The Resilience of Ecosystems to Environmental Change

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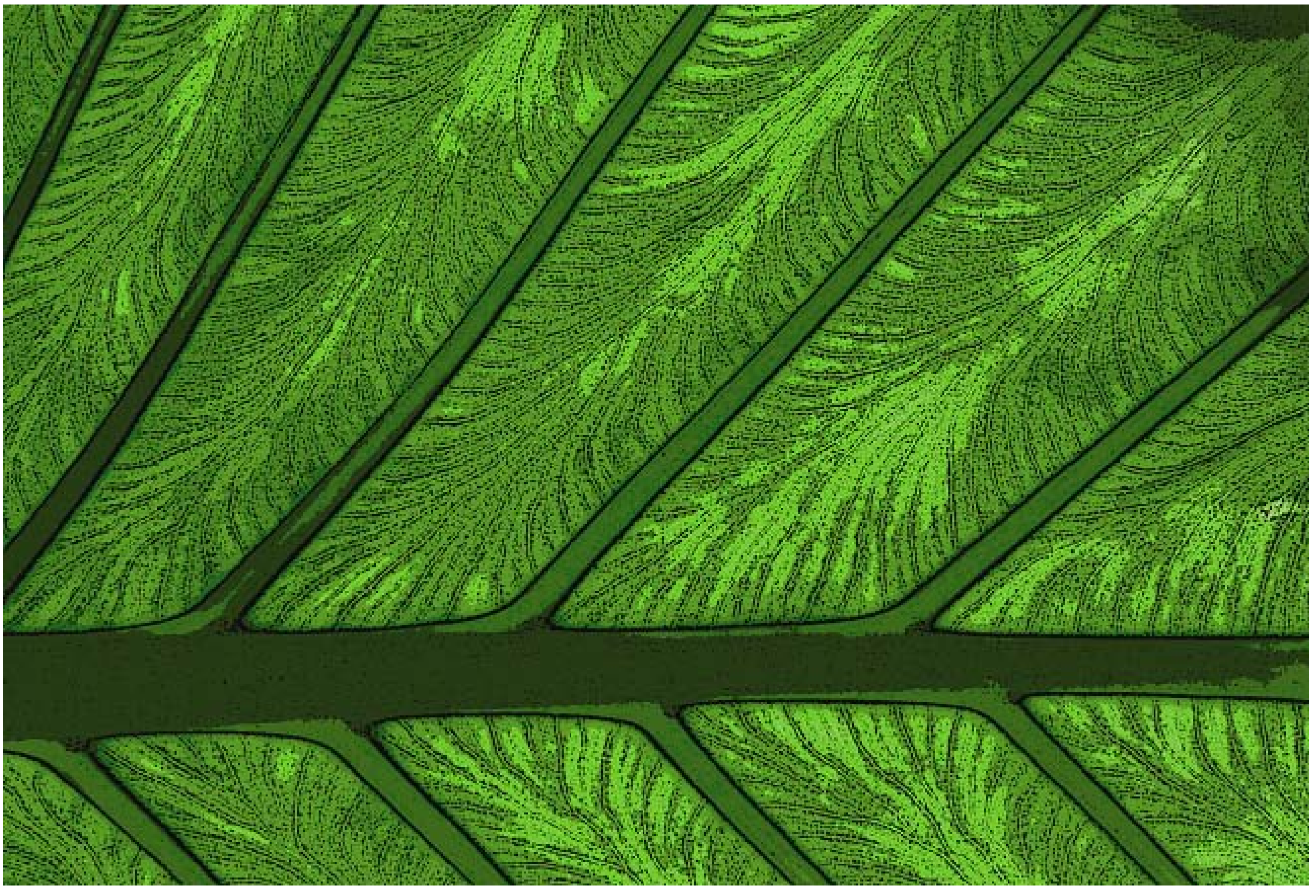

Full Technical Report

The University of Nottingham

CEM

Centre for Environmental Management

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Content

Executive Summary

Background

1. If we are to live with environmental change, then we need to understand the limits of ecosystem functioning so that we can sustain them in the face of increasing human pressure. The identification of such limits is dependent upon knowing how ecosystems react to and buffer external pressures and how well ecosystems recover if they are damaged. The ability of ecosystems to withstand disturbance or to recover from them is generally referred to as 'resilience'. This study aims to provide a critical examination of what is currently known about ecosystem resilience and how that knowledge can be used by the UK to 'secure a healthy natural environment for today and the future'.

Approach

2. The study seeks to apply the methods of a systematic review to this broad question and reflect upon the effectiveness of these techniques, given the different meanings that can be ascribed to the notion of resilience. The difficulties of working with the resilience concept in the context of making a systematic review were noted, and a broader strategy 'knowledge mapping' was proposed as a way of achieving the project aims.

3. An initial scoping phase involving the Project Steering Group, Subject Expert and Policy Advisors identified a set of broad topic areas and focal questions within which resilience thinking might be explored. This resulted in the production of four stand-alone studies that examined the resilience concept in relation to: soils, biodiversity, water and air quality. Within each topic area the aim has been to look at the dynamics of ecological systems and to explore:

   (a) what is known about the way the resilience of systems might be impacted by climate change; and

   (b) how policy or management interventions could mitigate potentially damaging effects. In each topic area the goal was to refine a set of questions that could be addressed using systematic review methods.

Outcomes

4. Each of the four sets of review activities was designed primarily to examine the extent to which resilience concepts had been used in the different topic areas, and whether, therefore there was a significant body of evidence that could support the use of the concept in policy debates. In reviewing these materials it should be noted that the search and review processes described below were **<u>not</u>** designed to produce full systematic reviews of the impacts of climate change on ecosystems when viewed through the lenses of soils, biodiversity, water and air quality. Rather the purpose of the work to critically examine if and how 'resilience thinking' had been applied.

Soils

5. For soils the review looked at the intersection of the literatures on the relationship between soil resilience and climate and soil resilience and management to explore the question:

   Can soil management enhance, restore or protect the resilience or resistance properties of soils, given the likely impacts of climate change?

   Although the question is an open-framed one, not ideally suited to a systematic review, the study had identified a number of important insights. These can be summarised as follows:

   a) There is good evidence to suggest that a number of key soil properties linked to soil carbon are vulnerable to soil warming, and that increasing temperatures could lead to reduced levels of carbon stored in the soil; this conclusion is supported by existing, published meta-analyses.

   b) While there is considerable uncertainty as to whether increased soil respiration under a warmer climate will lead to a net, global transfer of carbon to the atmosphere, there is good evidence to suggest that in localities where there is a loss of soil carbon soil quality would be reduced, making them potentially vulnerable to extreme events and physical disturbances.

   c) There is evidence that management interventions can increase the resilience of soils to disturbance by increasing soil carbon content and enhancing soil structure; it has been argued management practices based on 'reduced' or 'conservation' tillage, particularly effective in this regard, but recent work appears to question this conclusion.

   d) There is good evidence that as soil carbon levels are increased, there is a saturation effect, and that while the benefits of improved soils quality would persist, the strength of the carbon sink provided by soils would diminish.

   e) There is limited evidence as to the economic benefits of investing in soil management from a resilience perspective.

6. Thus in terms of the review question for soils it can be concluded that there is good evidence to support the assertion that soil management can enhance, restore or protect the resilience or resistance properties of soils, given the likely impacts of climate change. However, the economic benefits of maintaining or enhancing soil resilience in the face of climate change cannot be easily estimated.

7. Although the review identified a number of issues relevant to the discussion of resilience within the context of soils, it was felt that the volume and coverage of material was insufficient to proceed with a full systematic review. Nevertheless it was clear that there is a good body of work within the soils domain that could be used to underpin the use of the resilience concept in policy debates.

Biodiversity

8. Two related questions formed the basis for the review of biodiversity and resilience:

   Can management interventions mitigate the impact of environmental change on biodiversity characteristics of UK Broad Habitats?

   How resilient are the biodiversity characteristics of the UK Broad Habitats to environmental change?

9. The review was complex and potentially wide-ranging. To give some added focus to the work more the notion of 'environmental change' was interpreted more narrowly as potential future climate impacts.

10. The analysis of papers selected using the search protocols suggested that there appeared to be only a limited body of material that could be used to address these questions; little of it explicitly used the resilience concept explicitly. It was concluded that this situation probably does not reflect the level or kinds of research being carried in the UK (or elsewhere), but rather, that it is premature for studies on the efficacy of (adaptation) management strategies governing the mitigation of biodiversity impacts to be measured. In essence the review question poses an issue that the body of current research is unable to resolve. The expert opinion that we gained during the scoping process suggested that since climate change impact research is focused on future changes, most of the empirical data would be either modelling or experimental, a pattern that has been shown in this review.

Water

11. For water two questions formed the basis of the review:

    Can management interventions mitigate the impacts of environmental change on the water regulating characteristics of ecosystems? And

    How resilient are the water regulating characteristics of ecosystems to environmental change?

    As in the case for biodiversity the topics also proved to be complex ones which did not easily lend themselves to a full systematic review. The reasons were as follows:

    a) While there were a number of studies investigating the impacts of climate change on aspects of hydrology, many of them did not contain either the necessary ecological or the management component to make an analysis of their responses to environmental change.

    b) Not all studies had the necessary climate change component, or, as with historical studies, did not provide sufficient measures for assessing the effect of any management intervention.

12. The questions posed in this component of the study are, however, important to the future management of water resources, but it appears that research is currently unable to provide a clear, quantifiable answer at this stage in terms of questions about resilience. The reviewers concluded that a more flexible search approach to the question could have helped, as there does appear to be a body of research looking at management impacts (especially deforestation)

on hydrological parameters relevant to water regulating services (both quantity and quality), which were not captured for the final analysis because of their lack of an explicit (as opposed to inferential) climate change component.

Air quality

13. The question identified in this topic area was:

    How resilient are England's major ecosystems to changes in air quality and how might this change under future climates?

    Secondary issues considered in the analysis concerned the extent to which management interventions might mitigate these effects, and to what extent the impacts on economic values had been considered in the recent literature.

14. Given the rather general character of the review question, it was decided to develop more focused analyses around a limited number of important or potentially important air quality issues: ozone; and nitrogen and sulphur deposition, and acidification effects. The analysis looked at the evidence for current impacts and any work that gave insights into how these impacts might change under future climatic conditions. The results can be summarised as follows:

    a) There is good evidence to suggest that currently exposure to ozone can impact at the individual and habitat levels. Although species vary in their responses to elevated ozone levels, changes in growth patterns and reproductive performance can shift the competitive balance within communities, potentially resulting in biodiversity loss. The evidence for habitat level transformation is more extensive for grassland communities, although effects on growth and performance have been detected in forests. The evidence linking the effects of ozone exposure to components of climate change is more limited, but it seems to indicate that elevated concentrations CO_2 increase the damaging effects of ozone rather than offsetting them.

    b) There is a considerable body of evidence that atmospheric inputs of nitrogen and sulphur can have chronic effects on vegetation, soils and drainage waters. Effects have been detected at sub critical-load concentrations, and can result in significant community level changes. However, the body of that is relevant to the question of how air quality impacts would change under future climates or how management interventions might mitigate those impacts is more limited.

    c) Similarly, while there is a considerable body of evidence to suggest that acidification has modified ecosystem structure and function, fewer studies have considered how these effects might be modified under future climatic conditions or what factors control the extent and speed of recovery.

15. Given that the search protocols were mainly designed to examine how resilience concepts are reflected in the literature it is likely that the materials identified do not fully reflect the current 'state of the art' in relation to air quality and climate change impacts. However the range of materials probably are sufficient to draw some conclusions about the resonances between this

body of literature and more general notions of resilience. In this context, the key conclusion that can be drawn from the analysis of material on for air is that as a theoretical construct resilience is not widely applied in this segment of the literature. In the main, the work related to air quality looked at sensitivities in the form of dose-response relationships, critical limits and interactions between different drivers, and there appears to be much less attention to the dynamics of recovery, or threshold effects in the form of regime shifts. This is not to say such patterns of response cannot be imputed from the work, but rather that this kind of conceptual framework is missing from this literature.

Conclusions

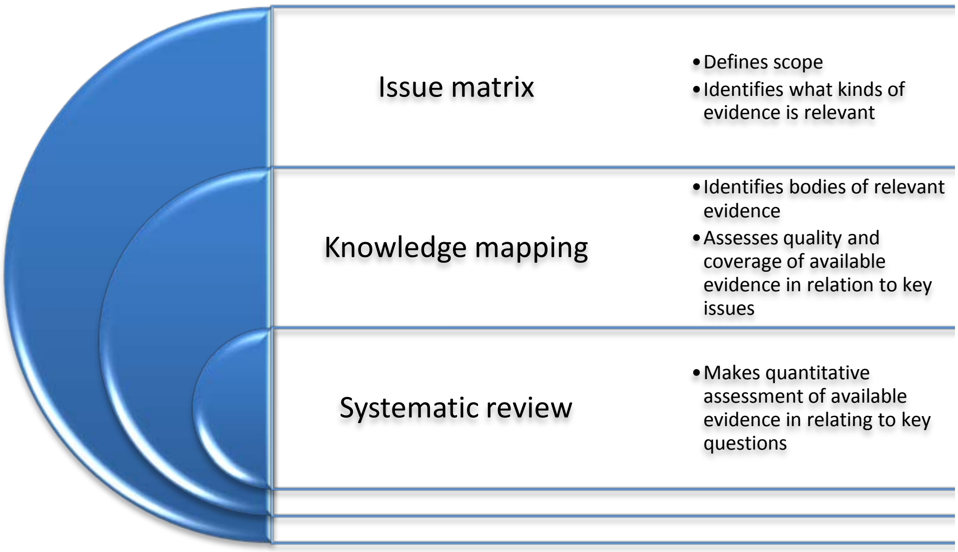
16. Although the aspiration of using systematic review to make an analysis of ecosystem resilience, climate change and management interventions was not realised in this study, the work has provided some insights into how such an investigation might be carried taken forward. The conclusions may be summarised in relation to the substantive scientific questions that surround the concept of resilience and the more general use of systematic review methods to explore complex 'open-framed' questions.

17. Although resilience as a general concept is widely discussed in the literature, there is limited consensus about how it can be assessed or characterised. However, in terms of specific types of ecosystem dynamic, the resistance of ecosystems to disturbance and their speed of recovery following some disruptive event are both highlighted as components of resilience. While both these ecosystem characteristics are in principle measurable, other attributes such as the capacity of ecosystems to transform and adapt in the face of environmental change are more difficult to operationalise.

