know who will be most insecure in a warming world, but poverty is generally recognized as one of the most important correlates of vulnerability (Liverman 1990; Dow 1992). On a global scale this is exemplified by far higher loss of life due to similar extreme events in the developing world than in the developed world (Meyer et al. 1998). If we consider the insecurity of particular communities, the IPCC particularly highlights the vulnerability of indigenous people to climate change;

"Even in regions with higher adaptive capacity, such as North America and Australia and New Zealand, there are vulnerable communities, such as indigenous peoples, and the possibility of adaptation of ecosystems is very limited" (IPCC 2001).

## *Drivers*

(question d)

Climate change can be described in the form of a DPSIR scheme, which allows us to characterize the different responses taken by the current policy regimes. DPSIR is a theoretical framework for analyzing environmental or other problems into five different types of characteristics (Figure 2) where D stands for driving forces, P for Pressure, S for State, I for impact, and R for responses (Smeets and Weterings 1999). Effective policy regimes should ideally include all four kinds of responses, from long-term actions directed towards the driving forces to immediate adaptive measures. The current international climate policy regime, however, contains predominantly responses on Pressure (emission reduction) and to some extent on State (carbon sinks). It lacks responses directed towards the Driving Forces and the Impacts (adaptation).

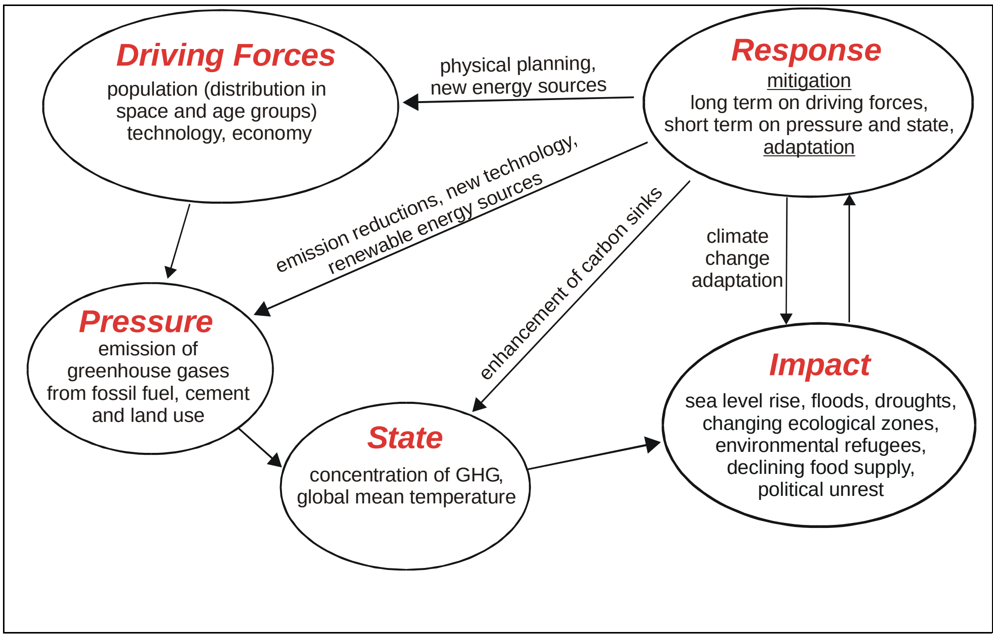


Figure 2. A DPSIR formulation of climate change.

It is important to realise the time dimensions of the different responses. Physical planning and new energy sources operate on a generation scale (several decades), emission reductions and shift to renewable energy sources operate on anything from immediate to decades, enhancement of sinks decades and adaptation on anything from immediate to generations.

### *Outlook and the need for future research*

(questions: h,i)

The process of shaping a post-2012 climate change agenda is well under way, both internationally and within the EU. The international discussion within UNFCC (e.g. at the COP11 last year) is so far mainly concerned about procedures for how to proceed rather than the concrete content of a future policy. In the EU, as mentioned above, a concrete target of 2°C has been adopted. An important question to discuss and reach consensus on is whether the Article 2 of the UNFCC should be operationalised and in what way. At some point in time the word "dangerous" might be replaced by a concrete level of either a certain Ppm level (such as 450 ppm), a temperature level (such as 2°C), a sea level rise level (such as 0.5 m) or perhaps a rate of change level (such as 0.1° /century). A very different kind of operationalisation would be to express the target in terms of avoiding the exceeding of one or several of the thresholds described above. However, the uncertainties and the substantial time lag between action and effect probably deem such a threshold both impossible and unsuitable.

Such a discussion must of course be based on a scientific understanding of potential risks of damage as well as costs and opportunities to avoid such damage.

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*Environmental Thresholds Review:*
**Levels of dispersal of toxic substances and the disposal of solid waste**

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## Introduction

The presence of toxic, or *potentially* toxic, substances in the environment is associated closely with issues of environmental quality, risk and liabilities. Contamination of the environment has been an emotive question since the connection was made between environmental quality and human health. The links between exposures to potentially toxic substances and health in the occupational environment are long established and can be traced back to the 1700s. However, it was not until after WWII that direct effects of a deteriorating environment on both human health and environmental quality became evident. Two of the best known examples of this are a) the deaths directly attributable to London smogs in the 1950s (Brimblecombe, 1987) and b) the reduction of wild bird populations in the 1950s and 1960s due to the widespread use of persistent pesticides, particularly DDT (Mellanby, 1992).

Attempts to develop environmental quality standards, or concentration thresholds, for the wide variety of potentially toxic substances dispersed within the environment have a history extending back several decades. The initiation of different systems of threshold values in different countries has sometimes been in response to major, unforeseen contaminating events. Threshold values have sometimes been adopted on the basis of informed guesswork, and have often been highly precautionary in nature. More recent moves within the areas of contaminated land and waste assessment in the UK have involved the derivation of more objective, quantitatively based thresholds or guideline values.

This review describes the development of Soil Guideline Values for metals and other toxic substances in soils in the UK in recent years It also describes similar guidelines for radionuclides, specifically Generalised Derived Limits and Intervention Levels, comparing and contrasting the basis on which these threshold values are set. The review concludes with a description of Critical Loads, originally developed for acid pollutants and nutrients, but more recently for metals and, to a limited extent, for radionuclides.

## Potentially Toxic Substances in Soils

Soils in the UK and other developed countries carry a legacy of contamination which can be traced back to the beginnings of the Industrial Revolution. The pressure in more recent decades for redevelopment of former industrial land and 'brown field' sites has led to the development of several discrete systems of maximum acceptable concentrations of toxic substances in soils by different nations. In some countries this pressure has been exacerbated by notorious incidents in which residential developments were made in ignorance of contaminant levels in the underlying soils. Thus, the experience at Lekerkerk in the Netherlands, where 87,000 $m^3$ of contaminated waste had to be removed from beneath a 10 year old housing estate, drove the Dutch Government to produce one of the most long-standing and rigorous systems of threshold values for soil contaminants (Bridges, 1991).

The first soil quality standards, or threshold values, to be developed and used in the UK were the 'Kelly Indices' (Guidelines for Contaminated Soils) developed on behalf of the former Greater London Council (GLC) specifically for former gasworks sites in the capital. These eponymous tables were proposed by the scientific advisor to the GLC, at a conference organised by the Society of Chemical Industry in 1979. The tables covered metals, cyanides and aromatic compounds (PAHs and phenol) likely to have arisen from the manufacture of town gas, as well as soil pH. Three years prior to this, the Interdepartmental Committee for the Redevelopment of Contaminated Land (ICRCL) was established by the Department of the Environment (DoE) to consider the numerous challenges presented by the redevelopment of contaminated sites which included landfills, gasworks, sewage works, scrapyards and mines. Such sites were all deemed to constitute potentially contaminated land. As part of its work the ICRCL devised a system of *tentative* 'trigger concentrations' for a range of potentially toxic substances which might be expected to occur on contaminated sites. Substances for which trigger concentrations were devised included a) inorganic contaminants and b) substances associated with coal carbonization works (former gas works), which were published in the ICRCL document 'Guidance on the assessment and redevelopment of contaminated land' (ICRCL, 1987).

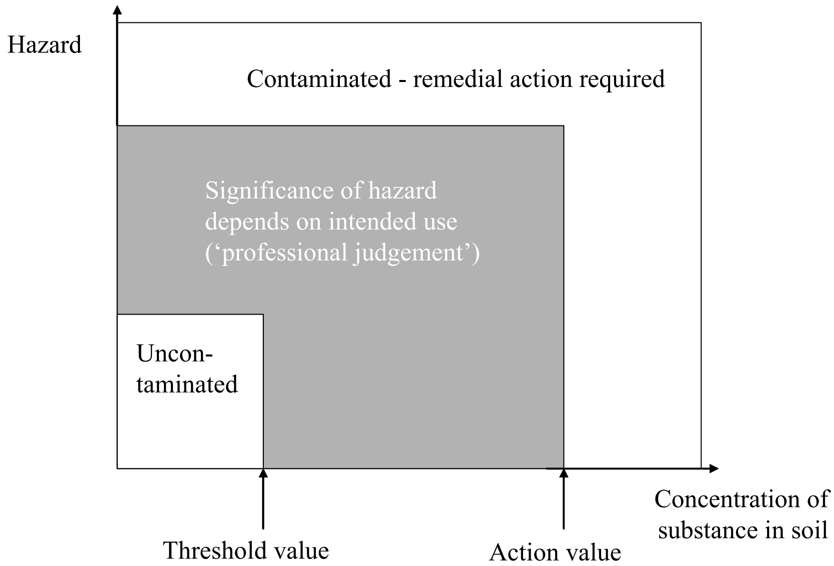


**Figure 1**: Interpretation of ICRCL trigger concentrations (redrawn from ICRCL, 1987).

Figure 1 indicates that the 'hazard' represented by soil contaminants increases with the concentration of the contaminant. ICRCL proposed two soil concentration values (mg $kg^{-1}$ air dried soil) for each substance: a) a threshold value and b) an action value. Below the threshold value it was considered that soils were uncontaminated, since soils naturally contain many potentially toxic substances at low concentration (eg. lead and cadmium). The higher action value represented a soil concentration above which it was considered that the soil was unequivocally contaminated and should therefore be considered for remediation. The ICRCL system thus defined three nominal concentration ranges, representing areas of 'low' and 'high' hazard separated by a range within which the degree of hazard was dependent on the use to which a particular site might be put (eg. domestic gardens or multi-storey car parks). One of the peculiarities of the ICRCL system was the recommendation that 'professional judgement' should be applied in evaluating the degree of hazard represented by soil concentrations falling between threshold and action values.

As well as forming the basis of risk assessments of contaminated sites, ICRCL trigger concentrations have also been applied as 'thresholds' in the classification of soils as wastes during remediation of urban and industrial sites, though new 'waste acceptance criteria' are expected to be implemented under the EU landfill directive[67].

There appears to be no record of the methodology used by the ICRCL to arrive at the published trigger concentrations. It is presumed that the committee used a formal or informal method of expert elicitation in which the professional opinions of the committee members were weighed and appropriate values agreed by consensus. While producing a useful framework of threshold values which was used in the UK for almost 20 years, it is now generally acknowledged that environmental quality standards based on judgement are less defensible, both scientifically and legally, than those with a more objective basis.

ICRCL Guidance Note 59/83 (ICRCL, 1987), which was first published in 1983 and updated in 1987, was withdrawn by DEFRA in 2002. In a letter dated 20th December 2002[68] DEFRA stated "These have been a useful tool, but are now technically out of date and their approach is not in line with the current statutory regime (Part IIA of the Environmental Protection Act 1990) and associated policy. In particular, they are not suitable for assessing the 'significant possibility of significant harm' to human health, which the regime calls for".

The 1980s and early 1990s saw the introduction of Quantitative Risk Assessment (QRA) as a formalised, quantitative and defensible methodology in the assessment of chronic risks associated with many environmental hazards and liabilities. The basis of QRA is the use of predictive models which are capable of forecasting risk(s) in the form of probability distributions. In the case of contaminated land assessments, such forecasts are focussed on the probability of adverse outcomes associated with individual contaminated sites, such as exposure of individuals to harmful doses of substances at the site, or the impact the site may have on a sensitive 'receptor' such as a controlled water body (surface or groundwater) or ecosystem.

Implicit in the construction of models for QRA is the Source → Pathway → Receptor linkage, which can be traced to the 'pollution pathway' concept described by Holdgate (1979). Based on the premise that 'Risk' is the product of 'Hazard' × 'Exposure', it follows that the presence of a toxic substance in a soil presents no risk to a receptor unless an exposure pathway also exists, linking the two. Starting with a specified concentration within the soil (or other environmental medium), exposure models quantify the degree of transmission of contaminants via defined exposure pathways, including:

- direct soil ingestion (important for children and grazing animals)
- plant uptake and consumption of vegetable matter
- inhalation of wind-blown dust or vapours
- absorption through the skin.

[67] http://www.environment-agency.gov.uk/yourenv/consultations/343078/?version=1&lang=_e
[68] http://www.defra.gov.uk/environment/land/contaminated/pubs.htm

The models calculate time averaged (daily, yearly) exposure rates resulting either from individual pathways or the sum of all pathways. Most important, however, is that such models can also be used to back-calculate from a prescribed exposure or risk threshold to determine the initial contaminant concentration which gives rise to that exposure/risk. Thus, risk-based thresholds for potentially toxic contaminants can be determined (Figure 2).

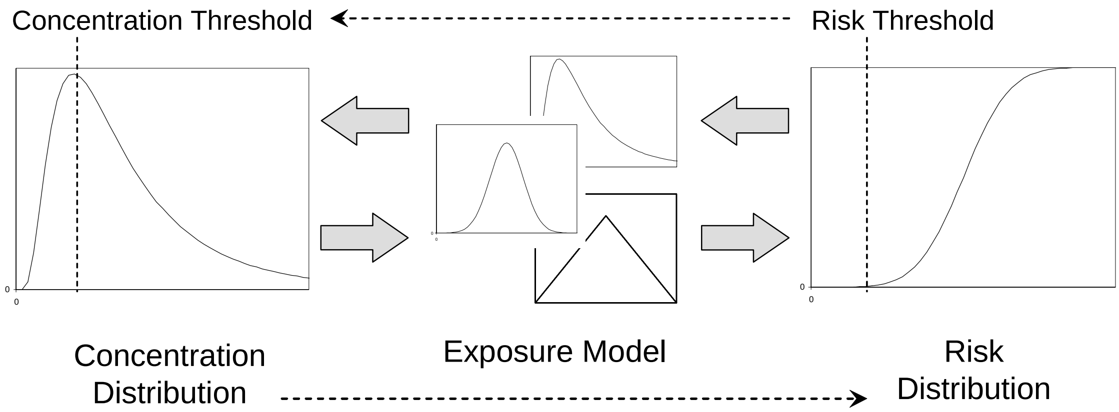


**Figure 2**: Schematic QRA modelling procedures. In practice, probabilistic exposure models can be used to calculate distributions of risk associated with distributions of environmental (eg. soil) contaminants, or they can back-calculate concentration thresholds from pre-determined risk thresholds.

The Contaminated Land Exposure Assessment (CLEA) model was developed in the 1990s for DEFRA and the Environment Agency of England and Wales. Its primary purpose was to provide an objective basis for the calculation of Soil Guideline Values (SGVs), a new system of threshold values for soil contaminants which have now replaced the ICRCL values. A limited set of SGVs was published in 2002, covering seven metals, phenol, cyanide and benzo-a-pyrene (DEFRA/EA, 2002a). This list is limited primarily by the availability of reliable data on which calculations for individual substances are based. The primary reference point on which SGV calculations are based is either a Reference Dose (RfD, mg / kg / d) in the case of non-carcinogenic substances, or a Slope Factor ($[\text{mg / kg / d}]^{-1}$) in the case of carcinogens[69], against which calculated chronic daily exposures (mg / kg / d) can be compared. In drawing comparisons between SGVs and similar threshold values in other countries DEFRA/EA (2002b) noted that “there is a considerable range of values” and that “A large component of this variation appears to come from uncertainty surrounding the toxicology …”. Thus, even though the rigorous methodology of QRA can be used to establish objective ‘safety’ thresholds for environmental contaminants, there are still uncertainties associated with these values resulting largely from an imperfect understanding of the toxicology of many of the substances of concern.