18. There were considerable differences in the extent to which resilience thinking had been taken up in the four topic areas considered in this study. In some areas (e.g. soils) the concept was used explicitly, in other (e.g. air quality impacts) it was less so. This feature made the identification and extraction of evidence across the topic areas difficult. Measures or resilience based on the resistance of systems to disturbance and speed of recovery were useful to identify material that was implicitly relevant to the overarching question of resilience, but this linkage was often based on judgement rather than the tight search protocols usually required in systematic review. **In each of the four topic areas we therefore concluded that there was probably insufficient material available to make either full systematic reviews or smaller targeted analyses. However, it was apparent that the more informal review process carried out was valuable in mapping out some of the key questions that have to be addressed in order to form some understanding of ecosystem resilience, climate change and management.**

19. The study therefore moved on to look critically at how systematic review might be used to explore complex open-framed questions like those that surround resilience. It was concluded that while the idea of knowledge mapping as suggested by a systematic review is a useful one, as a device to help make review questions more specific it also needed to be used in conjunction with other framing devices. The idea of an 'issue matrix' or 'issues mapping' was proposed and described, and it relationship to the systematic review process considered (Fig.1).

Figure 1: Relationships between issue and knowledge mapping and systematic review.



20. When contemplating the requirements of a systematic review, the 'situational logic' suggests a reductionist approach, in which perspectives are gradually refined and focused so that precise questions can be asked. Although knowledge mapping may help this process, our experience indicates that it cannot simply be viewed as a means of identifying where effort might subsequently be directed without any regard as to how the results of those individual reviews would contribute to some overall conclusion. We conclude that the process of issue mapping, involving dialogue between policy and topic experts, provides a framework in which this could be done in an efficient and transparent way. We provide an outline of how the investigation of ecosystem resilience is to be taken further by Defra using the outputs of this study.

21. Defra's *Action Plan* for embedding an Ecosystems Approach in decision making emphasises that adaptive management involves consultation and the co-construction of knowledge, as well as making the use of the best evidence available. The recommendations we have made about the construction of an issue matrix are clearly consistent with this idea. The experience gained in this study has provided some pointers as to how this can be taken forward by combining the focused methods of systematic review, with more open-ended deliberative approaches designed to better understand how broad, normative policy concerns can be translated into manageable review questions.

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- Dr Peter Costigan (Defra, Head of Natural Environment Science)
- Giles Golshetti (Evidence manager – Natural Environment Strategic Unit)
- Dr Mike Morecroft (Natural England – Climate Change)
- James Vause (Defra, Natural Environment Economics team)

During the scoping phase we ran an e-Forum to consult on draft questions and on our search strategy (see: www.recce.org.uk). We thank those who provided input. Defra's policy advisors also reflected on policy questions and search terms that we generated, and we hope we have reflected those comments sufficiently well.

We also interviewed a number of experts during the scoping and final phases of the project, and are grateful to the following people for their constructive comments on the draft version of the final report:

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1. Introduction

By Roy Haines-Young, Marion Potschin and Pam Berry

Living with environmental change poses a number of management and policy challenges. We need, for example, to understand how resistant ecosystems are in terms of buffering the impact of external pressures. We also need to know if they can recover from disturbances to their functioning. Finally, we need some understanding of the dynamics that ecosystems might exhibit in the future as a result of changes in external conditions, such as those related to climate, pollution loads or land management practices. Collectively the issues of ecosystem resistance and recovery have been addressed in the discussions surrounding the idea of 'resilience'.

The importance of the debate about resilience has been highlighted by recent initiatives such as the Millennium Ecosystem Assessment (MA), which showed how the well-being of people is linked to biodiversity (MA, 2005). The MA concluded that globally ecosystems are experiencing growing external pressures from drivers such as climate change, land use change, pollution and invasive species, which will impact on the functioning of ecosystems and on the provision of ecosystem services (Defra, 2007). In the wider research and policy literatures there is growing concern that losses in biodiversity may lower resilience to and/or recovery from disturbances (e.g. Loreau et al., 2002; van Ruijven and Berendse, 2010), although the relationship is yet to be confirmed. However the evidence that biodiversity and resilience are closely linked is growing. Thus Isbell et al. (2009) have shown that species richness and more diverse patterns of species interactions can promote ecosystem stability and thus sustain the output of ecosystem services.

1.1 Study aims and objectives

The aim of RECCE (The Resilience of ECosystems to Environmental ChangE) has been to undertake a review of resilience and how it relates to key policy areas of concern to Defra and its partners. The goal has been to better understand how policy action might help to sustain ecosystems in the face of environmental change or to protect the capacity of ecosystems to recover following disturbance. Thus the work has sought to take stock of the scientific, management and policy literatures on this topic, and assess the robustness of the current evidence base that could be used to frame policy and management responses. For details of the initial brief see Appendix 1. The work has also provided the opportunity of reflecting upon the appropriateness of the systematic review process when confronted with such a wide ranging topic as resilience.

The objectives of the study were as follows:

i. To work with Defra and other research partners to plan and refine the policy relevant questions and sub-questions relating to ecosystem resilience;
ii. To develop and test search appropriate protocols that will allow the published and grey literatures relating to the focal questions to be reviewed systematically;
iii. To identify a set of suitable publications for inclusion in the review, using clear and transparent inclusion criteria;
iv. To extract and analyse the key results from the selected reference base, and to synthesise the main conclusions and the strength of the evidence that underpins them; and,
v. To provide a commentary on the results of the study and its policy implications, and an assessment of apparent evidence gaps and the kinds of research that might be needed to resolve them.

1.2 Framing Notions of Resilience

The analysis of ecosystem resilience is challenging because there is considerable divergence in the way the concept of resilience has been framed. Moreover, since it is often discussed conceptually as a 'whole systems' property, it is often difficult to relate more focused empirical studies of individual ecosystem properties to the dynamics of entire ecosystems. Nevertheless, given present concerns that losses in biodiversity may lower the resistance of ecosystems to disturbances or their ability to recovery from external impacts (e.g. Loreau et al., 2002; van Ruijven and Berendse, 2010), it is important to examine what is known about what kinds of factors might enhance system stability and how policy or management intervention might help secure greater resilience to external pressures.

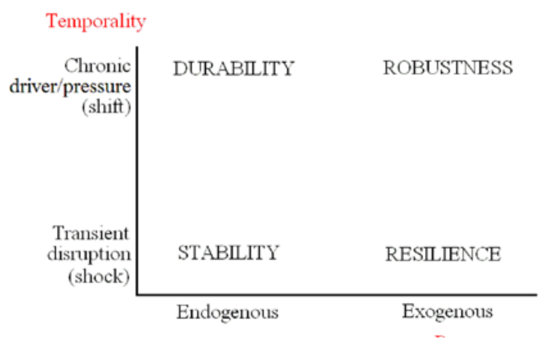
Brand and Jax (2007) provide a useful review of the different meanings ascribed to the term. They contrast usage in the ecological literature, with that from the social sciences, and then trace the evolution of a more hybrid concept that deals with problems at the interface between people and nature. Holling (1973) initially proposed the idea as a 'measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables'. Brand and Jax (2007) suggest that this formulation has been refined by subsequent work, especially that of Folke et al. (2002), Gunderson and Holling (2002) and Walker and Pearson (2007). Thus the term is now used to refer to two distinct ideas, namely:

- The magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour; and,
- The capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity.

However, there has also been some enlargement of the concept, and several other themes have been linked to discussions of resilience. For example, Janssen and Ostrom (2006) and Janssen (2007) have looked at the commonalities between three research domains concerned with the human dimensions of environmental change: resilience, vulnerability and adaptation. They found that not only have the number of publications referring to these concepts increased rapidly, but also that there is a growing overlap between them.

A further enlargement of the concept is also provided by Dawson et al. (2010) (Figure 1.1) who identify four distinct dynamic properties of ecosystems, based on the extent to which disturbance is transient or chronic and whether it is external (exogenous) or internal (endogenous) to the system. For them, resilience concerns the response of ecosystems to external shocks and must be looked at alongside other dynamics, namely durability, robustness and stability.

Figure 1.1: Dynamic system properties defined according to temporal characteristics and provenance (after Dawson et al., 2010)



Yet greater complexity has been introduced into the resilience debate by the fact that while some commentators confine their attention to the biophysical aspects of ecosystems, others focus on the resilience of coupled social and ecological systems. Brand and Jax (2007) suggest that when used broadly to refer to social, political and ecological characteristics of ecosystems or desirable goals of ecosystem management, the term 'socio-ecological resilience' might be used. When used in a more 'scientific' context, they argue that its meaning must be tighter. Thus following Carpenter et al. (2001) and Cummings et al. (2005) they advise that when speaking about 'ecosystem resilience' or 'ecological resilience' we must be clear about what kind of ecosystem property we are considering by specifying the resilience 'of what to what'.

To make a systematic review of resilience it is suggested that the 'of what to what' principle provided a useful general framework. We have therefore focused especially on ecosystem or ecological resilience in its broadest sense, and in terms of developing an approach for this study have taken:

- The 'of' term in the principle as referring to ecosystems and their associated services. Thus the first task has been to identify the ecosystems and services that are of policy relevance to the UK; and,
- The 'to what' component of the principle as referring to the major disturbances or shocks that these systems or services are vulnerable to. Given the motivation for this study these are taken as the kinds of disturbance that policy interventions could potentially mitigate or insure against in the UK. Thus the second task has been to identify the important policy relevant issues surrounding the notions of resilience.

These two tasks formed the basis of the scoping work undertaken for this study and set the context for the review process, which seeks to follow the guidelines prepared by the Centre for Evidence based Conservation (Centre for Evidence-Based Conservation, 2010).

1.3 Resilience and the Systematic Review Process

The power of the systematic review process depends on the formulation of a clear question and the transparent and reproducible way the available evidence is assembled to answer it. According to the 'Guidelines for Systematic Review in Environmental Management' (Centre for Evidence-Based Conservation, 2010), questions for a systematic review should have the general form, namely:

'How does intervention X on subject Y produce outcome Z?'

When making a review of the evidence about the efficacy of any intervention the identification of some kind of 'comparator' is also essential so that the magnitude of the intervention effects can be assessed.

A systematic review works best when the target question is sufficiently specific to enable interventions and outcomes to be assessed in measurable ways, and where the subject itself is well defined and identifiable across different studies. For example, Benítez-López et al. (2010) recently constructed a systematic review around the question: *Are mammal and bird populations declining in the proximity of roads and other infrastructure?* In this study the subjects are populations of birds and mammals, and the intervention disturbance associated with human infrastructure. The comparator is the distance from disturbance and the outcome a change in abundance.

Many other examples illustrating the structure of the systematic review process can be found though the Centre for Evidence-Based Conservation on-line library[1]. Such studies illustrate that the

[1] http://www.environmentalevidence.org/Reviews.htm

conclusions of systematic reviews are particularly effective when they are able to combine and summarise the results of a number of studies statistically, using meta-analysis techniques. For decision makers, the approach is therefore potentially more helpful than traditional literature reviews, which may be purely qualitative, subjective and open to publication bias. Systematic reviews can therefore be regarded as fundamental to the formulation of evidence-based policy.

Thus given the brief for this study, the components of the generic systematic review question were initially interpreted as follows:

- the **subject** element of the review question was taken as the 'of what' part in the 'of what-to what' principle noted above, and thus understood as an ecosystem, or an ecosystem component or an ecosystem property;
- the **intervention** element was taken as the 'to what' part in the 'of what-to what' principle, and was interpreted as either a specific management regime, policy or action which in the context of this study aimed at promoting the resilience of the ecosystem in its broadest sense, or the impact of another independent variable related to climate change; and,
- the **outcome** is the relevant objectives of the proposed management intervention that can be reliably measured, which in the context of this study is some measure of the resilience, resistance, durability or stability of an ecosystem to some transient or chronic disturbance (i.e. some kind of environmental change).

The **comparator** could then be considered as the availability of some baseline assessment that allows situations where an intervention or disturbance has occurred and to be measured against those where they have not.

Scrutiny of this initial attempt to translate the study brief into the format of a systematic review question suggests that it is probably too broad and open in its structure to be made operational. A number of difficulties are evident. The subject is, for example, heterogeneous, covering any ecosystem or ecosystem property. A further problem is that the intervention is complex in nature, involving two potentially independent influences: 'management' and 'climate'. Finally the formulation implies that the outcome in terms of the changes observed in a particular ecosystem parameter after intervention, can be measured in a number of ways, ranging from the ability to resist disturbance through to the speed of recovery. In other words, the initial formulation has too many sub-questions embedded within it to be viable s a starting point for a systematic review.

As the 'Guidelines for Systematic Review for Environmental Management' (see Centre for Evidence-Based Conservation, 2010, p.19), questions that are too broadly focused may not be suitable for a systematic review, and in these circumstances a two stage process might be considered, involving the construction of a 'knowledge map' for a given topic or research field, followed by one or more full syntheses on subsets of research identified in this map. The advantages of this approach is that it allows the users of the material to better understand the scope and content of the research that is relevant to a given issue before more detailed and specific investigations are made. The guidelines argue that knowledge mapping is distinct from a pilot review, which is often undertaken in preparation for a systematic reviews, in that the formulation of the search and inclusion criteria it is conducted with the same rigour as for the full review. However, knowledge mapping is also distinct from the full review in that the process may not initially extend to a final critical appraisal or data synthesis in the form of a meta-analysis. The assumption is that once a broad set of research findings have been described systematically in this way, 'pools of research' can be identified that can be explored to answer the more tightly specified question typical of a systematic review. The exercise can also help identify where the knowledge gaps appear to be. Examples of this strategic approach are to be found in the health and social science fields, and are illustrated by the recent review of nature and health by Bowler et al. (2010).

Given the difficulty of translating the study brief into a sufficiently narrow question suitable for a systematic review, it was decided to approach the task from the perspective of knowledge mapping. Thus the work began with scoping exercise, which was informed by two processes. First, a review of a set of policy-related documents suggested by Defra and its partners on the Project Steering group at an initial kick-off meeting. These documents were used to identify a set of broad thematic areas of current policy interest that could potentially be investigated. The second stage involved consulting a wider group of invited experts by means of a web-based discussion forum (www.recce.org.uk). The aim here was to develop a stronger review focus in each thematic area. The five thematic areas that were identified from the initial discussions were:

- Soils, resilience and the impact of environmental change
- Water futures and ecosystem integrity
- Biodiversity and vulnerability to environmental change
- Ecosystem resilience and air quality
- Economic values and well-being.

Further discussions suggested that the topic of economic values and well-being was so broad that it was not feasible to investigate this subject within the present study, and that the focus should be on soils, water, biodiversity and air quality. Even so, although it was agreed that the study should concentrate on these more specific topics, it was clear from the outset that the questions one might ask in the context of resilience remained very broad, and that the knowledge mapping approach was still the most appropriate way forward.