### Generalised Derived Limits and Intervention Levels for Radionuclides

QRA, as applied to chronic exposures to potentially toxic substances via environmental pathways, was still a relatively new concept in the 1990s. However, exposures to radioactive substances (radionuclides) from environmental sources have been quantified using detailed pathway modelling

[69] http://www.epa.gov/iris/

and QRA since at least the mid 1970s (Hoffman et al., 1978). The Source → Pathway → Receptor linkages relevant to metals and organic chemicals at contaminated urban or industrial sites apply equally to radionuclides dispersed either locally or globally within the environment[70] and, for many environmental transfer parameters, data can be transposed from models quantifying radionuclide exposures to those dealing with non-radioactive substances, and vice-versa. However, arguably the most uncertain parameter in metal and organic exposure models, the toxicological reference dose or slope factor, is often the most reliable element in radiological models. This is due to the large epidemiological data set which exists for human exposure to radiation, based largely on the Japanese atomic bomb survivors, and on extensive international records of industrial exposures and the effects of radiation in controlled medical therapies (UNSCEAR, 2000).

It is estimated from epidemiological evidence that an effective radiation dose of 1 mSv results in a 1 in 20 000 ($5 \times 10^{-5}$) risk of contracting a fatal cancer, averaged for the whole population including children. This degree of risk should be viewed in the context of average radiation exposure of the general population which is estimated to be of the order of 2.5 mSv per year (Clarke, 1996), approximately 90% of which is derived from natural (and largely unavoidable) sources. The primary radiological protection standard recommended by the ICRP (1992) for the general public is an annual effective dose limit of 1 mSv. For some years, this primary dosimetric standard has been used to calculate 'reference levels' for environmental media, including soils, waters, sediments and individual foodstuffs. These 'Generalised Derived Limits' (GDLs) are activity concentrations (Bq $kg^{-1}$ or Bq $L^{-1}$) within a soil or other specific medium which would give rise, through chronic exposure via environmental and/or dietary pathways, to an annual dose of 1 mSv (Jones et al., 2005). GDLs are thus environmental threshold levels for radionuclides calculated on the same basis as SGVs, as described in the preceding section. Like SGVs, GDLs are obtained using environmental exposure models although, in the case of GDLs, these models are deterministic, calculating point estimates of exposure rather than statistical distributions.

GDLs are intended primarily as reference levels to allow comparison of results from environmental monitoring surveys. They are calculated using cautious assumptions (eg. over-estimates of time spent in contaminated areas or foodstuffs consumed) and exceedance of only 10% of the GDL would be sufficient to trigger closer inspection of risks associated with a site-specific case. In this sense, therefore, the GDL is highly precautionary. Similarly, Intervention Levels (ILs) for radionuclides are precautionary 'maximum allowable' limits on radionuclide activity concentrations (Bq $kg^{-1}$ or Bq $L^{-1}$) in a wide variety of materials, including foodstuffs and natural products. Radiological protection protocols dictate that, in setting ILs, the values adopted must be 'justified' and 'optimised': in simple terms, the adoption of an IL must do more good than harm. Experience in Europe after the Chernobyl accident demonstrated that ILs were certainly precautionary, but sometimes arbitrary and subjective. For example, in Sweden an intervention level for radiocaesium of 300 Bq $kg^{-1}$ was introduced for all foodstuffs immediately after the accident (May 1986), though this was raised to 1500 Bq $kg^{-1}$ a year later for reindeer, game, fish, berries and mushrooms after it was realised that unnecessary disruption of hunting, fishing and wild food gathering had been caused in some areas which were not badly affected by Chernobyl fallout[71]. In the UK, it took several weeks before the Ministry of Agriculture Fisheries and Food imposed an IL of 1000 Bq $kg^{-1}$ for radiocaesium in the meat of sheep intended for human

[70] Although, external exposure to gamma and beta radiation also has to be taken into account for radionuclides.
[71] http://www.ssi.se/english/DN_Article_Eng.pdf., originally published in Swedish on the 24th April 2002 in Dagens Nyheter, the major Stockholm morning paper.

consumption, although, once imposed, this was rigorously enforced through the use of *in vivo* monitoring (Bell and Shaw, 2005).

## Critical Loads

The threshold concentrations of environmental contaminants described in the preceding sections have been designed as reference levels through which protection of the human population can be achieved from exposure to potentially harmful substances in the environment. The concept of the 'critical load' (CL) is somewhat different in that it was originally designed as a measure of the maximum capacity of an ecosystem to receive continued chronic deposition of acidic or eutrophying pollutants without sustaining lasting damage to its normal functioning. A CL is defined as "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge" (Nilsson and Grennfelt, 1988). In this sense CLs represent putative thresholds of environmental damage rather than risk.

Various methods are used to estimate critical loads, ranging from empirical determinations based on fundamental physico-chemical properties of soils in 1 km grid squares, to model-based estimates based on chemical and biological (diatom) responses of catchments subject to pollutant fluxes. A basic assumption underlying these methods is that the estimated critical loads apply only to chronic, long term deposition scenarios under steady state conditions and that exceedance of a critical load only provides an indication of potential harmful consequences (Hall et al., 2001).

In recent years efforts have been made to extend the critical loads concept to the chronic deposition of metals to soils (de Vries and Bakker, 1998). Definition of a critical load for metals relies on a 'critical limit' being identified, in other words "an acceptable maximum concentration of metal above which long term deleterious effects to an ecosystem should not occur" (Lofts et al., 2004). Using a soil pH based metal solubility relationship in tandem with toxicological data on plants, invertebrates, microbial processes and fungi, Lofts et al. (2004) defined critical limits for Cu, Zn, Cd and Pb which should protect 95% of soil dwelling species from metal toxicity. In this respect, the 'critical limit' of a metal within a soil can be regarded as a form of SGV, though with the purpose of evaluating risk of ecological damage rather than toxicological risk to humans.

Howard et al. (2002) have proposed CLs for radiocaesium in sensitive arctic and sub-arctic ecosystems of northwest Russia and Fennoscandia. In their study, the authors defined CL as "the amount of radionuclide deposition necessary to produce radionuclide activity concentrations in food products exceeding intervention limits": thus, the emphasis is on protection of human health in the context of widespread contamination of the environment. A fundamental tenet of international radiation protection philosophy has been that if humans are adequately protected from environmental sources of radiation, then it is likely that the environment at large and its biota are at least equally protected. This philosophy is now being questioned and significant efforts have been made to develop radiation protection thresholds for non-human organisms (ICRP, 2003; Larsson, 2004).

## Conclusions

The adoption of QRA as an accepted methodology for the evaluation and assessment of environmental contaminants probably began with the modelling of globally dispersed radionuclides. This gave rise to a capability to establish objective, risk based thresholds for radioactive materials in soils, waters and other environmental media. Particularly relevant to the issue of environmental thresholds is the concept of GDLs, which are maximum 'desirable' activity concentrations of radionuclides in environmental media, calculated using the internationally accepted radiological dose limit of 1 mSv per year.

Compared with radioactive substances, toxicological criteria pertinent to other toxic substances in the environment (heavy metals and organic chemicals) are much more uncertain. Thus, even though present day UK threshold values (SGVs) for such contaminants in soils are currently calculated using an objective QRA based methodology, considerable uncertainty still surrounds these values.

Both GDLs and SGVs are risk thresholds designed to protect human health. In the case of metal contaminants of soils, 'critical limits' have been proposed as threshold toxicity values. These are analogous to SGVs but are applicable to soil dwelling organisms. Furthermore, critical limits can be used to inform the calculation of critical loads (CLs) of metal deposition to soils, which are designed to be indicators of 'tipping points' of environmental damage due to chronic pollution. In the case of radioactive contaminants, questions have been raised in recent years as to the adequacy of the dose limit for humans in setting protective thresholds for the environment and non-human species. Significant efforts have been made to rectify this discrepancy and it is likely that environmental thresholds designed to protect the environment *per se* from radioactive contamination will be forthcoming in the near future.

A important *caveat* which should be applied to the interpretation of critical loads is that exceedance of a CL does not imply sudden and catastrophic ecological collapse. In truth, the exact response of an ecosystem exposed to chronic accumulation of any pollutant or contaminant is difficult to predict, which is why ongoing monitoring and research into pollutant effects are essential. Similarly, uncertainty applies to our understanding of the effects on human health of 'undesirable' levels of potentially toxic contaminants in the environment, which is why GDLs and SGVs are calculated using deliberately pessimistic assumptions. The nature of threshold values for potentially toxic environmental contaminants is, in general, precautionary.

As a final consideration it is useful to mention the notion of a 'chemical time bomb', as proposed by Stigliani et al. (1991). This envisages a situation in which a trigger mechanism may suddenly render potentially toxic contaminants already present in an environmental system to become suddenly more harmful, either because their physical location is altered or because their chemical state is altered. Trigger mechanisms may involve natural physico-chemical changes or human induced land-use changes (van Latesteijn, 1998). Current threshold values such as SGVs, GDLs and CLs may be adequate under steady state conditions, but may be irrelevant under conditions in which rapid environmental change occurs.

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# Critical loads for acidity to ecosystems - How environmental limits came to set the policy

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**ABSTRACT**
An assessment of critical loads is always entrenched in the effects-based principle. Discussion of the criteria and the numerical value of the limiting parameter is closely linked to the aspect that is to be protected as well as whether the precautionary principle of the maximum allowable damage philosophy is adapted. For the aspect of acidity which has been illustrated here, many quantitative limits have been employed for creating policy. The critical loads approach has been successful in connecting environmental effect to policy driven measures and in proactive policy formation in Europe.

### 1. Introduction
Since the beginning of the industrialisation in the middle of the 19th century, the industrial emissions of nitrogen and sulphur resulted in increasing deposition of nitrogen and acidifying substances over Europe. This has caused acidification of European soils, resulting water acidification as well as in a net accumulation of nitrogen in large areas. Soil acidification, interferes with nutrient uptake, the cycling of N and increase the leaching of base cations from the forest soil. and increase of the $Al^{3+}$ concentration in the soil solution. Soil acidification cause a temporary increase in base cations but simultaneous elevated concentrations of $Al^{3+}$ disturb plant root vitality and impede the uptake of essential nutrients, eventually, acid water leaks from the soil and we have stream and lake acidification. By 1980, the problem was wide spread and recognized as a major ecosystem threat in Europe. In order to establish a principle that would ensure levels of pollution that would yield a sustainable environment the concept of critical load was developed.

## *2. Political relevance*
The UN/ECE Convention on Large Transboundary Air Pollution adopted the concept of critical load in 1988, providing the basis of future developments of international agreements on reductions of the emission of air pollutants. Input from the UN/ECE process is being used as foundation for the EU policies in long-range air pollution policies. Once a nation has joined the convention (36 nations are now signatory to the convention), there is an inclination to integrate the concept of critical loads and critical levels into their National regulations and standards for sulphur, nitrogen, ozone, volatile organic compounds (VOC) and most lately also the heavy metals lead, cadmium and mercury, eventually something for persistent organic compounds is in preparation. The work of the UN/ECE moved gradually from a Best Available Technology -based approach towards a full ecosystem effects based approach, leading to the 1999 Göteborg multi-protocol, regulating European emission ceilings, targeting European ecosystem protection objectives.

## 3. Principles for using critical loads in policy assessment

The European effects based approach to pollution abatement is called the critical load approach. The critical load approach is depending on standards and limits for its implementation into policy. For critical loads in Europe the following definition was adopted:

*Critical load is the deposition of pollutant compounds that will not cause chemical changes leading to long-term harmful effects on ecosystem structure and function.*

The effects-based approach implies that the critical load is derived following a causal chain from ecosystem to effect:

**Ecosystem – Ecosystem indicator component – Indicator function – Causative parameter – Applied limiting value – Calculation – Critical load – Exceedance**

This follows the normal progress of scientific reaseach. The maximum acidity permitted to the system is the acidic input that does not cause the limiting parameter value to be transgressed. For policy formation and scenario assessment during policy creation the chain illustrated above was reversed:

**No exceedance – required state parameter value – required functionality or stock - required maximum pollution input – required emittor to receptor transmission – technology demand – policy codification**

In this chain the models used and discovered in the first chain have been inverted to be able to back-cast from basic principles of environmental protection. This is the basic approach of an engineered design, of back-casting from goals.

## 4. Principles for calculating critical loads

In the calculation of the critical load, the applied value is found by looking in the appropriate cause-effect diagram such as shown in Fig. 1. How the value is found depend on the environmental protection approach adopted. Examples could be:

- For aquatic systems, we may take the fish population, in the fish population, the salmon may be chosen as the indicator organism, the weak link in this population is the rejuvenation process, because eggs and fish smolt are very sensitive to [Al3+], or as Brown and Schofield (1983) discovered that it was a function of the ratio of $Ca^{2+}$ plus $Mg^{2+}$ to $Al^{3+}$ and $H^{+}$ that gave the best prediction of population survival.

- For a forest, the forest function to protect may be potential for growth of timber. The growth rate of the grown tree is the function we want to protect. This function is directly dependent on the roots and their capacity to take up nutrients. The causative parameter has been shown to be disturbances through aluminium, and subsequent studies have shown that this was best described by a function based on the (Ca+Mg+K)/Al parameter. This can by approximations be transferred to a corresponding Al or pH value, but these require a set of assumptions to be true and are less general.
- If the issue is survival of the tree in the forest ecosystem, then the sensitive component is the rejuvenation stage with the sprout and the seedling. These stages are quite sensitive to disturbances through toxic effect and nutrient uptake prevention by aluminium and hydrogen ions, best described by a function based on the (Ca+Mg+K)/Al parameter. Traditionally, critical loads depend on tree vitality, based on a BC/Al limit set for the root vitality of a specific tree species (Sverdrup and Warfvinge 1993).

## *5. Philosophy of application of critical loads*

An assessment of critical loads is always entrenched in the effects-based principle. Discussion of the criteria and the numerical value of the limiting parameter is closely linked to the aspect that is to be protected as well as whether the damage philosophy. The two available are:

- The precautionary principle (PP), foresees precaution, and we should set the limiting value before any detectable damage is occurred.

- The maximum allowable damage (MAD) draws the line for damage when a securely measurable damage can be shown, thus no limit before damage can be proven.

Setting the limiting value involves interpreting the available response data. An important in this works was the attitude to use the best information available at the moment, not letting the process be stalled by the wait for better data or information, a wait that because of the nature of the research process, has no end. Thus, even imperfect information was allowed. Any assessment or expert judgment was deemed better than just doing nothing but wait. This implies that the estimates may be easily critisized as well as improved if an effort is made. The diagram in Fig. 1 shows

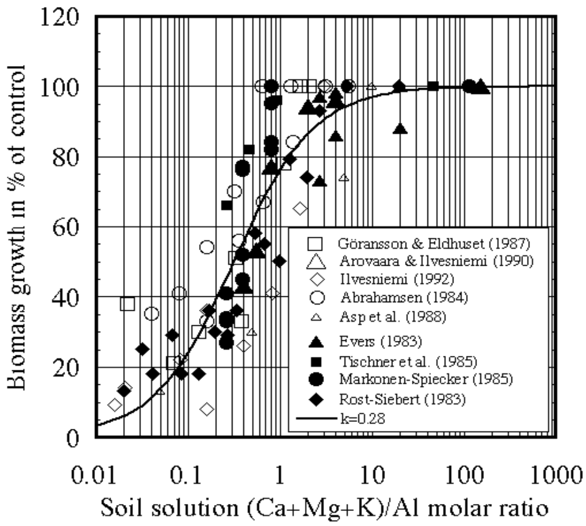


Fig. 1. *Relationship between a chemical parameter and the response of Norway spruce seedlings and smaller plants The limit value is read from the diagram by setting a maximum impact level.*

some of the data available for Norway spruce. It can be seen that the data show a spread around the response line drawn as the average. The spread is wide and reflects the effect of several disturbing factors in the experiments; differences in nitrogen availability, phosphorus availability, light conditions, water conditions as well as differences in the genetic material. This in itself is not a problem, but emphasises that whether we apply the precautionary principle or the Maximum Allowable Damage will have a large effect. In the same way, preventing growth impact will lead to one value, preventing die-off of the forest implies another limit to be set. Applying the precautionary principle for a forest ecosystem, appointing the tree species Norway spruce as the indicator organism, and the tree function to protect from acidification damage, would be stem growth through root vitality. Then the limit for Norway spruce should be set at BC/Al=10-20 or pH=5.2, whereas the maximum allowable damage (MAD) principle would set it at BC/Al=1.2 or pH=4.

The example given above is by no means unique, all response diagrams have similar shape with a spread of the responses. This can be found regardless of which effect parameter that is chosen. Initially, the diagrams like those above were vigorously discussed and at times strongly attacked. The major line of critisizm was aimed along the lines of a scarcity of response data from the field (Most experiments were from short term laboratory experiments on seedlings) as well as frustrations arising from inability to fund and reproduce useful response experiments over the long term in the field that had clear one-dimensional observable responses. Many researchers with experimental background felt the use of integrated models to be threatening and unfamiliar, as well as were unwilling to make decisions involving an easily visible uncertainty. However, at several reoccurring workshops, it was concluded, that the used relationships, standards and limits were the best available, despite several open questions and limitations, that the alternatives were not better and that the existing relationships served the purpose of allowing the approximate protection need to be estimated. Similar response diagrams were created for surface water ecosystems, but these were after an initial period of academic clashes, slowly becoming less controversial. The ones actually being used for waters were better founded in data from field observation than was possible for forests. However, policy is all about making plans when there are still significant uncertainties involved.