1.4 Structure of the report

Thus, while the aim of this study was to undertake a systematic review of resilience, the difficulty of formulating the study brief as a single, specific reviewable question meant that the focus of the study shifted to an investigation of the way resilience notions could be framed in relation to four distinct topic areas. The results of this study are therefore presented in Chapters 3 through 6, as four 'stand-alone' reports dealing with resilience thinking as it relates to soils, water, biodiversity and air quality. In each case the work seeks to describe how resilience concepts have been framed, and what insight resilience thinking has brought to the debate, rather than to provide a comprehensive analysis of the impacts of climate change across the different subject areas

Since it was the ambition of this study to bring the results into an integrated framework, we have attempted to use a common definitional and methodological approach across each of the topic areas. This is described in Chapter 2 of this document. In the last part of this Report we then bring the results together and reflect on what implications follow in terms of using resilience concepts in contemporary policy debates.

If we are to live with environmental change, then we need to understand the limits of ecosystem functioning so that we can sustain them in the face of increasing human pressure. The identification of such limits is dependent upon knowing how ecosystems react to, and buffer, external pressures and how well ecosystems recover if they are damaged. This study attempts to provide a critical examination of what is currently known about ecosystem resilience and how that knowledge can be used by the UK to 'secure a healthy natural environment for today and the future'.

2. Methodology

By Roy Haines-Young, Pam Berry, Paula Harrison, Richard Mercer, Marion Potschin and Gabriella Silfwerbrand

Given the wide-ranging nature of recent debates about ecosystem or ecological resilience, this study has sought to balance two contrasting pressures. First, the need to develop and refine a set of questions that are specific and suitable for investigation by means of a systematic review. Second, the need to retain a sufficiently broad focus so that the outcomes of the study cover a sufficiently wide spectrum of issues that allow us to look at what 'resilience thinking' might contribute to management and policy. As noted in the introduction, the result has been that four distinct, but linked reviews have been made, that collectively give some insight into the resilience of different aspects of ecosystems in relation to the impacts of climate change. The ambition is to provide a knowledge map that can be used to take these debates further.

In order to give unity to this study, we have used a common set of definitions and synonyms for key concepts throughout, and applied a similar search methodology across the four topic areas. The separate studies also drew on a shared scoping study. In the first part of this Chapter we describe the scoping work in more detail. The Chapter concludes by summarising the search terms used to explore different aspects of resilience and types of intervention and the sets of published materials identified for each thematic area.

2.1 Scoping the review - ecosystems, services and policy themes

In addition to the initial discussions with a project steering group, we invited a number of subject ah and policy experts to contribute to an on-line discussion forum on the RECCE website (Figure 2.1)

Figure 2.1: The RECCE Website (www.recce.org.uk)

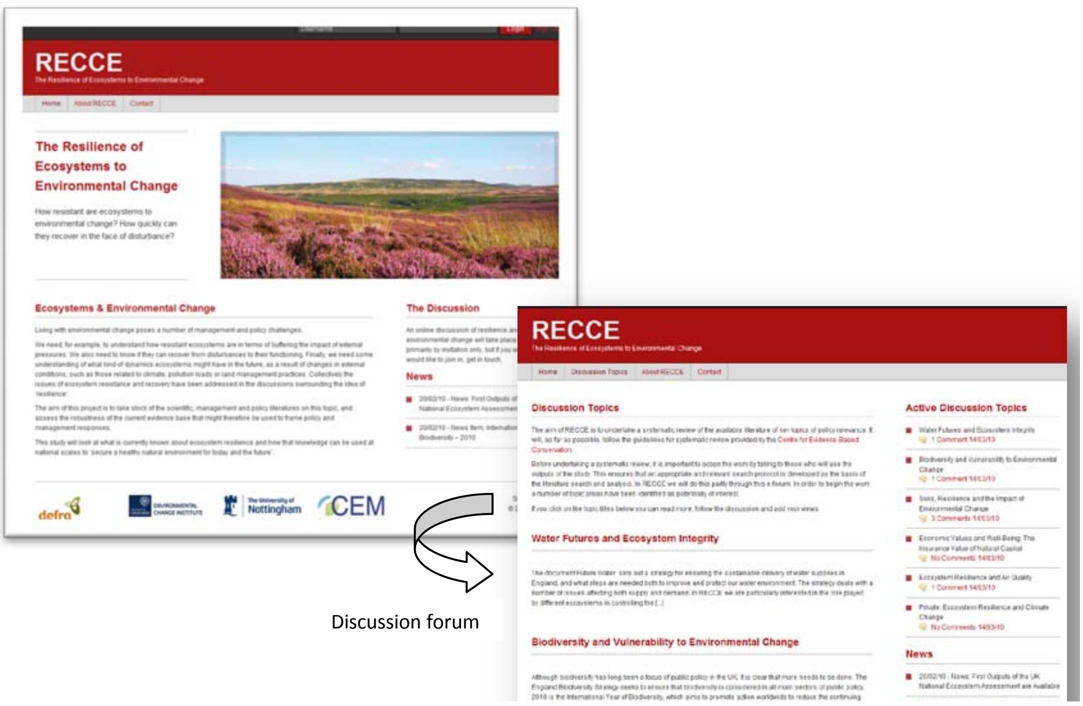


Table 2.1: Candidate focal questions posed in the scoping study (the questions shown in italics were proposed to stimulate discussion; questions not in italics are those suggested by the consultees)

Thematic area	Potential questions
Soils, Resilience and the Impact of Environmental Change	• *How resilient is soil function to pollution inputs?* • *How is the risk to human health and the environment from soil pollution likely to change under future climates?* • *What kinds of land management intervention are needed to ensure that soils cope better with drought and regulate drainage of heavy rainfall and flooding?* • *How do changes in levels of soil carbon affect the resilience of soils?* • *To what extent can the integrity of soils be restored through remediation and restoration measures?* • *How is the resilience of soils affected by the spreading of organic and inorganic materials as part of recycling?* • What are the win-win options that improve resilience and reduce GHG emissions and increase soil carbon? • Can agricultural production be enhanced or maintained in a sustainable way? • How can soil resilience be managed and how (and over what periods of time) can we practically impart resilience properties on soils that would not otherwise be stable?
Water futures and ecosystem integrity	• *How does drought affect the capacity of bogs to regulate water?* • *How can surface water management be used to promote the resilience of freshwater ecosystems to extreme weather events?* • *How significant is water abstraction, eutrophication, drainage and physical modification of river courses in reducing the resilience of freshwater ecosystems to climate change?* • *How can we understand and value the resilience of an ecosystem at the scale of a river catchment so as to better manage land and water in a more integrated way to provide optimum goods and services. Thus:* • *What proportion of the land should be assigned to different ecosystem goods and services (ESS) – producing food, biodiversity, landscape, and water protection – and how can we combine these roles in the landscape?* • *How can we develop a better understanding of the connectivity between environmental compartments?* • *What tools can we use to help land/water managers understand the interactions?*
Biodiversity and Vulnerability to Environmental Change	• *Is the maintenance of native biodiversity in ecosystems important in terms of their resistance to alien species and how might this change under future climate regimes?* • *What level of ecological habitat variability is beneficial to providing suitable future conditions under climate change?* • *How far can maintaining habitats in favourable condition help their resilience to environmental change?* • *Where are 'buffer zones' most effective for conserving biodiversity and what characteristics should they have?* • *Do ecological networks promote ecosystem resilience?* • Which UK Broad Habitats are most vulnerable to climate change?
Ecosystem Resilience and Air Quality	• *Which pollutants are most important in reducing the resilience of ecosystems (e.g. woodlands, heathland, grasslands and wetlands) to climate change?* • *How significant is acid rain in reducing the resilience of ecosystems to environmental change?* • *How significant is eutrophication in reducing the resilience of ecosystems to environmental change?* • How significant is the interaction between ozone and climate change?

Users could login to the discussion forum and suggest or make comments on a range of potential review questions. The website was designed to provide input across the topic areas: soils, water biodiversity and air quality, as well as economic valuation and human well-being. Altogether 17 people signed up for the discussion forum. The number of comments was small than anticipated, but they were nevertheless useful in identifying area of potential interest. The outcomes of the scoping phase is described below.

2.1.1 Soils

The background to the issue of soils and resilience was provided by the *Soil Strategy for England* (Defra, 2009). This document has set out the aim that all soils will be managed sustainably and degradation threats tackled successfully by 2030. The *Strategy* argues in particular that we have to better understand the impact of climate change on our soils and identify what must be done to enable them to adapt. To do this the *Strategy* suggests we need to develop the evidence base dealing with the impact of climate change on soils, and consider what might be done to ensure that our soils are resilient in the face of a changing climate.

Given this background an initial broad, policy relevant question that suggested itself as a starting point for a systematic review in this area was:

> ***What kinds of soil management interventions will protect the integrity of soils, given likely patterns of climate change?***

At the outset we recognised that this was such a broad issue for a systematic review that the study would have to possibly break it down into a set of more specific questions. Thus from our reading of this document and more general experience in this area a more focused set of questions were suggested through the discussion forum (Table 2.1).

In Table 2.1 the questions shown in italics are the examples proposed to stimulate discussion. Those questions not in italics are those suggested by the consultees. During the scoping stage there was no attempt to make their form correspond to that used in a systematic review; the main purpose of the consultation was to explore the subject areas of interest in a policy context.

In relation to the soils theme one consultee endorsed the relevance of the questions initially proposed and suggested a number of further issues, namely the resilience of soils to loss of soil carbon and release of Green House Gases (GHG). Although not framed as a set of questions, another consultee suggested that an important focus for review in this area could be the soil biota and its critical role in governing soil function. The specific areas suggested for investigation were the relationships between 'biomass vs diversity', 'the importance of the community configuration, community conditioning' and how these properties might be managed. However, they also cautioned that any investigation should be careful to note the different meanings that surround the resilience concept and be clear about what particular aspect of resilience is being investigated.

2.1.2 Biodiversity

No additional questions on biodiversity were proposed through the consultation process, although the one respondent who added comments in this area confirmed that the initial questions posed were relevant. However, they doubted that there was sufficient literature available to review most of them. Although the question on ecological networks was considered particularly timely. However, given the 'Lawton Review' that was being undertaken at the time of this study[2], it was agreed that this topic should be avoided to prevent duplication of effort.

In relation to climate and biodiversity, the study by Mitchell et al. (2007) on the England Biodiversity Strategy and adaptation to climate change was noted. It was suggested that the tabulation of vulnerabilities of the UK Broad Habitats to climate change provided by this study that was based on expert judgement could be followed up through systematic review – but again there were some doubts about the volumes of literature available. On the basis of our inspection of these materials, one strategy might be to investigate first those areas considered to be at the high or medium risk, in terms of ecosystem function; about 19 habitats fell into this category. The suggestion for a follow-up study to that of Mitchell et al. (2007) confirmed the general question posed by the study team in this topic area, namely:

> ***Which ecosystems are most vulnerable to climate change and what can be done to protect the biodiversity and ecosystem services associated with them?***

2.1.3 Water

The document *Future Water* (Defra, 2008) has set out a strategy for ensuring the sustainable delivery of water supplies in England, and what steps are needed both to improve and protect the water environment. The strategy deals with a number of issues affecting both supply and demand, and from our reading of this publication we suggested the following broad question as the basis for discussion:

> ***How can we best protect the capacity of England's major ecosystems to supply and regulate the quantity and quality of water?***

In response it was suggested that a primary focus for review might be the resilience of ecosystems at the catchment scale, and what types of land management strategy might best deliver a range of ecosystem services, including water quantity and quality. It was also suggested that in general terms, policy makers needed to understand better the 'connectivity between environmental compartments', and that land and water managers needed better tools for understanding the interactions between ecosystems. None of the additional comments obtained through the forum were, however, in a form that could easily be used as the basis of a systematic review and further refinement of thinking was needed in this area in the main phase of the study.

2.1.4 Air quality

Only one additional question was suggested as a result of the consultation process in relation to air quality. Our initial broad question was:

> ***How resilient are England's major ecosystems to changes in air quality and how might this change under future climates?***

and the more detailed variants used to stimulate discussion are shown in Table 2.1. The additional topic suggested dealt with the effects of interactions between ozone and climate change.

The questions identified in this topic area concerned the impacts of changes in air quality on ecosystems, rather than the regulation of air quality by ecological structures and processes. This perspective was suggested by the discussions at the initial kick-off meeting and the more general

[2] http://www.defra.gov.uk/environment/biodiversity/documents/201009space-for-nature.pdf

policy concerns expressed in the recent document *Air Pollution: Action in a Changing Climate* (Defra, 2010a). The latter noted that while compared to human health effects, the damage caused by air pollution on ecosystems may be less obvious and more difficult to quantify and monetise, but it nevertheless remains important. Issues include the impacts of sulphur and/or nitrogen deposition when critical loads for acidity are exceeded.

2.1.5 Economic Values and Well-Being

Ideas about ecological resilience, economic values and human well-being are currently being widely debated by the policy and research communities. As the work undertaken through international studies such as TEEB has argued, biodiversity may in fact have an 'insurance value', and serve to buffer society against the impacts of sudden shocks or disturbance. The case of mangroves in protecting coastal areas from damage due to tsunamis is often quoted as an example in the international literature. In the UK it is accepted that appropriate land management may also mitigate the risk of flooding or other hazards.

Following the discussion at the kick-off meeting it was suggested that one area that might be explored was the extent to which ecosystems can provide some kind of buffering or insurance service to society, and how this might change under future climates. From a policy and management perspective it is clearly important to know both what the costs associated with promoting or maintaining resilience are, as well as the size of the resulting benefits of any intervention. Thus the following general question was therefore posed in the discussion forum:

> ***How might climate change affect the capacity of England's major ecosystems to buffer human well-being against shocks or disturbances?***

However, no comments from the e-forum were received. Compared to the other topic areas being explored in this study the capacity of ecosystems to buffer communities against environmental shocks and disturbances and the implications for people both in monetary and non-monetary terms is a more wide ranging issue. It would take in the whole spectrum of regulating services potentially provided by ecosystems. It was concluded that if a systematic review was to be undertaken in this area, it would be useful to consult further to prioritise which of the many areas might be looked at, or consider whether any literature exists in relation to the economic or other benefits arising from the main regulation services provided by UK ecosystems. The topic was therefore dropped from the present study, although it was decided to look at whether in relation to the other four topic areas, there was any associated material dealing with economic issues, and whether any insights into changing values could be derived.

2.1.6 Conclusions arising from the scoping work

Although the questions posed in the discussion forum did not conform to the structure needed to undertake a systematic review, it was clear from the preliminary work that an investigation of a broad range of issues linked to notions of resilience would be of general relevance to current policy debates. Any systematic review is, however, limited by the volumes of material available, and so while the identification of policy relevant questions is important; they must also be looked at in relation to the extent of the evidence base. We therefore turned to look more closely at what resources were available and how they might be accessed efficiently.

2.2 Development of search protocols for the knowledge mapping and review

With the structure of the type of question needed for a systematic review in mind, a series of search protocols to cover the cross-cutting issues of resilience and environmental change were developed and tested.

To ensure that the results of the reviews in the different topic areas could later be integrated, a hierarchical or tiered approach was proposed, involving extracting a common set of studies that make reference to 'resilience' or one of its synonyms, that could be used in conjunction with general descriptors of some aspect of environmental or climate change and management intervention.

Table 2.2: Synonyms and associated concepts used to create common search strings

Concept	Synonyms and associated concepts
Resilience:	*resilience, resilient, adaptation, adaptability, adaptive, resistant, resistance, threshold, vulnerable, vulnerability, recover, recovery, stability and variability, durability and threshold, limit, resistance.*
Environmental change:	*Climate change, climatic change, global warming, environmental change, land use change, shocks, extreme events, outbreaks, disturbances.*
Intervention:	*Manage, management, restoration, restore, conserve, conservation, protect, protection, remediate, remediation, intervene, intervention.*

Table 2.3: Results of pilot study using common search strings

Search	Concepts	Search Strings - Web of Science (incl. conference proceedings)	Hits
A1	Resilience	TS=(resilien* OR adapt* OR resistan* OR threshold* OR vulnerab* OR recover* OR stability OR variability)	>100,000
A2	Environmental change	TS=(climat* change OR global warming OR environment* change* OR land use change* OR shock* OR extreme event* OR outbreak* OR disturbance*)	>100,000
A3	Management	TS=(manage* OR restor* OR conserv* OR protect* OR remediat* OR interven*)	>100,000
A4	Combined	TS=(resilien* OR adapt* OR resistan* OR threshold* OR vulnerab* OR recover* OR stability OR variability) AND TS=(climat* change OR global warming OR environment* change* OR land use change* OR shock* OR extreme event* OR outbreak* OR disturbance*) AND TS=(manage* OR restor* OR conserv* OR protect* OR remediat* OR interven*)	27,994

Search date – 2010/05/28: Databases=SCI-EXPANDED, CPCI-S Timespan=All Years, All searches, unless otherwise explicitly stated, are conducted using the "Topic" field tag (denoted as TS). The "Topic" field tag includes searches within Title, Abstract, Keyword and Keyword Plus fields within Web of Science.

The concepts that were common to each of the topic areas form the top tier of the proposed search strategy. The subject specific searches could then be nested beneath them as appropriate. In this way the separate topic reviews could effectively draw from the same 'virtual' database if they each used the same search engines.

Our initial review of the resilience literature and the set of documents identified as setting the broad policy context were used to develop a set of synonyms and associated terms for the key concepts (Table 2.2). For resilience, *associated* terms such as threshold and limit were included because these ideas are often used in conjunction with the more theoretical discussions that surround the resilience concept, and it was thought that they might potentially identify papers that could provide further insights. The development of the search terms and synonyms followed an iterative process of testing that involved reviewing a random but small number of the publications identified with a view to identifying additional search terms and synonyms or deleting or modifying existing ones.

Using Web of Science as the test-bed, the search strings for the individual concepts were found to identify very large numbers of studies (>100,000). However, when they were combined (Table 2.3) a set of about 28,000 references was extracted. Although this was still large, it was taken as a potentially suitable pool from which the more topic specific papers could be derived.

As a test of the approach during the pilot phase, a set of more focused searches from this large pool was made using subject specific terms (e.g. 'soils', 'biodiversity', 'water', 'air quality') **and various inclusion or exclusion criteria, such as studies only dealing with terrestrial ecosystems or location of an empirical investigation**. These subsets were used both to check the relevance of the material to the broad questions identified during the scoping phase, and the extent to which independent experts agreed on their inclusion within some kind of analysis.

The pilot results were as follows:

- For ***soils,*** a subset of around **500** papers were identified within which the most frequently investigated topics were changes in soil organic carbon and GHG emissions in relation to land use change, and how different agricultural practices (e.g. tillage or no tillage) impact the physical properties of soil and aggregate composition.
- For ***water,*** a subset of **1100** was identified. The topics covered by the material included the effects of ecosystem modification on flood risk, environmental or management impact on river regimes, eutrophication management and risk assessment in relation to water quality and quantity.
- For ***biodiversity,*** a subset of around **450** papers was identified. The subject was taken to include species diversity, ecosystem diversity, morphological diversity and genetic diversity at a range of scales; marine and coastal systems were however excluded from the analysis. The analysis suggested that the most common subjects considered were the responses of biodiversity (across all its definitions) to disturbances. The majority of these disturbances were anthropogenic and most of these were single factor impacts with few studies examining the confounding effect of multiple disturbances on biodiversity. Promoting biodiversity, through land management practices and conservation, and restoration or regeneration studies made up the next major component of the literature.

- For ***air quality,*** a subset of **400** papers was identified. A scan of a sample of these suggested that three themes were common, namely: the effects of disturbance on CO_2 flux in terrestrial ecosystems and the effects of elevated CO_2 levels for biomass production; the impact of nitrogen compounds including ammonia, on ecosystems; and, the effects of phosphorous and heavy metal deposition.

Again, although the subsets identified were still quite large, they were considered to be of manageable size to be useful in the systematic review process.

In the chapters that follow the form of the final search strings varied in some cases from those shown in Table 2.2, as seemed appropriate given the particular area being considered. It was found, for example, that the management string was too general to be applied across the board and that in the case of soils, for example, more topic specific concepts like 'tillage' were needed. Elsewhere other search and exclusion criteria had to be introduced to constrain the search outcomes. The application of the general search terms is therefore discussed in more detail in the four specific topic areas described in the subsequent parts of this Report. An assessment of the general search strategy and the extent to which it was possible to develop a common search strategy is given in the final Chapter.

2.3 Wider consultation

Following the preparation of a draft of the knowledge mapping and reviews in each of the four topic areas, two further rounds of consultations with subject experts was undertaken. The aim of the exercise was to examine whether they felt the searches were sufficiently comprehensive, and subsequently whether they felt the balance between issues suggested by the searches was appropriate. Their comments on the initial draft text have, where possible, been built into this finalised version.

3. Soils and their resilience to climate change impacts

By Roy Haines-Young, Marion Potschin and Gabriella Silfwerbrand

3.1. Background

The background to the issue of soils and resilience was provided by the *Soil Strategy for England* (Defra, 2009). This document sets out the aim that all soils will be managed sustainably and degradation threats tackled successfully by 2030. The *Strategy* argues, in particular, that we have to better understand the impact of climate change on our soils and identify what must be done to enable them to adapt. To do this the *Strategy* suggests we need to develop the evidence base dealing with the impact of climate change on soils, and consider what might be done to ensure that our soils are resilient in the face of a changing climate.

The resilience concept has been used in the context of understanding the functioning of soils and how they might respond to various types of disturbance. Greenland and Szablocs (1994) in their book on *Resilience and Sustainable Land Use*, report on a meeting designed to address the challenges of AGENDA21, which looked particularly at degradation of soils through inappropriate land management. In their introduction they suggest that resilience is simply 'the soil's ability to recover after disturbance'. Szabolcs (1994, p.36) refines this idea further by suggesting that soil resilience includes all the processes that enable soils to 'counteract stress and alterations' such as the buffering capacity of soils in respect to physical, chemical and biological impacts. The definition is broadly endorsed by Blum and Aquilar Santelises (1994) in the same volume. However, neither paper attempts to explore the ambiguity that is apparent in the definition which clearly conflates ideas both about speed of recovery after disturbance and resistance to change.

The subsequent reviews by Seybold et al. (1999) and Herrick (2000) attempt to draw a clear distinction between the two ideas and proposes two distinct attributes of soil, namely *soil resilience* and *soil resistance*, with the former being used only to refer to recovery following disturbance. Both, these authors argue, are fundamental to understanding the broader idea of soil quality, which Seybold et al. (1999) define (following Karlen, 1999) as 'the capacity of a specific type of soil to function, within natural or managed ecosystem boundaries, to sustain plant or animal productivity, maintain or enhance water and air quality, and support human health and habitation'. These authors go on to suggest that both are dependent of soil type and vegetation, climate, land use, disturbance regime and spatio-temporal scales, and identify the relationships between the major types of soil function and the recovery processes or mechanisms that underpin them (Table 3.1). More recently Lal (2004, 2009), Orwin and Wardele (2004), Orwin et al. (2006) and Kuan et al. (2007) have taken similar positions.

Table 3.1: Soil processes and associated recovery processes (after Seybold et al. 1999)

Soil functions and associated recovery processes or mechanisms

Soil function	Recovery processes or mechanisms
Nutrient cycling	Biological activity, biological diversity, plant growth
Partitioning of water	Soil fauna activity (earthworms, termites, etc.), shrink-swell cycles, freeze-thaw cycles, and plant growth, aggregation processes, vegetation establishment.
Productivity	C sequestration, aggregation processes, nutrient cycling, biological diversity.
Water storage	C sequestration, aggregation processes, biological activity
Decomposition	Biological activity
Absorbing and detoxifying pollutants	Biological activity, C sequestration, biological diversity, mineral weathering, clay formation
Nutrient supplying capacity	Biological activity, mineral weathering, nutrient cycling

The importance of distinguishing between 'resistance' and 'recovery' in the context of discussions about the resilience of soil systems has also been emphasised in the recent study commissioned by Defra, which has explored the evidence about what makes soils more resilient to change and the extent to which resilience can be conferred to soils[3] (Stuart, 2010 pers. Com.). This study noted the importance of making a distinction between ideas about resistance and recovery, and the potential confusion that sometimes surrounds the term resilience, especially when it is used in a policy context. It concluded that when dealing with these general issues it is important to describe precisely the nature of the disturbance the intrinsic and extrinsic soils factors and the time-scales being considered.

Robinson et al. (2009) note that soil quality defined in terms of soil productivity and functionality is essentially 'soil-centred' and have argued that it is useful to consider other conceptual frameworks, such as that of 'natural capital'. They suggest that a definition of soil natural capital is needed that fits with broader work on ecosystem services that is now developing, so that the contribution soil systems makes to human well-being can be valued. For them, soil natural capital is defined in terms of quantitative and qualitative soil properties related to mass, energy and organisation/entropy, which may be either fixed or dynamic. The integrity of soil as natural capital is they argue, essential in maintaining many of the supporting services associated with ecosystems more generally. Following Andrews et al. (2004) they identify the supporting soil functions, or ecosystem services that contributing to productivity, waste recycling, and environmental protection, namely nutrient cycling, water relations, physical stability and support, filtering and buffering, resistance and resilience, plus diversity and habitat.

Whether one regards the concepts of resilience or resistance from a soil quality or natural capital perspective, the way soils reacts to and recovers from disturbance is critical in the context of sustainable management. If we are to appreciate the potential impacts of climate change on soils then we need to better understand how changes in the different parameters of climate can affect the dynamic characteristics of soils and so transform soil function thereby modifying the way they resist and react to disturbance. The aim of this review is to take stock of some of the key literature on the topic, and to examine how climate change might modify the supporting services associated with soils and what we might do to mitigate those effects.

3.2. Objectives

If we take the *Soil Strategy for England* (Defra, 2009) as setting the broad framework for this study then the general, underlying issue or objective that needs to be explored is:

> ***Can soil management enhance, restore or protect the resilience or resistance properties of soils, given the likely impacts of climate change?***

As noted in Chapter 1, this is a very 'open-framed' question and probably unsuitable as it stands for a systematic review even though it has been refined and recast in terms of soil-based issues. The question does not, for example, specify what aspects of soil management might be considered, nor does it specify what soil dynamic characteristics need to be looked at and how sensitive they might

[3] http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=16978

be to changes in climate. Moreover it does not follow the conventional format of a question that can be used in a systematic review because it combines issues about interventions and external drivers. Before we can understand, for example, the extent to which management can mitigate the effects of climate change, we need to know whether and by how much management might affect the resistance and resilience of soils controlling for any variation in climate. Furthermore, we also need to know how large the potential effect of climate on soils might be before we can make any judgements about the efficacy of any mitigation effects that management might have.

3.2.1 Primary objective

Given the open-framed character of the question discussed above, the primary objective of this study must be to develop strategies for refining it, or of breaking it down into a series of simpler, more tractable components that might be addressed using the tools of a systematic review. The complexity of the task may be seen by inspection of Table 3.2, which attempts to represent the initial question using the formal elements of a potentially reviewable question (Centre for Evidence-Based Conservation, 2010). Table 3.2 also indicates the kinds of experimental or observational design that might potentially yield evidence to answer the question.

Table 3.2: Definition of generic components of a potential systematic review question for soils

Subject (Population)	Dynamic properties of soils that are sensitive to climate change
Intervention	Soil management, land use change, climate change
Outcome	Changes in the ability of soils to resist or recover from disturbance OR changes in soil properties likely to make soils more vulnerable to disturbance
Comparators	Land management regimes or different land use change events
Designs	Any studies comparing 'climate-sensitive' response of soils to disturbance under different management regimes, or any studies comparing soil properties likely to modify their vulnerability to disturbance under different management regimes

Each of the question components clearly need to be broken down further if any aspect of these issues is to be investigated by means of a systematic review. While this may produce a large array of related questions, this kind of strategy is one that is used when tackling these interesting but open-ended topics, and where the first task is to map the knowledge domain rather than review it in detail. The construction and review of such a knowledge map for soil resilience, land management and climate change is therefore taken as the primary objective of this study.

3.2.2 Secondary objective

As noted in the general introduction to this study, discussions about resilience are particularly relevant in the context of current attempts to value ecosystem services in monetary terms. If soils are able to resist disturbance or recover from it rapidly then this may, for example, have some kind of insurance value in the face of damage that might be caused by future shocks arising from climate change. Although it is acknowledged that few studies have probably been made on valuing marginal changes in soil resilience and resistance, it was considered useful for this study to examine what work is available and what conclusions might be derived from it. Thus the secondary objective of this study is to examine the question are management interventions for soil resilience or soil resistance cost effective?

3.3 Methods

3.3.1 Question formulation

The initial question relating to soils was refined through discussion on the RECCE website, through consultation with the Advisory Group established by Defra for RECCE, and through input from invited experts. The initial steer from the Advisory Group was that the work might look at soil resilience from the perspective of sustaining the supporting services that are provided by soils. From the expert advice we received the importance and relevance of this approach was confirmed. It was suggested that the impact of climate change in particular is a relevant and urgent area to study and some of the effects can be studied through heating studies in soil patches or fields, and altered precipitation rates on covered soil systems that can modulate precipitation rates.

In interview with the invited expert (see Appendix 1), the problem of defining resilience was discussed and it was confirmed that generally the idea was used to refer both to the time it takes for a system to return to an earlier state, and from the perspective of the resistance of soils to various drivers of change. Thus discussion of resilience also linked to questions of how 'fragile' or 'brittle' a given soil system might be. Given the complexity of the topic the advice was that to understand the properties and processes of soil, the review would have to consider a wide spectrum of variables. The soil bio-community might be regarded as the most sensitive marker of the dynamics in a soil ecosystem type, since it both depends on and drives other variables (cf. Harris, 2009; Barrios, 2007). It was felt that there is on-going work in the area of soil biology and soil stability although it is still somewhat limited. On the other hand, the expert advice suggested that there is possibly more solid data underpinning the proposition that microbiota are essential for the physical and chemical properties of soil such as the nutrient cycling. Clearly both points could be tested by the present study.