## *6. Previous calculations of critical loads*

Initially, only spruce trees and salmon fish were considered for critical loads in Europe. The reason for this is historical and one of pragmatism. The use of productive tree species as indicators are relatively uncontroversial, the trees have a well defined monetary value and an abundance of response data is available. The next step was to enlarge this to Spruce, Pine, Birch, Beech and Oak for forests, and several different fish species for waters. Proposals was made to use BC/Al=1 for any kind of tree or plant, but this is an oversimplification and for many trees and plants outright wrong. The general trend would be to use very simple receptor aspects in the beginning of the process, and over time develop sophistication and discriminate details and diversity of ecosystems. The next development was adding nutrient supply, and the next step would be adding biodiversity of the ground vegetation. For surface water the path was similar. There was always a diversity among the European nations in priorities and degree of detail, varying with national interest and priorities.

## *7. Is there a need for improvements?*

It has been repeatedly suggested that only BC/Al=1 should be used. This is quite a limited view of what an ecosystem is. The limitation to BC/Al=1, inherently implies that all the trees are assumed to be Scots Pine, regardless of what we later write in our reports. Norway spruce gets too poor protection, Beech, Oak and Birch too much. For a single tree, more aspects than root vitality may be considered, for the forest ecosystem, all major tree species must be considered if we intend are serious. Each tree species has its individual critical limit, depending on aspect to be considered and species. For the forest ecosystem, many further aspects can be considered both on the component level:

1. Tree species
2. Ground vegetation plants
3. Soil fauna and micro-organisms
4. Critical soil processes

And at the systemic level:

1. Forest cover stability and composition
2. Forrest production
    a. Growth potential and performance
    b. Natural rejuvenation
3. Nutrient cycling functionality
4. Ecosystem resource stocks
5. Biodiversity
    a. Tree layer,
    b. Ground vegetation layer
    c. Soil fauna
    d. Canopy fauna
    e. Large animal fauna
    f. Essential structural functions

For aquatic ecosystems the aspects to protect are suggested to be:

1. The most sensitive fish species native to the water body
2. Crayfish in those water bodies it is native to
3. The biodiversity of the aquatic community

The availability of response data on the component level is good, and we need not be limited to the root vitality of certain tree species only. A more holistic ecosystem view is both possible and from an environmental point of view better. However, such approaches require both the response data on the component level as well as the use of integrated models in order to combine the components and their feedbacks.

#### 8. Possible criteria

Given the list as outlined above, we may use the available literature and work out the causal chain for every aspect and derive the critical limit. This process has been shown in the Tables 1-4. Tables 1 and 2 are valid for terrestrial ecosystems. Tables 3 and 4 relate to aquatic ecosystems, and tries to define limits by strictly working with the causal chains. These represent a rationalization of the best available information. Better, more mechanism oriented limits and thresholds are available, but these involve the use of integrated process-oriented system models, which is sometimes beyond the policy horizon.

Table 1. *Preliminary proposal for limiting values for terrestrial systems.*

| ***Ecosystem Type*** | ***Ecosystem component*** | ***Indicator organism*** | ***Indicator function*** | ***Causative parameter*** | ***Limiting value*** | ***Diagnostic Monitoring parameter*** |
|---|---|---|---|---|---|---|
| Forest ecosystem | Tree cover | Norway Spruce | Root vitality, Growth potential | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 1.2<br>4.4<br>0.5 mg/l | Growth, Needle loss, Tree vitality |
| | | | Natural rejuvenation | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 0.7<br>3.9<br>1 mg/l | Rejuvenation rate, Species long term survival |
| | | Scots pine | Root vitality, Growth potential | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 1.2<br>4.4<br>0.5 mg/l | Growth, Needle loss, Tree vitality |
| | | | Natural rejuvenation | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 0.6,<br>3.9<br>1 mg/l | Rejuvenation rate, Species long term survival |
| | | Birch | Root vitality, Growth potential | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 0.8<br>4.0<br>0.8 mg/l | Growth, Needle loss, Tree vitality |
| | | | Natural rejuvenation | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 0.5<br>3.7<br>1.5 mg/l | Rejuvenation rate, Species long term survival |
| | | Beech | Root vitality, Growth potential | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 0.6<br>3.9<br>1 mg/l | Growth, Crown thinning, Tree vitality |
| | | | Natural rejuvenation | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 0.6<br>3.9<br>1 mg/l | Rejuvenation rate, Species long term survival |
| | | Oak | Root vitality, Growth potential | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 0.6<br>3.9<br>1 mg/l | Growth, Needle loss, Tree vitality |
| | | | Natural rejuvenation | (Ca+Mg+K)/Al<br>pH<br>$[Al^{3+}]$ | 0.6<br>3.9<br>1 mg/l | Rejuvenation rate, Species long term survival |
| | Soil fertility | Tree biomass production possibility | Excess leaching of base cations/ excess acidity | Soil acidity | Acidity input must be less than W+D | Base saturation |
| | | Root enhanceme nt | Mycorrhiza | Soil acidity | BC/Al<br>PH<br>Al | 0.9<br>4.2<br>0.6 mg/l |

Table 2. *Preliminary limiting values for ground vegetation, soil fauna and key soil processes.*

| ***Ecosystem Type*** | ***Ecosystem component*** | ***Indicator organism*** | ***Indicator function*** | ***Causative parameter*** | ***Limiting value*** | ***Diagnostic Monitoring parameter*** |
|---|---|---|---|---|---|---|
| *Terrestrial ecosystem* | Ground vegetation | Individual plant species | Survival in the vegetation | (Ca+Mg+K)/Al<br>pH | See Table 2 | Abundance in ground |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | cover |
| | Ground vegetation biodiversity | 42 plant groups | Loss of more than one group, Increase in more than one group | (Ca+Mg+K)/Al pH | See Table 3 | Shift in ground vegetation cover |
| | Soil fauna | Earthworms | Nutrient turnover | pH $[Al^{3+}]$ | 4.9 | Abundance of earthworms |
| | Organic matter decomposition process | Fungal decomposers | Reduction of decomposing activity | pH | 4.0 in top layers | Not yet available |

For European priorities, key aspects to protect for ecosystems have been suggested to comprise:

1. The production forest system
2. Natural pristine forested ecosystems
3. Open lands and heaths
4. Mountain vegetation and high elevation ecosystems
5. Biodiversity of the ground vegetation
6. Lake ecosystems
7. Stream ecosystems

For both terrestrial and aquatic, the maintenance of essential structures and connections within the system may also be defined into a limit. For each of these, a quantitative limit may be found (See Tab. 1-4), it can be backed up with field data and experimental bioassays, sometime statistical estimates of robustness is possible. Thus, for policy purposes, these stand on a firm footing.

#### 9. Links between terrestrial and aquatic ecosystems

As critical loads are effects based, then any critical load must have the causal chain in good order. Setting a limit using biological effects in aquatic ecosystem is not a forest critical load, as it has not causal link to any forest ecosystem part. The most important aquatic limiting parameter originating from processes in the forest soil is $Al^{3+}$. Other parameters of interest are pH and $(Ca+Mg)/Al^{3+}$. The final effects of toxic Al in the stream or lake are dependent of interactions with pH, ANC and DOC in the water. Seasonal variations and episodes indicate the potential need for safety margins of the limiting parameters. In critical load calculations for forest soil, the term ANC leaching at the limiting value can sometimes be seen.