In terms of developing the search strategy the expert advised that the inherent properties of soils that were important in the context of the supporting services associated with soils can be measured through components that are commonly included in experimental soil studies, such as porosity, bulk density, and nutrient retention. Other indicators of soil functioning and transient properties are also important however, because they are more sensitive to management changes. Soil Organic Matter (SOM) was suggested as a good indicator of soil functioning, although it is a slow variable and thresholds may be passed before the impacts are noticed by management.

3.3.2 Search strategy

Relevant published research articles were identified through searches of the following electronic databases:

- ISI Web of Science
- Scopus
- Science Direct

To standardise the review with the other parts of this study, we used the generic strings discussed in the introduction to cover the concepts related to 'resilience' and 'climate change'. These were used together with a more specific set of terms designed to identify empirical papers and to explore the set of papers identified as being those relevant to soils. The results are summarised in Table 3.3.

Table 3.3: Search strategies designed to identify papers dealing with soil resilience in the context of climate change

ID	Strategy	Search string	Number
	Scopus		
S1	*All papers using terms soil and climate change or global warming in their abstract*	ABS(soil* AND "clim* change" OR "global warming")	5360
S2	*All papers using terms soil and climate change or global warming in their abstract along with resilience synonyms in their abstract*	(ABS(soil* AND "clim* change" OR "global warming")) AND (ABS(resilien* OR recover* OR stab* OR vulnerab* OR sensitiv* OR resist*))	1554
S3	*All papers using terms soil and climate change or global warming in their abstract and resilience terms in their keyword field*	(ABS(soil* AND "clim* change" OR "global warming")) AND KEY(resilien* OR recover* OR stabil* OR vulnerab*)	336
S4	*Subset from S3 of empirical, journal articles*	(ABS(soil* AND "clim* change" OR "global warming")) and (KEY(resilien* OR recover* OR stab* OR vulnerab* OR sensitiv* OR resist*)) and (ALL(evidence OR empirical OR assessment OR quantification* OR sampl* OR experiment*))	297
	Web of Science		
WS1	*All papers using terms soil and climate change or global warming in their abstract*	TS=(soil*) AND TS=("clim* change" OR "global Warming")	7377
WS2	*All papers using terms soil and climate change or global warming in their abstract along with resilience synonyms in their abstract*	TS=(soil*) AND TS=("clim* change" OR "global Warming") AND TS=("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*")	2330
WS3	*All papers using terms soil and climate change or global warming in their <u>title</u> field*	TS=(soil*) AND TS=("clim* change" OR "global Warming") AND TS=("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*")	335
WS4	*Subset from WS3 of empirical, journal articles*	WS3 and TS=(evidence OR empirical OR assessment OR quantification* OR sampl* OR experiment*)	139
	Science Direct		
SD1	*All papers using terms soil and climate change or global warming in their abstract*	(ABS(soil*) AND ("climate change" OR "global warming"))	7710
SD2	*All papers using terms soil and climate change or global warming in their abstract along with resilience synonyms in their abstract*	ABS((soil*) AND ("climate change" OR "global warming") AND ("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*"))	342
SD3	*All papers using terms soil and climate change or global warming in their abstract and resilience terms in their keyword field(s)*	ABS((soil*) AND ("climate change" OR "global warming")) AND (specific-authkey("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") OR specific-otherkey ("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*"))	43
SD4	*Subset from SD3 of empirical, journal articles*	WS3 and ABS(evidence OR empirical OR assessment OR quantification* OR sampl* OR experiment*)	17

Table 3.4: Search strategies designed to identify papers dealing with soil resilience in the context of management

ID	Strategy	Search string	Number
	Scopus		
S5	*All empirical papers using terms soil and manage* and till* in their abstract plus resilience synonyms*	(ABS(soil* AND "manag*" OR "till*")) AND (KEY(resilien* OR recover* OR stab* OR vulnerab* OR sensitiv* OR resist*)) AND (ABS(evidence OR empirical OR assessment OR quantification* OR sampl* OR experiment*))	1108
S6	*All empirical papers using terms soil and manage* and till* in their abstract plus resilience synonyms in KEYWORDS, PLUS* reference to specific soil properties	(ABS(soil* AND "manag*" OR "till*")) AND (KEY(resilien* OR recover* OR stab* OR vulnerab* OR sensitiv* OR resist*)) AND (ABS(evidence OR empirical OR assessment OR quantification* OR sampl* OR experiment*)) AND (ABS(carbon OR "organic matter" OR respiration OR nutrient* OR micro*))	463
	Web of Science		
WS5	*All empirical papers using terms soil and manage* and till* in their abstract plus resilience synonyms*	TS=(soil*) AND TS=("manage*" OR "till*") AND TS=("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") AND TS=(evidence OR empirical OR assessment OR quantification* OR sampl* OR experiment*)	5368
WS6	*All empirical papers using terms soil and manage* and till* in their abstract plus resilience synonyms in their TITLE, plus* reference to specific soil properties	TS=(soil*) AND TS=("manage*" OR "till*") AND TI=("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") AND TS=(evidence OR empirical OR assessment OR quantification* OR sampl* OR experiment*) AND (TS=(carbon OR "ORGANIC MATTER" OR respiration OR nutrient* OR micro*))	352
	Science Direct		
SD5	*All empirical papers using terms soil and manage* and till* in their abstract plus resilience synonyms in their KEYWORDS*	ABS((soil*) AND ("manage*" OR "till*")) AND (specific-authkey("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") OR specific-otherkey ("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*"))	384
SD6	*All empirical papers using terms soil and manage* and till* in their abstract plus resilience synonyms in their KEYWORDS, plus reference to specific soil properties*	ABS((soil*) AND ("manage*" OR "till*")) AND (specific-authkey("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") OR specific-otherkey ("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*"))AND(ABS(carbon OR "organic matter" OR respiration OR nutrient* OR micro*))	169

The three search engines identified between 5000-7000 documents that included the terms 'soil' and 'climate change' or 'global warming' in their abstract. In order to reduce these large sets to subsets that reflected our primary and secondary objectives concern, the search sets were refined using the synonyms that we have identified for resilience. Initially we searched for the synonyms in the abstract and then the keyword fields of the record. The searches on the abstract field for resilience terms produced subsets of over 1000 papers, and so it was decided initially to use the stricter condition of the words appearing as a keyword. Finally the general search terms designed to identify 'empirical' works was applied. This strategy produced subsets for Scopus, Web of Science and Science Direct of 297, 139 and 17 papers respectively. Although elimination of papers using these criteria seemed particularly harsh for Science Direct it was felt that overall the number of references identified using this sequence was manageable for an initial assessment. Thus the three subsets were downloaded into EndNote. After duplicates and all types of publications other than journals were eliminated, the combined set of 453 records was reduced to 386.

The selected set was screened for relevance, first on the basis of title, then through a reading of the abstract. Given that the 'empirical' search terms were only intended to helping to make the 'first cut', the manual screening was designed to eliminate papers which were not empirical (i.e. reviews or modelling studies) and to categorise papers according to whether they were based on experimental or observational evidence. Using these procedures a final set of 135 empirical papers dealing with some aspect of soil resilience in relation to climate change was identified; we will refer to this set of papers as, the '**Climate-Soil-Resilience'** subset, **CSR**. The inclusion/exclusion criteria are discussed in more detail below.

A preliminary inspection of the CSR subset suggested that relatively few dealt with soil management, and so to establish the wider context a second search protocol was set up to look more closely at the literature dealing with aspects of resilience in the context of management or tillage regimes. The results are shown in Table 3.4

The same three search engines were used, together with the same search strings designed to identify empirical papers dealing with resilience. The searches only differed from the earlier set in that the terms 'climate change' and 'global warming' were substituted by the terms 'manage*' and 'till*'. Since Scopus and Web of Science yielded a potentially large number of papers for consideration a further qualifier string was added that sought to identify papers dealing with a specific set of soil properties: 'soil carbon' and 'organic matter', 'nutrient*' and microbiological characteristics ('micro*'). In part these qualifiers were selected on the basis of the advice of the soils expert. The selection was also informed from the preliminary screening of the CSR subset in order to focus on the kinds of soil property papers dealing with the impacts of climate change.

Using the three search engines a set of 645 empirical papers dealing with aspects soil resilience for the selected soil properties in the context of some kind of management intervention were identified after the elimination of duplicates and non journal articles using EndNote. We will refer to this set of papers as, the '**Management-Soil-Resilience'** subset, **MSR**. The inclusion/exclusion criteria for this subset are also discussed in more detail below.

3.3.3 Study inclusion criteria

For a study to be included in the review it was required to meet the following criteria:

Relevance: empirical studies from any part of the world dealing with some aspect of soil resilience (resistance to change or recovery from disturbance) were to be considered, providing they either linked soils to changes in some climate parameter or some change or difference in management practice or intervention. Only studies designated as 'journal articles' by the search engines with titles and abstracts in English, were included. No geographical restriction was applied[4].

Types of intervention: as noted above, the topic selected for review was a complex one, involving an investigation of the extent to which management might mitigate the impacts of climate change on the resilience of soils. Thus papers were included if they included consideration of one or both types of intervention (i.e. a change in some climate parameter or a change in some management regime). Since the pool of soil management papers was found to be large, the types of management intervention were restricted to a subset of soil properties, namely soil carbon and 'organic matter', nutrient cycling and microbiological characteristics.

Types of outcome: quantitative measurements of the degree to which a defined soil property is either buffered against the management or climate impact, or recovers following some disturbance related to either of these two factors. Outcomes had to be measurable in terms of some biotic or abiotic characteristic of soils; papers that looked at whole plant-soil, or plant measures were excluded.

Types of comparators and designs: both experimental (manipulative) or observational studies were considered relevant providing they made a controlled comparison of relevant outcomes under either different climate regimes (simulated or actual) or different management regimes. Observational studies based on spatial comparisons between sites having different climate or management regimes were included, as well as studies that looked at the impact of changes over time at a single site. Given the dual focus on climate and management, potential interaction effects may arise. Thus studies that compared either the response of different soil types under changed or contrasting management or climate conditions were also included.

The titles and abstracts of the articles in the CSR and MSR subsets were examined in EndNote, and those meeting the criteria for inclusion were identified. These were downloaded into an Excel spreadsheet for further analysis and coding. Although selection from the CSR and MSR sets was undertaken by a single reviewer, levels of potential bias were tested in the early phases of the study when the effectiveness of the initial search protocols were being tested. Using a set of 514 papers extracted using Web of Science for soil resilience papers and climate change effects, two independent reviewers showed moderate agreement (Cohen's Kappa= 0.49, after Fleiss, 1981) on the selection of papers using the inclusion criteria discussed above based on title and abstract.

3.3.4 Study quality assessment

Basic information relating to the quality of the individual studies was extracted for the articles in the CSR and MSR subsets. Although these studies had already met the inclusion criteria outlined it was considered important to examine them more closely to determine what kinds of experimental or observational design underpinned the evidence that they provided. Although evidence generated

[4] Note some studies were initially identified as meeting the inclusion criteria because they had English titles and abstracts, but were later excluded when the full paper was inspected on grounds that the main text was not in English.

from Randomised Controlled Trials (RCTs) is to be preferred in any systematic review, in the environmental arena such demanding experimental designs cannot always be used. For example, given the nature of the data that can be collected, and the problems of long time lags between treatments and outcomes, observational studies have to be made involving comparisons against some assumed baseline.

Although a number of generic quality criteria have been suggested (e.g. Thomas et al., 2004), the *Guidelines for Systematic Review in Environmental Management* (Centre for Evidence-Based Conservation, 2010) suggests that it is generally more appropriate to devise a set of *a priori* review-specific assessment criteria that can be used to assess the quality of methodology used by the studies considered for review. Given that the investigation of soil resilience implies an understanding of the response of some component of the soil system over time (e.g. how sensitive it is to disturbance, or how quickly it recovers from disturbance), it was felt that the way the study dealt with the temporal dimension was important. Moreover, given that the ability to devise experimental interventions is more limited in the environmental sciences, it was also felt that it was important to distinguish between studies that used some kind of controlled manipulation of the soil system from those that merely observed the differences in soil properties between sites over space or time in the context of some specific disturbance or controlling factor. Finally studies involving site comparisons, rather than those that track the characteristics of sites over time, need to be identified. These studies are based on the 'ergodic' assumption that space can be substituted for time, and face the problem of how other confounding influences can be controlled for.

On the basis of whether a study is experimental or observational and whether it follows soil response using time or space comparisons, a four-fold classification of papers can be devised (Table 3.5). While generally experimental studies are to be preferred over observational ones, they are often limited in terms of the time span that can be considered. Within the observational group, however, those that consider changes to individual sites over time are probably superior to those that simply make spatial comparisons. The length of time over which changes in soil properties are considered is also a potentially important factor affecting the quality of evidence, although it is difficult to combine such information in any simple metric alongside that of overall design.

Table 3.5: Classification of soil resilience studies based on experimental and observational designs

	Experimental	Observational
Time comparisons	*Studies that manipulate some independent variable in a controlled way within a laboratory or field situation, and which follow the dynamics of some response variable over time*	*Studies based on artificial or 'natural' experiments, in which the management history of study sites is known and the present day state can be compared with some known or inferred baseline from the past (e.g. long-term management experiments, or chronosequences)*
Space comparisons	*Studies that simulate changes in independent driving variables by the translocation of an experimental system in a controlled way (e.g. moving soils between different climatic zones and comparing dynamics against baseline conditions)*	*Studies based on artificial or 'natural' experiments, in which the management history of study sites is known and the effects of treatments can be inferred from a spatial comparison (e.g. comparison of agricultural sites with natural cover, or making the ergodic assumption that space can substitute for time)*

In addition to experimental and observational investigations, model-based studies can also clearly make a contribution to knowledge. It was apparent from inspection of the papers that might be included in the review that some were either wholly or partly based on modelling techniques, and so these were noted, but initially excluded from the analysis.

3.3.5 Data extraction

For each study that met the inclusion criteria the following basic data were extracted and assembled in an excel spreadsheet.

Design: Whether the study was experimental or observational in design.

Dependent variable: The soil property or properties used to assess resilience.

Independent variable: In the case of the CRS set, this was the climate parameter used as in the independent variable in the comparison, whereas in the case of the MSR set, this was the type of management situation being considered.

Comparator: The type of comparison being considered, defined in terms of the independent variable.

Space or Time Perspective: Whether the study looked at differences in soil response over space or time.

Time-span considered: If time comparisons were involved, how long the time span being used to track the response was.

Resilience perspective: Whether the study provided insights into the ability of the soils system to resist disturbance or to recover from disturbance.

Ecosystem and Location: How the authors described the geographical context of the study.

3.3.6 Data synthesis

Given the diversity of experimental and observational designs encountered, no quantitative data were extracted from the included studies. Instead, it was decided to proceed initially with a qualitative synthesis of the materials and use this experience to identify appropriate sub-groups that could be used to make a quantitative synthesis. As noted in the introduction, our review question was a potentially wide ranging one, and part of the objective of this study was to identify which 'climate sensitive' soil parameters were being considered in current work and what is known about the way management interventions might modify them.

As part of the qualitative synthesis, therefore, the full text of the included articles was read and the outcomes reviewed in more detail. In doing so the papers were inspected to determine whether they contained sufficient information to make them suitable for a more detailed quantitative synthesis using the Comprehensive Meta-Analysis V2.0 programme[5]. The latter was available to the review team and provides a typology of 100 treatment formats that can be used to capture the statistical outcomes of experimental or observational studies. The typology was used to classify the treatment formats of the included studies. Following other recent systematic reviews we chose a threshold value of four studies measuring the same outcome in order to decide whether to pursue a meta-analysis for a particular soil attribute. The treatment format was only classified if it fell into a group of four or more studies.

[5] http://www.meta-analysis.com/

3.4 Results

3.4.1 Review statistics

The two sets of included studies, CSR and MSR contained 386 and 635 references respectively. These were constructed by combining the results from the three search engines using the search protocols shown in Tables 3.3 and 3.4. On inspection of their titles and abstracts, and applying the more stringent inclusion criteria discussed in Sections 3.3.2 and 3.3.3, 35% and 25% of each reference set were considered relevant, leaving 135 and 157 references to be taken forward for analysis.

3.4.2 Description of studies

Papers dealing with soil resilience and climate change

The basic data described in section 3.3.5 were extracted from the CSR set that were taken forward for close scrutiny, and 44 were identified as relevant[6]. Table 3.6 shows the characteristics of climate covered in the studies, cross-referenced by the resilience component being considered. Table 3.7a & b lists the soil characteristics covered in the studies and the independent, climate variables used as comparators. As these tables show, the majority of studies making reference to both climate change and soil resilience look at the issue of warming either alone or in combination with moisture availability, or in terms of the interaction of warming with acidification or productivity effects. The studies overwhelmingly appeared to consider resilience from the perspective of resistance to change, rather than recovery from disturbance. It should be noted however, that this was the interpretation made by the review team; sensitivity of some measurable parameter of the soil system to a warming effect was taken to represent resistance to change.

Table 3.6: Climate parameter cross-referenced by resilience component considered by included studies

Climate attribute	Recovery	Resistance	Resistance and Recovery	Grand Total
CO_2-conc		2		2
Extreme events related to water availability		1		1
Fires	2			2
Precipitation/drought		1		1
Rainfall		1		1
Rainfall intensity		1		1
Temperature and microbial community		1		1
Warming	2	27	1	30
Warming, moisture availability		2		2
Warming, water table		1		1
Warming vs acidification		1		1
Indirectly, via increased productivity		1		1

[6] Note we have not restricted the search to soils likely to be similar to those found in the UK because the focus was to discover how resilience concepts had been used.

A large range of soil properties were covered in the 44 studies (Table 3.7a). Since studies often considered more than one soil characteristic, the number of entries shown is larger than the number of studies; measures related to soil organic matter, soil organic carbon, decomposition for soil organic matter, soil respiration and CO_2 flux, were the most frequent. Comparisons of the effects of warming were mostly based on experiments or observations involving treatments based on manipulated or inferred temperature differences. Studies variously dealt with air and soil temperatures, and frequently looked at warming effects in conjunction with other climate or atmospheric parameters such as rainfall and elevated CO_2 concentrations (Table 3.7b). Studies considered the effect of climate on the capacity of soil to retain carbon (carbon storage) and the extent to which changes in climate might modify the ability of soil to take up additional carbon from the atmosphere (carbon sequestration).

Table 3.7 a&b: Soil Properties and experimental or observational comparators used in selected studies.

(a) Soil properties

Soil property	Count
Aggregate stability	1
C and N emissions	1
C cycling	1
C flux, soil microbiology	1
C loss, DOC	1
C-balance	1
C-dynamics and microbial activity	1
CO_2 flux from soil	3
C-turnover	2
Decomposition of old carbon	1
Decomposition of SOM	1
DOC production	1
Erodability	1
Forms of soil carbon, C:N ratio	1
Microbial, N-mineralisation and enzyme	1
Mycorrhizae, aggregate stability	1
N	1
N mineralisation, soil N and P	1
N-dynamics	1
Organic and inorganic N	1
Rhizosphere resp., decomposition, SOM oxid'n	1
SOC	2
SOC, age	1
Soil biotic processes	1
Soil moisture	1
Soil respiration	5
Soil respiration and C-loss	1
SOM	9
Grand Total	**44**

(b) Comparators used in studies

Comparator	Count
Aspect	1
Carbon pools	1
Ca rich and carbon poor landscapes, acidification	1
Climate gradient	1
Deglaciation and succession	1
Different forest types	1
Drought, heavy rainfall	1
Elevated CO_2	2
Elevation gradient	1
Fire frequency	2
Litter manipulation	2
Old and young carbon pools	2
Rainfall events of different intensity	1
Rainfall exclusion	1
Rainfall variability	1
Soil biology	2
Soil temperatures	3
Soil temperatures and depth	1
Temperature	1
Temperature (MAT) and forest type	1
Temperature and elevated CO2	1
Temperature and moisture availability	3
Temperature and rainfall	1
Temperature CO_2-conc, water availability	1
Temperature differences	3
Temperature gradient	3
Temperature, ambient	1
Temperature, drying-wetting, decomposition	1
Temperature, respiration	1
Temperatures, water level depth	1
Vegetation removal	1
Grand Total	**44**

Table 3.8: Management considered in the studies, cross-referenced by the resilience component

Management	Resistance	Recovery	Resistance and Recovery	Recovery threshold	Grand Total
Agricultural	46	15	1	1	63
Conservation		1			1
Forestry	5	1			6
Land use change	6				6
Grand Total	**57**	**17**	**1**	**1**	**76**

Table 3.9 a&b: Soil Properties and comparators used in selected studies

Soil Property	Count
Active C, N	1
Aggregates	22
Aggregates SOC, TN	1
Aggregates, bulk density, porosity	1
Aggregates, C, CO_2 loss	1
Aggregates, C, N	1
Aggregates, Labile C	1
Aggregates, resistance	1
Aggregates, SOC	3
Aggregates, soil quality	1
Aggregates, SOM	2
Aggregates, SOM, microbial response	1
C, microbial response	1
C, N storage	1
C-flux	1
Compressibility	1
Earthworm activity	1
Enzyme activity	2
Erodability	1
Erodability, SOM pH, erosion ratio, etc	1
Microbial response	4
Microbial response, C, N	1
Mycelial fungi	1
SOC	8
Soil loss and runoff	1
Soil quality	5
Soil structure	4
SOM	5
SOM, earthworms	1
SOM, TN, NOT, TP EC	1
TC, TN	1
Grand Total	**77**

Comparator	Count
Abandonment of cropping	1
Afforestation	1
Alpine pasture types	1
Arable/grassland	2
Biological/chemical characteristics	1
C additions	1
Compaction	1
Compost additions	1
Cover crops management	1
Cropping sequences	2
Cropping systems	2
Cultivated/Uncultivated	1
Different land use and management	1
Erosion control	1
Fertilisation	1
Forest conversion	4
Land use characteristics	1
Management systems	1
OM additions	1
One-time/Continuous	1
Organic vs inorganic farming	2
Rainfall intensity	1
Removal of manure inputs	1
Residue input	1
Tillage	37
Tillage and crop rotations	1
Tillage and cropping	1
Tillage and depth	1
Tillage and grazing on NT	1
Tillage intensity	2
Tillage, drainage	1
Tillage, stubble management	1
Vegetation type and management	1
Abandonment of cropping	1
Grand Total	**77**

Papers dealing with soil resilience and management

The basic data described in section 3.3.5 were extracted from the papers from the MSR set taken forward for close scrutiny, and 77 were identified as relevant. Table 3.8 provides a note of the characteristics of management considered in the studies, cross-referenced by the resilience component being considered. Table 3.9 a & b lists the soil characteristics covered in the studies and the independent, management variables used as comparators. As noted in section 3.2, the number of papers dealing with soil resilience and management was potentially large, and so the search was constrained by adding a string to select papers dealing with soil carbon and organic matter, nutrients and soil microbiological characteristics. The selection of these terms was informed by the results for the most frequently investigated soil characteristics in the climate studies (Table 3.7a).

In terms of the general type of management intervention, papers dealing with some type of agricultural practice were the most frequent, followed by the more general effects of land use change and forestry (Table 3.8). As with the climate studies, the majority of papers dealt with the sensitivity of some soil property to a disturbing factor, rather than the rate of recovery, although proportionally the latter was considered more often here than for the earlier set. The most frequently measured soil properties were aggregate stability, soil organic carbon and soil organic matter (Table 3.8a). Treatments related to different tillage regimes (especially no tillage vs tillage) were considered most often, together with the effects of forest conversion (Table 3.9b).

In terms of the general type of management intervention, papers dealing with some type of agricultural practice were the most frequent, followed by the more general effects of land use change and forestry (Table 3.8). As with the climate studies, the majority of papers dealt with the sensitivity of some soil property to a disturbing factor, rather than the rate of recovery, although proportionally the latter was considered more often here than for the earlier set. The most frequently measured soil properties were aggregate stability, followed by soil organic carbon and soil organic matter (Table 3.9a). Treatments related to different tillage regimes (especially no tillage vs tillage) were considered most often, together with the effects of forest conversion (Table 3.9b).

3.4.3 Study quality assessment

Table 3.10 a & b shows how studies were allocated into the four design categories used to assess the quality of items included in the CSR and MSR sub-groups (see section 3.3.4). In both cases the majority of the studies drew on spatial observations, and thus potentially were in the lowest quality class. The proportion of experimental studies was higher for the CSR subset, but the number of studies that looked at the impacts of climate on soils was roughly a quarter of that identified for management.

Table 3.10 a & b: Experimental and observation designs used in studies

(a) Designs used in studies considering soil resilience and climate (CSR subset)

	E	O	total
T	3	4	7
S	2	10	12
total	**5**	**14**	**19**

Note: Some (25) experimental studies did not consider time responses but only final differences and so are not included here

(b) Designs used in studies considering soil resilience and management interventions (MSR subset)

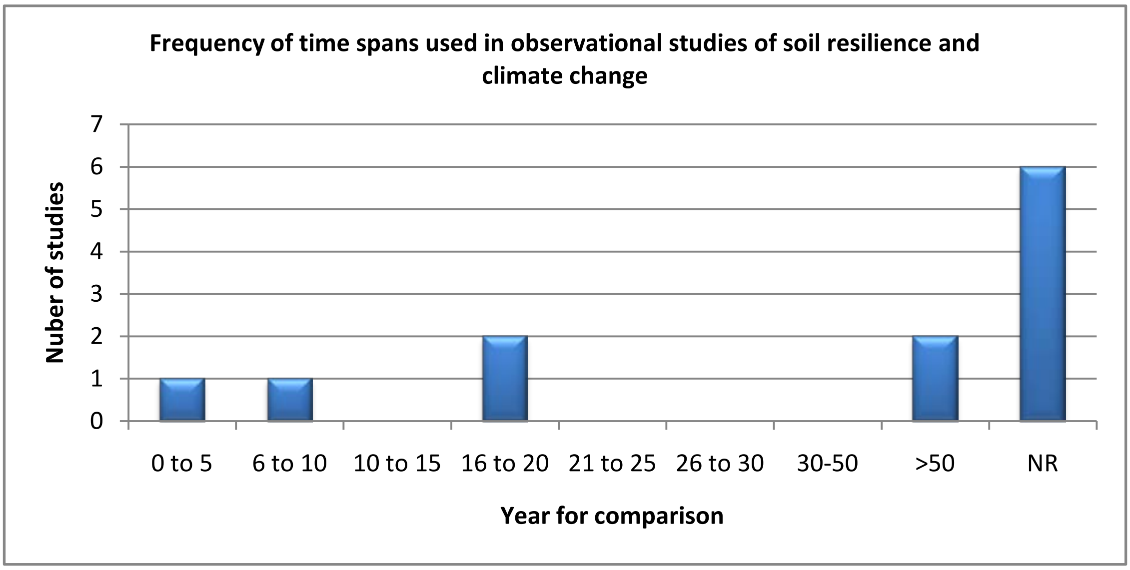
	E	O	total
T	4	15	19
S	13	44	57
total	**17**	**59**	**76**

Figure 3.1 shows the lengths of time over which comparisons have been made within the sets of observational studies identified in CSR and MSR. The latter include studies which considered a wide range of time spans, whereas the former is more restricted in its content. For the CSR group the large number of studies designated as 'NR' were those which only looked at spatial comparisons and did not make reference to the time over which the differences in treatments developed. Note, the number of studies in the management set differs from that shown in Table 3.6 because some studies included comparisons based on more than one time-span; these were treated as two instances for Figure 3.1, but only counted as one study in Table 3.6.

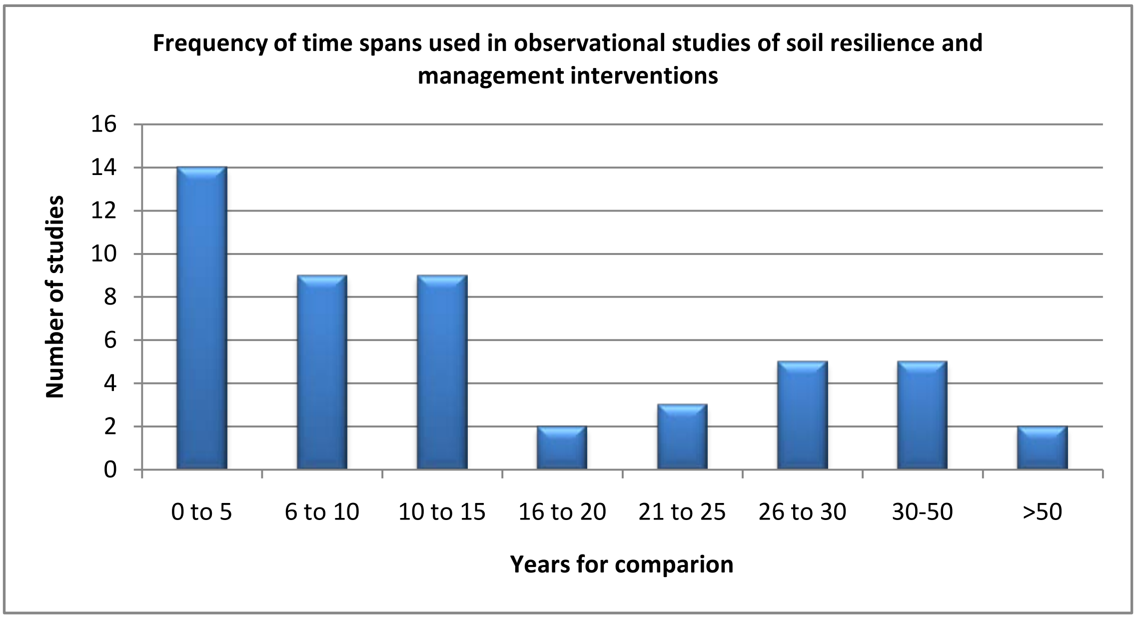
The analysis suggests that the studies included in the review fall at the lower end of the quality spectrum, in that they are mainly based on observed, spatial comparisons from which the effects of changes in independent variables related to climate or management have been inferred. The time periods over which effects have been considered however, are fairly long, so it might well be that the differences seen are potentially real ones. It was considered acceptable to proceed with the review on the basis of the studies identified. The fact that we are forced mainly to consider less easily controlled observational studies is not, however, unique to this study, but fairly common to all such reviews dealing with environmental systems.