*Table 3. Preliminary limiting values for lake ecosystems*

| *Ecosystem Type* | *Ecosystem component* | *Indicator organism* | *Indicator function* | *Causative parameter* | *Limiting value* | *Diagnostic Monitoring parameter* |
|---|---|---|---|---|---|---|
| Aquatic ecosystems, lakes | Fish | Salmon | Survival of population Weak link: Smolt | (Ca+Mg)/(3H+Al) pH $[Al^{3+}]$ | 1.2 5.2 0.05 mg/l | Abundance in habitat, Rejuvenation rate, Species long term survival |
| | | Trout | Survival of population Weak link: Smolt | (Ca+Mg)/(3H+Al) pH $[Al^{3+}]$ | 1.2 4.9 0.2 mg/l | Abundance in habitat, Rejuvenation rate, Species long term survival |
| | | Perch | Survival of population Weak link: Smolt | (Ca+Mg)/(3H+Al) pH $[Al^{3+}]$ | 0.8 4.5 0.3 mg/l | Abundance in habitat, Rejuvenation rate, Species long term survival |
| | | Pike | Survival of population Weak link: Smolt | (Ca+Mg)/(3H+Al) pH $[Al^{3+}]$ | 0.8 4.5 0.3 mg/l | Abundance in habitat, Rejuvenation rate, Species long term survival |
| | Crustaceans | Crayfish | Population survival | (Ca+Mg)/(3H+Al) pH $[Al^{3+}]$ | 2 5.5 0.03 mg/l | Abundance in habitat, Species long term survival |
| | Molluscs | Margaritifera shell | Population survival | (Ca+Mg)/(3H+Al) pH $[Al^{3+}]$ | 2 5.9 0.01 mg/l | Abundance in habitat, Species long term survival |

This is an intermediate parameter of the technical calculation, and not a causative parameter. ANC or alkalinity has no physiological effect, but it is correlated through series of indirect relationships to several of the causative parameters, and thus an intermediate step in the calculation to go from limiting value of the causative parameter to the critical load. However, ANC in the aquatic environment is commonly used as an indicator of the buffering system, protecting fish and other organisms from effects of low pH and high concentrations of inorganic Al. Applying a limit for ANC that leaches from the soil can be used if it's important for the ANC that really enters the stream and the criteria is effects on organisms in aquatic ecosystem. Dynamic modelling, using for instance ForSAFE for terrestrial ecosystems and forests and MAGIC for lakes and catchment, is capable to describe the links between soil and water. The reference state, the acidification phase and the recovery in both soil and surface water can thus be calculated with time resolution in order to estimate both Critical Load and the anthropogenic effect.

*Table 4. Preliminary limiting values for stream ecosystems*

| *Ecosystem Type* | *Ecosystem component* | *Indicator organism* | *Indicator function* | *Causative parameter* | *Limiting value* | *Diagnostic Monitoring parameter* |
|---|---|---|---|---|---|---|
| Aquatic ecosystems, **streams** | Crustaceans | Crayfish | Population survival | pH<br>$[Al^{3+}]$ | 5.5<br>0.03 mg/l | Abundance in habitat, Species long term survival |
| | Molluscs | Snails | Population survival | pH<br>$[Al^{3+}]$ | 4.9<br>0.1 mg/l | Abundance in habitat, Species long term survival |
| | Benthic organisms | | | pH<br>$[Al^{3+}]$ | | Abundance in habitat, Species long term survival |
| | Water plants | | | pH<br>$[Al^{3+}]$ | | Abundance in habitat, Species long term survival |

#### 12. Societal impacts

Within the UN/ECE LRTAP work, efforts are made to grasp the whole chain of environmental impacts and their causes, assessment of cost effective and technically feasible measures as well as to assess the benefit as compared to the cost of the measures. Thus models are utilized to estimate impacts in points. The points or polygons are geaographically aggregated and counted to obtain stock at risk and affected part of total stock. The thresholds find nev use in the impacts and benefit assessments**,** as the threshold for where effect ends and benefit begins.

#### 13. Conclusions

Within the acid rain research sprang the critical load concept that effectively utilizes quantitative limits and standards for environmental effect, according to a strickt and stringent system. The critical loads concept has gained much popularity for providing environmental policies and programs of preventive measures with quantitative policy goals and for being able to effectively yield estimates of both cost, externalities and benefits. Critical load concept and its derivative, critical levels, has because of its merits for sulphur and nitrogen pollution abatement policy been successfully transferred to ozone, volatile organic chemicals, heavy metals, persistent organic pollutants as well as revived the idea for phosphorus from where it in obscurity once rose. There has been a paradigm shift from end-of-pipe treatment of problems towards a philosophy of engineered designs of measures based on backcasting from environmental objectives. We think the basics of the concept could in principle be transferred to any impact or pollutant. The critical loads approach has strongly emphasized the usefulness of employing connected integrated system models in a systematic way. This is necessary in order to be able to utilize large accumulated scientific knowledge and projects its use onto large amounts of distributed data and information. Thus, any assessment involves the construction and use of assessment models.

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**Renewable and Non-Renewable Resource Use: environmental thresholds and UK policy applications**

*Short position paper for Centre for Environmental Management, University of Nottingham, and DEFRA*

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**1. Summary**

Discussions of *limits to physical resource use and the scale of the human economy* have largely been limited to the ecological economics literature and to texts with ethical and/or 'green' political motivation, in modern times from the 1970s onwards. This notwithstanding, economy-wide materials flow analysis in the UK is currently engaging key stakeholders – notably via the REAP and REWARD tools. What is required is to move to the next stage of setting absolute targets for the resource inputs and waste outputs related to those flows.

Economy-wide resource use targets inevitably involve some degree of normative judgement, such as the principle of *international per capita equity in environmental consumption,* embodied in the Environmental Footprint method and in the contraction and convergence approach to climate policy. Normative judgements are both useful and necessary, alongside waste assimilation thresholds, as a basis for deriving protocols for resource use limits. As 'The Natural Step' approach to sustainability argues, while we don't always know how much consumption is too much, it is increasingly obvious that we cannot consume as we have done indefinitely.

The associated concept of *resource efficiency* is now established in EU policy and is intrinsic to the UK Government's sustainable development and sustainable consumption and production strategy. Eco-efficiency is an area where private and social interests have a high potential for congruence. Politically more attractive than the idea of limits to consumption, it is an explicit objective of the IPPC Framework Directive, Design for Environment and 'Factor 4' concepts, life cycle analysis, eco-labelling and associated initiatives.

Arguably, we now need to introduce *stronger incentives for secondary materials use*, to encourage a more rapid improvement in materials efficiency and materials loop closure, so minimising the need for further extraction and downstream impacts. Such targets would move us beyond the limited materials and product recovery targets that we now have. It should be noted, however, if materials reprocessing industries are more strongly stimulated and are sited in the UK rather than overseas, this could increase environmental stress in the UK even though total impact should be reduced.

## 2. A review of renewable and non-renewable resource limits in the sustainability literature

Discussion of limits to physical resource use and the scale of the human economy has largely taken place in the ecological economics literature and texts with ethical and/or political motivations, in modern times from the 1970s onwards. The discussion has typically been in the context of an articulation of sustainability principles and (in answer to question [c]) relatively general. Notable cases are listed below.

### *2.1 Ecological economic approach (I) (Goodland and Daly, 1996)*

Herman Daly has promoted the significance of thermodynamics for ecological-economic relationships for nearly three decades. His definition of environmental sustainability is contained in the input-output rule as follows:

*Output Rule*: Waste emissions from a project should be within the assimilative capacity of the local environment to absorb, without unacceptable degradation of its future waste-absorptive capacity or other important services.

*Input Rule*: (a) *Renewables*: harvest rates of renewable-resource inputs should be within the regenerative capacity of the natural system that regenerates them.
(b) *Non-renewables*: depletion rates of non-renewable-resource inputs should be equal to the rate at which renewable substitutes are developed by human invention and investment." (Goodland and Daly, 1996, p.1008).

From this, basic environmental economic conditions for environmental sustainability are derived:

1. Maintenance of per capita manufactured capital (e.g. artefacts, infrastructure).
2. Maintenance of per capita renewable natural capital (e.g. healthy air, soils, natural forest).
3. Maintenance of per capita non-renewable substitutable natural capital (at present values, to account for increasing scarcity).
4. Maintenance of non-substitutable, non-renewable natural resources (e.g. waste absorption by environmental sinks such as rivers, oceans etc. Zero deterioration implies no net increase in waste emissions beyond absorptive capacity (Goodland and Daly, 1996, p.1008).

### 2.2 *Ecological economic approach (II) (Holdren et al, 1992)*

Holdren *et al* (1992) begin their discussion of the nature of sustainability with a definition that is non-specific to that which is to be sustained:

"A sustainable process or condition is one that can be maintained indefinitely without progressive diminution of valued qualities inside or outside the system in which the process operates or the condition prevails" (excluding the depletion of the sun's energy over several billion years) (Holdren *et al*, 1992, p.3).

Although this definition is logically sound, it is insufficiently specific to inform practical choices regarding the maintenance or improvement of human life quality in the context of a finite planet (*op cit*, p.3). Among the more specific issues that need resolving are the kinds of processes and conditions that need to be sustained, and the sources and dimensions of the main threats to their sustainability (*op cit*, p.3).

Holdren *et al* (1992) observed that despite the rapid growth of "sustainability" literature in recent years, much of the related analysis and discussion has been terminologically and conceptually ambiguous. It has also been subject to disagreement regarding facts and practical implications (*op cit,* p.4). This is due to not only differing technical and disciplinary backgrounds and perspectives, but also to the way in which sustainability in a broad sense involves technological, economic, political and cultural factors (*op cit*, p.4).

Taking account of the above, Holdren *et al* (1992) advocate sustainability conditions that:

1. Limit levels of harm to those that are tolerable on a consistent basis (i.e. levels that are non-cumulative), in return for the benefits of the activity that causes the harm.
2. Limit the degradation of monitorable environmental stocks of “essential” resources only, to not more than 10% per century, which is 0.1% per year in order to give societies the time to develop substitutes and alter related systems. Current degradation rates are thought to be in the range of 100% or more per century (Holdren *et al*, 1992, p.11).

Essential resources are defined as those for which substitution at a scale judged to be required for sustainability is currently and foreseeably impossible. This definition excludes substitutable renewable resources, which - it is argued by definition - could be “sustainably” exhausted on the same basis as non-renewable resources (*op cit*, p.10, after Daily and Ehrlich, 1992).

### 2.3 *Ecological economic approach (III) (Weterings and Opschoor, 1992)*

The Netherlands Advisory Council for Research on Nature and Environment have used environmental sustainability criteria as part of an estimation of required national percentage reductions in environmental impact (Weterings and Opschoor, 1992, pp.9-13). The criteria are based, in turn, on the distinction made by Udo de Haes (1984) between depletion, pollution and encroachment:

a) *General sustainability criterion for depletion*:
No absolute exhaustion of renewable resources, and residual stocks of non-renewables sufficient for 50 years' use.

b) *General sustainability criterion for pollution*:
No accumulation of pollution or lasting effects for future generations.

c) *General sustainability criterion for encroachment*:
Encroachment relates to interventions that affect natural structures and systems. Loss of acreage must not exceed the area added or restored by natural or artificial means.

### 2.4 *Environmental economic approach (I) (Jacobs, 1991)*

There are two main elements to this environmental economic approach to sustainability. The first is the distinction between weak and strong sustainability. The second is the use of an optimality decision rule that recommends the limitation of environmental protection expenditure to the point at which the monetary costs of doing so equal the monetary benefits. Though influential, economic optimality thus conceived has been widely criticised as failing to offer a reliable guide to progress toward sustainability (e.g. Daly and Cobb, 1989), and is not discussed further here.

A weak version of sustainability requires only that future generations be guaranteed the avoidance of environmental catastrophe. A strong version requires that they are left the opportunity for a level of environmental consumption that is at least equal to that experienced today (Jacobs, 1991, p.72). Jacobs makes the value choice to focus on the strong version, and defines environmental consumption as the enjoyment of the economic services that the natural environment provides. Those services are defined as the provision of (1) resources, (2) the assimilation of wastes, (3) life-support services and (4) various amenities (*op cit*, p.73).

Environmental services (1-4) are conceptually divided into their component parts so that they are amenable to measurement, in order to establish whether or not the level of their consumption is sustainable (*op cit*). Jacobs makes this sub-division for services 1-3, as below.

1. For *renewable* resources, defined as those that can regenerate of their own accord, (*op cit*, p.87), sustainability of the current state is achieved while the harvest or use rate does not exceed the regeneration rate (*op cit*, p.87). For *non-renewable* resources, sustainability is defined as maintenance of the stock level relative to demand, given that use and hence absolute decline is held to be inevitable (*op cit*, p.90). Maintenance of relative stocks can be achieved through the development of new, economically viable reserves; through re-use and recycling; and through reduction in demand, including the development of substitutes. Measurement of relative stock size requires the calculation of aggregate stock and projected demand (*op cit*, p.91).

2. For *waste assimilation capacity*, sustainability is maintained when the rate and concentration of non-persistent, or flow, waste discharges remain within the assimilative capacity of the environmental medium (*op cit*, p.93). Jacobs adds that this is indicated by constant or falling pollution levels within the medium (*op cit*). By this, he presumably means levels averaged over due space and time, since pollution levels geographically close to an outflow will necessarily rise for some time period following a discrete emission (Environment Agency, 1997). In the case of stock wastes, such as heavy metals and other toxic materials, all waste discharges reduce the purity of the medium. Such discharges may be permitted for as long as "safe" sites for their disposal can be found (Jacobs, 1991, p.94), which presumably limits disposal to land containment only.

3. For *life support services*, Jacobs suggests that sustainability be indicated by a variety of "life support indicators" (*op cit*, p.95), such as average global temperature as an indicator of climate stability. He is unable to offer a specific decision making principle, however, because these services are not *discretely* consumed. This means that they cannot fit his organising economic metaphor, in which sustainability pertains

when environmental output - and hence consumption - can be maintained at current levels (*op cit*, p.94).

### 2.5 ***Environmental economic approach (II) (Ekins, 1994; 1996)***

Ekins offers six sustainability principles that are precautious relative to the general tenor of the environmental economics (1994; 1996, p.142-3):

1. Destabilisation of global environmental features must be prevented. This particularly involves the maintenance of biodiversity, prevention of climate change and protection of the ozone layer.

2. Important ecosystems and ecological features must be absolutely protected to maintain the functional biological diversity that underpins the productivity and resilience of ecosystems.

3. The renewal of renewable resources must be ensured by maintaining soil fertility, hydrobiological cycles and necessary vegetative cover, and by the rigorous enforcement of sustainable harvesting.

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

5. Emissions into air, soil and water must not exceed their critical load, that is the capability of the receiving media to disperse, absorb, neutralise and recycle them, nor may they lead to life-damaging concentrations of toxins. A precautionary approach should prevail.

6. Risks of life-damaging events from human activity must be kept at very low levels. Technologies with high damage potential, even if low risk, should be foregone.

### 2.6 ***An ecological approach (Moser and Narodoslawsky, 1993)***

Moser and Narodoslawsky (1993, sec. 2.2) define four, largely ecological requirements for sustainable technologies, and express them as the following principles. They are described as ecological because they emphasise the sustenance of natural processes per se more than the sustenance of these processes for human benefit.

- Anthropogenic material fluxes must not exceed the local assimilation capacity of natural cycles, and should be smaller than natural perturbations in material flows.
- Anthropogenic material flows must not alter the content and quality of natural storage systems, such as aquifers and fossil raw material deposits.
- Renewable resources must only be extracted at a rate not exceeding local fertility.
- The natural variety of species and landscapes must be sustained and improved in their natural states and interactions (Moser and Narodoslawsky, *ibid*).

**2.7 *A precautious approach (Upham, 1999 and 2001, after Holmberg, 1995 and Holmberg et al, 1996)***

The following reasoning is a precautious response to threshold uncertainty and builds on reasoning embodied in 'The Natural Step' (Holmberg, 1995, Holmberg et al, 1996). Defining and indicating sustainability will always be a value-laden and contentious process, however extensively scientific knowledge is used. It requires choices as to which natural and social features are to be sustained, and in what form. A particular instance of such environmental loss, damage or stress may be globally sustainable, but it will nevertheless remain an instance of local environmental loss, damage or stress. Whether this constitutes a local contravention of the assimilative or regenerative principles of sustainability depends upon what environmental features, services or level of environmental quality are *judged* to require sustaining.

When considering emission and consumption thresholds, in addition to the need to define exactly what is to be sustained, expressing the concept of local, global or national environmental sustainability requires protocols for relating the condition of critical environmental features to a discrete enterprise, economic sector or nation. These protocols would define the proportion and hence level of environmental consumption permitted to the enterprise. [Even if corresponding critical thresholds are known, without an allocation or permit protocol for environmental consumption (i.e. materials consumption targets or emissions limits) it can at best be said that a single entity has consumed some small proportion of the total distance to those thresholds. It cannot meaningfully be said that the enterprise, or a sector or nation, is sustainable or unsustainable, because there are also many other enterprises, from whose consumption the enterprise in question cannot meaningfully be isolated if we are considering the sustainability of the global habitat].

Relating actual consumption to allocated shares, rather than simply using consumption itself as an indicator, is necessary because operationalising sustainability requires thinking in terms of limits, quotas and thresholds. Sustainability involves limits because it implies an opposite state of unsustainability: sustainability implies that at some point an enterprise can be unsustainable. The eco-efficiency concept that larger businesses now find more acceptable also implies its opposite of eco-inefficiency. However, while eco-inefficiency is considered undesirable, it is not necessarily considered threatening to global life-support (though inefficiencies in aggregate may actually be so). In contrast, unsustainability is a state relating to cessation: whatever should have been sustained has not been, and some threshold or limit has been passed.