Figure 3.1: Time spans considered in selected studies

(a) CSR



(b) MSR



3.4.5 Qualitative synthesis

At the outset it was recognised that the focal question 'can soil *management enhance, restore or protect the resilience or resistance properties of soils, given the likely impacts of climate change?'* was an open-framed one, which was unlikely to be answered simply through the process of a systematic review. Rather, it was suggested that the primary objective of this study should be to produce a knowledge map describing the relationships between the literatures on soil resilience, land management and climate change that could be used to develop more targeted investigations. The purpose of this qualitative synthesis is to construct such a mapping of concepts. In constructing this map we also draw upon a number of review articles identified during the literature search and/or referred to by the included studies.

Soil resilience and climate change

The analysis of soil properties considered by the included studies suggests that the sensitivity of soil carbon to temperature change was the topic investigated most frequently. As recent reviews have argued, a better understanding of the nature of this relationship is essential if we are to predict the response of the terrestrial carbon balance to climatic warming (Goh, 2004; von Lützow and Kögel-Knabner, 2009). Davidson and Janssens (2006) note, however, that considerable disagreement exists as to the effects of climate change on global soil carbon stocks. Put simply, if warming accelerates below-ground decomposition then there may be a net transfer of carbon to the atmosphere. On the other hand if productivity increases, and the carbon inputs to the soil exceed the increases in decomposition then the soil would become a sink for carbon, rather than a source.

A qualitative review of the papers from the CSR set that confirms the apparent sensitivity of soil carbon stocks to changes in temperature, with increased temperatures leading to higher decomposition rates (Table 3.11). However, the picture is complex, with significant interaction effects being reported. Thus there is evidence that the different carbon pools may vary in their sensitivity to warming, with the more easily mobilised (labile or active) stocks showing higher decomposition rates (Knorr et al., 2005), although there is some debate about the magnitude of the differences (e.g. Conen, 2006; 2008 a&b). There is also evidence that sensitivity may decrease over time as a result of acclimatisation (Luo et al., 2001 and Peng et al., 2009). Following a study of tall grass prairies in the US, Lou et al. (2001) report that temperature sensitivity of soil respiration appears to decrease under warming and that acclimatisation is greater at high temperatures. This is also evidence that sensitivity may decrease over time as a result of acclimatisation (Luo et al., 2001 and Peng et al., 2009). Following a study of tall grass prairies in the US, Lou et al. (2001) report that temperature sensitivity of soil respiration appears to decreases under warming and that the acclimatization is greater at high temperatures. This effect, they suggest, might weaken the positive feedback that is assumed to exist between the terrestrial carbon cycle and climate. The recent review by Schils et al. (2008) also seems to confirm that the relationship between temperatures and carbon storage may change under elevated CO_2 levels.

Table 3.11: Summary of literature dealing with effect of warming on soil function

Author	Year	Title	Soil Property	Climate parameter	Comparator	Where?	Is soil function sensitive climate parameter?
Briones et al.	2010	Soil biology and warming play a key role in the release of 'old C' from organic soils	C flux, soil microbiology	Warming	Soil biology	Peat soils, Pennines, UK	Yes, via increased biological activity
Briones et al.	2007	Invertebrates increase the sensitivity of non-labile soil carbon to climate change	SOM	Warming	Soil biology	NR	Yes, via increased biological activity
Cai et al.	2009	Rising temperature depletes soil moisture and exacerbates severe drought conditions across southeast Australia	Soil moisture	Warming	Temperature and moisture availability	Agricultural land, Murray Darling basin, Australia	Rising temperature depletes soil moisture and exacerbates severe drought
Cerdà	*2000*	*Aggregate stability against water forces under different climates on agriculture land and scrubland in southern Bolivia*	*Aggregate stability*	*Warming*	*Climate gradient*	*Agricultural land, Bolivia*	*The higher the mean annual rainfall the greater was the soil aggregate stability.*
Clark et al.	2009	Increased temperature sensitivity of net DOC production from ombrotrophic peat due to water table draw-down	DOC production	Warming, water table	Temperature and rainfall	Ombrio-trophic peat, North Pennines, UK	Interaction effects significant
Conant et al.	2008	Experimental warming shows that decomposition temperature sensitivity increases with soil organic matter recalcitrance	SOM	Warming	Temperature	Prairie Grassland, near Mandan, North Dakota	Yes, varies with soil carbon pool
Conen et al.	2008 b	Temperature sensitivity of young and old soil carbon - Same soil, slight differences in 13C natural abundance method, inconsistent results	SOM	Warming	Old and young carbon pools	NR	Yes, but differences between carbon pools not significant
Conen et al.	2006	Warming mineralises young and old soil carbon equally	SOC, age	Warming	Old and young carbon pools	NR	Yes, but differences between carbon pools not significant
Conen et al.	2008a	Relative stability of soil carbon revealed by shifts in delta N-15 and C N ratio	Forms of soil carbon, C:N ratio	Warming	Elevation gradient	Grasslands, Swiss Alps	NR
Egli et al.	*2010*	*Soil organic matter formation along a chronosequence in the Morteratsch proglacial area (Upper Engadine, Switzerland)*	*SOM*	*Warming*	*Deglaciation and succession*	*Pro-glacial, Swiss Alps*	*NR*
Egli et al.	*2009*	*Effect of north and south exposure on organic matter in high Alpine soils*	*SOM*	*Warming*	*Aspect*	*Alps, Italy*	*Yes, via increased biological activity*
Evans et al.	2007	Evidence against recent climate-induced destabilisation of soil carbon from 14C analysis of riverine dissolved organic matter	C loss, DOC	Warming vs acidification	Carbon rich and carbon poor landscapes, acidification effects	UK	No, other drivers significant (recovery from acidification)
Fissore et al.	2008	Temperature and vegetation effects on soil organic carbon quality along a forested mean annual temperature gradient in North America	SOC	Warming	Temperature (MAT) and forest type	Forest, North America	Yes in terms of quantity and quality
Fissore et al.	2009	Variable temperature sensitivity of soil organic carbon in North American forests	SOC	Warming	Temperature gradient	Forest, North America	Qualified yes, but vegetation dependent
Hakkenberg et al.	2008	Temperature sensitivity of the turnover times of soil organic matter in forests	SOM	Warming	Temperature gradient	Forest, Italian Alps	No, not for labile SOM
Hartley et al.	2008	Substrate quality and the temperature sensitivity of soil organic matter decomposition	SOM	Warming	Carbon pools	North Yorkshire	Yes, but substrate quality important

Table 3.11, cont: Summary of literature dealing with effect of warming on soil function

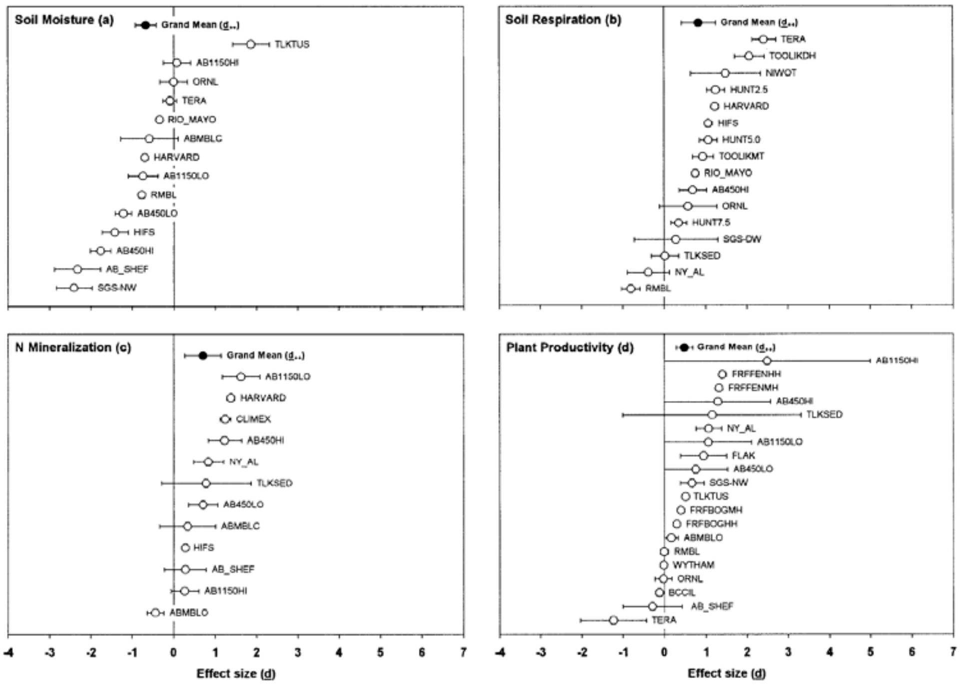
Author	Year	Title	Soil Property	Climate parameter	Comparator	Where?	Is soil function sensitive climate parameter?
Hashimoto	2005	Temperature sensitivity of soil CO2 production in a tropical hill evergreen forest in northern Thailand	CO2 flux from soil	Warming	Temperature differences	Boreal Forest soil, Thailand	Small, esp. at higher temperatures
Illeris et al.	2004	Moisture effects on temperature sensitivity of CO2 exchange in a subarctic heath ecosystem	CO2 flux from soil and vegetation canopy	Warming	Temperature and moisture availability	Sub-arctic dwarf shrub	Yes, but interaction with soil moisture
Jamieson et al.	1998	Soil N dynamics in a natural calcareous grassland under a changing climate	N-dynamics	Warming, rainfall and drought	Soil temperatures, moisture availability	Calcareous grasslands, UK	Summer rainfall had no direct effect on N mineralisation but reduced rates in autumn and winter. Summer drought increased N mineralisation in autumn and winter. Winter warming had no effect on N mineralisation in winter but decreased rates in spring.
Karhu et al.	2010	Temperature sensitivity of organic matter decomposition in two boreal forest soil profiles	SOM	Warming	Soil temperatures and depth	Forests, Finland	Yes, but depends on soil carbon pool
Koch et al.	2007	Temperature sensitivity of microbial respiration, nitrogen mineralization, and potential soil enzyme activities in organic alpine soils	Microbial respiration, N-mineralisation and enzyme activity	Warming	Temperature gradient	Alpine soils, Austria	Yes via enzyme activities
Lin et al.	1999	Elevated CO2 and temperature impacts on different components of soil CO2 efflux in Douglas-fir terracosms	Rhizo-resp, litter decomposition, oxidation of SOM	Warming	Temperature and elevated CO2	Douglas fir experimental system, fine loam soil samples	Yes for organic matter decomposition rates
Luo et al.	2001	Acclimatization of soil respiration to warming in a tall grass prairie	Soil respiration	Warming	Soil temperatures	Grass prairie Oklahoma, USA	Qualified yes, acclimatisation may reduce dependency
Mäkiranta et al.	2009	Indirect regulation of heterotrophic peat soil respiration by water level via microbial community structure and temperature sensitivity	Soil respiration	Warming and microbial community	Temperatures, water level depth	Forested peatlands, Finland	Yes, but impact of soil moisture on soil respiration important
Oelbermann et al.	2008	Evaluating carbon dynamics and microbial activity in arctic soils under warmer temperatures	C-dynamics and microbial activity	Warming	Temperature, ambient	Subarctic heath, arctic soils NW Finland	Yes
Peng et al.	2009	Temperature sensitivity of soil respiration in different ecosystems in China	Soil respiration	Warming	Temperature differences	Range of ecosystems, China	Qualified yes, acclimatisation may reduce dependency
Rasmussen et al.	2008	Litter type and soil minerals control temperate forest soil carbon response to climate change	C-turnover	Warming	Litter manipulation	Forest soils, California	Yes, but dependent on litter type and soil minerals
Reichstein et al.	2005	Does the temperature sensitivity of decomposition of soil organic matter depend upon water content, soil horizon, or incubation time?	Decomposition of SOM	Warming	Temp-erature, drying-wetting, decom-position dynamics	Spruce Forests, Germany	Interaction effects significant

Table 3.11, cont: Summary of literature dealing with effect of warming on soil function

Author	Year	Title	Soil Property	Climate parameter	Comparator	Where?	Is soil function sensitive climate parameter?
Rillig et al.	2002	Artificial climate warming positively affects arbuscular mycorrhizae but decreases soil aggregate water stability in an annual grassland	Mycorrhizae, aggregate stability	Warming	Temperature differences	Grassland, California	Yes
Schindlbacher et al.	*2009*	*Carbon losses due to soil warming. Do autotrophic and heterotrophic soil respiration respond equally?*	*Soil respiration and C-loss*	*Warming*	*Soil temperatures*	*Forest soils, Norway*	*Interaction effects significant*
Suh et al.	2009	Temperature and moisture sensitivities of CO2 efflux from lowland and alpine meadow soils	CO2 flux from soil	Warming, moisture availability	Tem-perature and moisture availability	Grasslands, East Asia	Yes, but ecosystem dependent
Vanhala et al.	*2007*	*Old soil carbon is more temperature sensitive than the young in an agricultural field*	*Decomposition of old carbon*	*Warming*	*Tem-perature, respiration*	*Grasslands, Finland*	*Yes, but effect dependent on management (crop type)*
Wan et al.	2007	Responses of soil respiration to elevated CO2, air warming, and changing soil water availability in a model old-field grassland	Soil respiration	Warming, moisture availability	Temperature CO2-conc, water availability	Old filed grasslands, USA	Interaction effects significant
Yang et al.	2007	Soil organic carbon decomposition and carbon pools in temperate and sub-tropical forests in China	SOM	Warming	Different forest types	Forests, China	Yes, but ecosystem dependent

The insights obtained from the papers included in the CSR set are consistent with those provided by earlier systematic reviews of the effects of warming on a range of soil and ecosystem properties by Raich and Schlesinger, (1992) and Rusted et al. (2001). The latter, for example, reviewed 32 studies from four broadly defined biomes and found that across all sites and years, 2–9 years of experimental warming in the range 0.3–6.0°C, there were significant increases in soil respiration rates by 20% (with a 95% confidence interval of 18–22%), net N mineralization rates by 46% (with a 95% confidence interval of 30–64%), and plant productivity by 19% (with a 95% confidence interval of 15–23%). In terms of refining these analyses in the future, these authors argued that a particularly important area of concern was to the relative importance of key influencing factors, such as temperature, moisture, site quality, vegetation type, successional status, land-use and history at different spatial and temporal scales, and especially the interactions between them (Fig. 3.2).