This said, setting wholly reliable limits for global environmental sustainability is precluded (Tyteca, 1999) because we have insufficient ecological understanding to relate ecological system values to specific scales and limits (Gudmundsson and Höjer, 1996). We cannot be certain which system components are critical, or what their critical levels of functioning are. Any allocation protocols and hence consumption and emission limits that may be chosen and justified may have only a provisional relationship to actual requirements for sustainability.

The implications of the above in terms of general principles, for indicating the environmental sustainability of a business, sector, or nation are as follows:

1. Conceptual research and sectoral negotiation is needed to establish emissions and consumption quotas, with supporting fiscal or other regulatory incentives, the quantitative values and design of which aim to bring the human economy within the critical levels of large-scale environmental systems.
2. Indicating sustainability requires absolute measures of material input and waste outputs to air, water and land, as well as the same relative to business or economy performance. Waste output means all unwanted emissions to air, water and land. [Decoupling indicators (DEFRA, 2005) are useful but potentially misleading if used alone]. Non-waste output (products) will consist of input material less waste output material.
3. As absolute input and output measures increase in magnitude, sustainability is reduced, assuming no major changes in types of material. Substitution of biologically-derived materials for mined and some synthetic materials, and increased use of this bio material, may be desirable if the material can be biodegraded, is grown on degraded land, or otherwise has a lower impact than the mined or synthetic materials. Consumption targets, quotas and indicators should reflect this.

### *2.8 Per capita and land area approaches (footprinting)*

The Stockholm Environment Institute in York specialise in this area. The *Sustainable Process Index* (SPI) (Krotscheck and Narodoslawsky, 1996) and Environmental Footprint method (Wackernagel, 1994; Wackernagel and Rees, 1995) are both area-based aggregate sustainability indicators. SPI is described here, as it is less well known. The SPI is, unusually, explicitly designed for technology choice based on environmental sustainability criteria, though it could be applied to a larger entity such as a region or nation. It is intended to represent the proportion of that area, theoretically available to each person, which is occupied by the process (or entity) under assessment (Narodoslawsky and Krotscheck, 1996, p.247). The SPI uses the *area required for a process* as the main assessment criterion, because area is deemed as the limiting factor for waste assimilation and the capture of solar exergy in biomass. The area required for a particular production process is taken as consisting of the sum of the area required for the extraction and production of raw materials and fuel, the area of the installation, the living area of the process staff, and the dilution area for waste dissipation (Sage, 1993, and Narodoslawsky and Krotscheck, 1995, in Hertwich *et al*, 1997, p.21). In the SPI proper, this area is divided by the per capita area of the region in which the production takes place, as an indicator of how many local persons' "life-support capacity" the process requires. This division could be adapted for national indication.

The calculation of an SPI centres on the computation of the total area required ($A_{tot}$):

$$A_{tot} = A_R + A_E + A_I + A_P \text{ m}^2$$

where $A_R$ is the area required to produce the raw materials, $A_E$ is the area needed to produce process energy, $A_I$ is the area required for the process installations (equipment/plant), and $A_P$ is the area required for the accommodation of products and by-products (Narodoslawsky and Krotscheck, 1996, p.246).

It is recognised that area per se does not account for the differing ecological or economic significance of the range of terrestrial surfaces encompassed in the proposed measurement. A land use term is less relevant to products and processes derived from marine or river sources. Moreover, it cannot distinguish between more or less sustainable use of land, except for the single criterion of area. It would be as well to regard a land-take indicator critically and supplement it with qualitative judgements, as Andersson *et al* (1998a) suggest. If data on land use were unavailable, this would be necessary in any case. In its defense, ecologically undifferentiated area as reflected by the amended *SPI* term does have some merit beyond relative simplicity. The preservation of genetic information through protected reserves in the mega-diversity regions of the world is not an adequate approach to securing a biodiversity that will sustain the ecosystem services that humans rely on (Folke *et al*, 1996, p.1018). From this it can at least be inferred that the while the qualification of area with a species diversity index would be a more reliable indicator of the micro-ecological significance of the land used, it would not necessarily increase the reliability of the indicator's relationship to securing the biodiversity element of environmental sustainability.

**3. Conclusions**

Sustainability concepts for renewable and non-renewable resources are intended to set a context for consumption in more specific realms. The concepts are typically in the form of general rules, and these rules are intended to apply across an economy, or all human economies in aggregate.

s. To what extent have 'threshold concepts' or similar ideas been developed or explored in you subject area?
t. Are you aware of any physical or biological limits that been identified or conjectured in your subject area, that have a consequence for people or communities? If so how have they been defined?

The ways in which the different concepts treat thresholds differs substantially. In general, the *ecological economic approaches* (e.g. Goodland and Daly, 1996; Weterings and Opschoor, 1992; Holdren *et al*, 1992) tend to establish substitution rules for non-renewables. The rules for renewables involve non-deterioration, with time-scale typically not precisely defined. *Ecological approaches* (Moser and Narodoslawsky, 1993; Azar et al, 1996) relate human materials use to the magnitude of natural flows: i.e. nature is used as a reference point. The *precautious approach* (Upham, 1999 and 2001, after Holmberg, 1995 and Holmberg et al, 1996) assumes that thresholds for both non-renewables consumption and their downstream emissions will often be contentious and/or difficult to establish. This assumption is also held to apply to environmental media, regarding which quality disputes are frequent. This approach therefore advocates indicators that register virgin non-biological material flows as negative for sustainability. Finally, *per capita area (footprint)* approaches (e.g. Wackernagel, 1994; Wackernagel and Rees, 1995; Narodoslawsky and Krotscheck, 1996) use as a sustainability criterion the size of the Earth's surface area required to supply resources and dilute wastes. Typically in eco-footprinting, this is referenced to Earth's biologically productive land area (with variants that account, for example, for marine productivity) divided by Earth's human population, to give a standard per capita allowance. This gives an entitlement in the order of 1-2 ha per person, compared to actual consumption of 4-6 ha per person in wealthy industrialised nations.

u. What kinds of evidence or data have been used to test the idea that such thresholds or limits exist?

The thresholds discussed above are heavily normative. While the approaches make reference to environmental science, this at a general level that assumes the pre-existence of environmental thresholds, without further specificity or validation.

v. What kinds of factor are thought likely to drive the environmental system towards or beyond such thresholds or limits?

Environmental consumption is generally treated as the starting point. Disaggregated material stocks and flows are associated with economic activity and are quantified. They are then related to different decision rules, as discussed above.

w. Have any of these thresholds been embodied in standards or targets that have then be used in regulations or management policies?

Materials flow analysis, environmental accounting with physical and monetary inducators and eco-footprinting have become increasingly mainstream – hence the data underpinning DEFRA's (2005) de-coupling indicators, and the data, driver and impact categories used in the REAP tool and Reward tool. However, I am not aware of any regulations relating to absolute reduction of materials flows coming into economic systems, though control on rate of discharge is commonplace with respect to downstream emissions to air and water. Solid waste quantities are relatively uncontrolled, though their destination (for recycling) is increasingly specified.

x. Do these thresholds vary over time or space, and if so, how is that variation represented?

The thresholds discussed above are generally conceived as of universal applicability.

y. What kinds of uncertainty are associated with defining or identifying the thresholds or limits?

For the ecological economic approaches, uncertainty would relate to defining material stocks and flows, and what to include and exclude. Similarly, the precautious approach requires definition of relevant data categories. For per capita approaches, there is uncertainty over the areas required for waste assimilation and resource supply. The ecological approaches require definitions of what is 'natural'.

z. What kind of future research is needed in relation to identifying or operationalising the threshold concept for policy or management?

Research would likely consist of data standardisation protocols and use of data to compare some of the different approaches reviewed above.

aa. How useful do you think the threshold idea is in taking forward our general thinking about sustainable development?

Thresholds are intrinsic, fundamental and essential to meaningful sustainability concepts. Sustainability implies that an entity has a sustainable and unsustainable state, with a threshold being the boundary between the two. Unfortunately, this notion has only been applied with respect to downstream emissions, and then only in part. A next stage in the evolution of environmental protection may well need to be the application of upstream consumption/extraction limits/targets to individuals, even if this is at a notional rather than mandatory level. Without these, it is likely that generations will gradually impoverish the planet's natural wealth, with increasing displacement of productive ecology. Sectoral targets and fiscal support for resource efficiency and secondary materials use would begin to move us beyond the realm of monitoring and into actual reduction of primary resource flows.

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