Figure 3.2: Results of meta-analyses for soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming (after Rustad et al., 2001)



Schils et al. (2008) provide an overview of the ***expected*** qualitative responses of soil carbon in relation to a range of different drivers (Figure 3.3).

Figure 3.3: Expected responses of soil carbon and the underlying processes to key environmental change factors (after Schils et al., 2008)

		Process response			Soil carbon response	
		Plant and litter production	Decomposition	Erosion	Soil carbon	Uncertainty
Environmental change	Increased CO_2	↗	⇦	–	↗	Medium
	Increased temperature	⇦	↗	–	⇦	High
	Dry spells on mineral soils	↘	↘	–	⇦	High
	Dry spells on organic soils	–	↗	↗	↘	Medium
	Heavy rain events	–	–	↗	↘	Medium
	Increased nutrient availability	↗	⇦	–	↗	Low

They emphasise that impacts of climate change on soil carbon are pools are poorly understood and quantified and that there are considerable uncertainties associated with predicting any overall responses because of the varying sensitivity of different ecosystem components. Thus, in relation to the impacts of increasing temperatures on soil carbon, both increase and decreases might be anticipated, depending upon the way rates of plant and litter production are affected. Further complexity arises as a result of the extent to which losses due to increased decomposition rates might be offset by the effects of increasing CO_2 concentrations, or changes in nutrient availability. They conclude, however, that there is evidence from experimental studies to suggest that higher temperatures do increase the rate of soil respiration and that this can lead to a loss of soil carbon through higher rates of decomposition. While it has been suggested that the effect would be most marked in higher latitudes because decomposition is temperature limited in these areas they observe, however, that the available evidence does not uniformly support this hypothesis. They also suggest that the impact of higher temperatures on decomposition rates is likely to be greater and more lasting in relation to soil carbon, than the effects of temperature through productivity.

In terms of significant interaction effects identified by the studies included in the CSR set, the influence of atmospheric CO_2 concentrations and soil moisture also emerge as important factors in mediating the effect of temperatures on decomposition rates, along with litter, and land cover type generally. The study in the UK by Clarke et al. (2009), showed, for example that the production of dissolved organic carbon (DOC) from peat soils was more sensitive to increases in temperature under aerobic conditions when water tables were low, compared to anaerobic conditions, when water tables were higher. Clearly many of these interaction effects operate through their impact on soil biology. Several papers from the included set emphasise this point. Working with peat soils from the uplands of the UK, Briones et al. (2010), for example, found that warmer temperatures promoted higher reproduction rates of enchytraeids, and that in the top soil layer higher animal densities and biomass could be detected. Enchytraeids are especially important in decomposition and mineralisation processes in acidic or nutrient-poor habitats such as heathland and boreal forests, where they are often the major group of soil fauna in terms of their biomass. The study made a comparison between soil microcosms in which enchytraeids were present and those where they had been removed. The results showed that the rates of release of carbon as dissolved organic carbon (DOC) was not only higher in the presence of these organisms but also that the rates exceeded those detected at the same temperature when they were not present. The authors also reported that there was a strong positive link between the ages of the carbon assimilated by the animals and released through mineralization which indicated the importance that soil biology played in the mobilisation of the older C pools in soils. However, Maraldo and Holmstrup (2010) note in their review of enchytraeids in a changing climate that there is a general deficiency of research looking into the interactions between various climate change factors and the response of this species group. While little is known about the potential of enchytraeids themselves to adapt to a changing climate, there is some suggestion that they may be vulnerable to extreme weather events, such as heat waves and summer droughts.

In a recent 'mini-review' Bardgett et al. (2008) argued that an understanding of soil microbial ecology is central to our understanding of terrestrial carbon-cycle feedbacks. They argue that while our understanding of the potential effects of climate change on ecosystem productivity is well advanced, there are knowledge gaps in relation to soil respiration. This they suggest is determined by a complex array of factors and feedback mechanisms between climate, plants, the herbivores and symbioants that depend upon them, and free living heterotrophic soil micro-organisms. Davidson and Janssens (2006) make a similar point, and suggest that a number of environmental constraints may mask the intrinsic dependence of decomposition rates on temperature. These include:

Direct effects: While the rates of soil respiration are generally understood to be more sensitive to temperature than productivity, there is considerable uncertainty about the strength of the relationship. As implied by the papers discussed above, it may depend upon the substrate (litter), type of carbon being considered and the balance between aerobic and anaerobic conditions due to fluctuating water tables. It may also be affected by the incidence of drought and freezing, and snow cover (Bardgett et al., 2008).

Indirect effects: Any prediction of the way in which climate might impact upon soil respiration and the mobilisation of carbon is difficult because the composition of microbial communities may themselves be affected indirectly by climate through its impact on plant growth and vegetation above ground. Higher productivity may increase the rate of transfer of carbon fixed by photosynthesis to microorganisms, and CO_2 concentrations in the soil may be increased. Moreover, the composition of vegetation may itself be transformed under conditions of climate change potentially resulting in modifications to microbial communities. However, patterns of response may also be modified by concomitant impacts on N-mineralisation, which may limit availability to plants (Bardgett et al., 2008).

While inspection of the references in the CSR subset suggests that the search protocol has been partially successful in identifying and confirming some of the important issues picked out by recent reviews of the dependency of soil respiration on temperature, it is equally clear that they are the set is somewhat restricted. The number of articles looking at the effects of elevated CO_2 levels on soil processes is, for example, limited; it is widely acknowledged that elevated atmospheric CO_2 tends to stimulate plant productivity, which could either enhance or suppress the processing of soil carbon (Langley et al., 2009). The review by Schils et al. (2008) also suggests that the evidence to supporting the proposition that elevated CO_2 levels lead to an increase in soil carbon is ‘limited and variable’. However, they note the recent meta-analysis of Jastrow et al. (2005), which suggests that mineral soils associated with a range of temperate ecosystems have the potential to store additional carbon in response to CO_2 enrichment.

In addition, the search protocol does not, it seems, pick up a sufficient range of articles, particularly in relation to the complex interactions between the factors that affect the biological communities that live in soils. Moreover it does not include a significant proportion of the records on available for soil respiration as documented by Bond- Lamberty and Thompson (2010 a, b, & c).

Table 3.12: Summary of literature dealing with effect of moisture availability and other climate drivers on soil function

Author(s)	Year	Title	Soil Property	Climate parameter	Comparator	Where?	Is soil function sensitive to climate parameter?
Chou et al.	2008	The sensitivity of annual grassland carbon cycling to the quantity and timing of rainfall	C cycling	Rainfall	Rainfall variability	Grassland biome, Browns Valley,Yuba County, California	C cycling sensitive to changes in rainfall quantity and timing, with a longer or later wet season resulting in significant C losses
Davidson et al.	*2008*	*Effects of an experimental drought and recovery on soil emissions of carbon dioxide, methane, nitrous oxide, and nitric oxide in a moist tropical forest*	*C and N emissions*	*Rainfall and drought*	*Rainfall exclusion*	*Forest, Amazon*	*Dominant effect of through fall exclusion on soil aeration conditions that transiently affected CH4, N2O, and NO production and consumption; no treatment effect on soil CO2 efflux*
Durán et al.	2009	Changes in net N mineralization rates and soil N and P pools in a pine forest wildfire chronosequence	N mineralisation, soil N and P	Fires	Fire frequency	Forest, Canary islands, Spain	Soils showed low resilience after wildfires, esp. for N, which might induce long-term changes in ecosystem functioning
Durán et al.	2010	Long-term decrease of organic and inorganic nitrogen concentrations due to pine forest wildfire	Organic and inorganic N	Fires	Fire frequency	Forest, Canary islands, Spain	Significant decrease in microbial biomass N, mineral N and dissolved organic N. No recovery 20y after fire, suggesting low resilience
Kreyling et al.	2008	Soil biotic processes remain remarkably stable after 100-year extreme weather events in experimental grassland and heath	Soil biotic processes	Extreme events related to water availability	Drought, heavy rainfall	Grasslands, heathlands, Germany	Heavy rainfall events increased below-ground biomass and stimulated soil enzyme activities as well as decomposition rates. Extreme drought did not reduce below-ground plant biomass and root length, soil enzyme activities, and other processes
Lichter et al.	2008	Soil carbon sequestration in a pine forest after 9 years of atmospheric CO2 enrichment	C-balance	CO_2-conc	Elevated CO_2	Pine forest, USA	N transferred at a higher rate under elevated CO2 suggesting enhanced SOM decomposition is increasing mineralization and uptake
Víctora et al.	1997	Soil vulnerability in Uruguay Potential effects of an increase in erosive rainfall on soil loss	Erodability	Rainfall intensity	Rainfall events of different intensity	Agricultural soils, Uruguay	Soil loss resulting from increases in the amount of rainfall

These authors note that a substantial body new data have been generated other publications of Raich and Schlesinger (1992) and Rusted et al. (2001), and have therefore constructed a global database covering all peer-reviewed scientific literature reporting soil respiration measured in the field. The database, which consists of 3379 records data from 818 studies, provides a potentially rich resource for future systematic review and meta-analysis. They analysis of current data suggests that mean annual temperature, precipitation and leaf area index explain about 40% of the mean annual variability in soil respiration at global scales.

As the review by Schils et al. (2008) emphasises, however, the evidence relating to the effects of changes in moisture levels on decomposition rates in soils is much more limited than that for temperature, and that its impacts can drought, for example, can have very different effects depending upon whether one is dealing with mineral or organic soils (Figure 3.3).

Although most of the studies that considered warming as the independent variable looked at outcomes related to carbon decomposition and soil respiration, work dealing with other soil parameters was identified by the search protocol (Table 3.11); these included, principally, the effects of warming on nitrogen mineralisation. Impact of climate factors other than temperatures on nitrogen budgets was also identified by the papers selected. Table 3.12 summarises the studies included in the CSR set that considered climate factors other than warming. Although the studies are few in number, both carbon cycling and nitrogen mineralisation appears to be sensitive to variations in moisture availability, and differences in soil micro-biology. Fires also appear to significantly impact on nitrogen mineralisation.

A reading of the paper in CSR set suggested that while the notion of one of the dimensions of the resilience concept was implicit in all of them, generally it was not a key theme of the analysis. Indeed, only one paper (Durán et al., 2010) explicitly used the term resilience, in the title or abstract. A more useful framing of the ideas being explored was provided by the terms ‘sensitivity’, ‘stability’ or ‘recovery’. Moreover, when used in these contexts the authors were generally referring to a specific relationship between variables rather than some ‘whole systems’ property. This clearly consistent with the suggestion that designing questions about resilience ought follow the ‘of what, to what’ approach suggested by Carpenter et al. (2001) and Cummings et al. (2005), but it does seem challenge the suggestion that the concept of ‘resilience’ is more than a descriptor of how sensitive some dependent variable is to some independent factor or factors.

Soil resilience and management

As we have argued, the open-ended character of the target review question suggested that a two stage process was required, involving the identification of the set of climate sensitive soil characteristics that have been the focus of recent work, and then an investigation of the extent to which there is any evidence that management interventions can be used to mitigate these effects and to protect aspects of soil that are vulnerable. The first stage of our analysis suggests that the sensitivity of soil decomposition rates and the status of soil carbon under change climatic conditions are key themes being actively explored in the literature. Although warming may, under controlled conditions increase the rate at which CO_2 is transferred to the atmosphere from terrestrial ecosystems, it does not follow that overall soil will act as a net source of carbon, because other factors, such as increased productivity and changes in land management might intervene.

In fact, as Canadell et al. (2007) point out, evidences suggests that the terrestrial biosphere has acted as a net carbon sink over the last 25 years, removing about one third of the CO_2 released to the atmosphere from fossil fuels. In the light of present international efforts to stabilise and reduce emissions, this they suggest represents a significant subsidy to the economy. Moreover, since many aspects of the terrestrial carbon sink can be modified by 'purposeful management', Canadell et al. (2007) conclude that it is important to that the interrelationships are better understood.

Because a potentially large number of papers were identified that related various kinds of management action to aspects of soil quality, the papers included the MSR set were constrained by including search terms that reflected the soil parameters identified as being particularly sensitive to climate change in the first part of our study. Although aspects of soil structure were not included explicitly the resulting set strongly reflected the important of this topic area, with the largest number of papers looking at soil aggregate stability and the importance of understanding the dynamics of soil carbon in promoting resilience.

Table 3.13 provides an overview of the papers that looked at aggregate stability either as a single topic or in relation to other soil properties. An important limitation to note is that they mainly concern agricultural systems, although some did consider wider aspects of land use change. As comparators, papers looked at the differences between cropping systems, and in particular the contrasts between 'no-till' and more conventional cropping practices. A review of the papers that looked at the differences in soils quality with and without tillage suggests that the evidence appears to point to the benefits of reduced inputs, in terms of promoting increased levels of soil carbon, greater levels of biological activity and greater soil aggregate stability.

Table 3.13: Summary of the literature dealing with aggregate stability as an outcome of management intervention

Author	Date	Title	Outcome
Abid and Lal	2008	Tillage and drainage impact on soil quality. I. Aggregate stability, carbon and nitrogen pools	No-till treatments influenced porosity, and water stable aggregates in terms of their size and weight, and their C and N content, compared to tilled systems
Albuquerque et al.	2005	Relationship of soil attributes with aggregate stability of a Hapludox under distinct tillage systems and summer cover crops	Soil recovery by cover crops was more effective when using reduced tillage, evidencing the importance of management systems of low soil mobilization and high input of plant residues to increase organic carbon.
Alvaro-Fuentes	*2009*	*Soil Aggregation and Soil Organic Carbon Stabilization Effects of Management in Semiarid Mediterranean Agroecosystems*	*Adoption of no-till together with the suppression of long-fallowing period can significantly increase the amount of SOC stabilized in the soil surface and improve soil structure and aggregation.*
Angers et al.	1993	Early changes in water-stable aggregation induced by rotation and tillage in a soil under barley production	Different rotations had no effect on soil aggregation, but tillage reduced aggregate size compared to no-till treatments.
Arshad et al.	2004	Surface-soil structural properties under grass and cereal production on a Mollic Cyroboralf in Canada	There were few significant differences in soil-structural properties among the various annual cropping systems, but conservation tillage (continuous cover) promoted greater aggregate stability.
Ashagrie et al.	2007	Soil aggregation, and total and particulate organic matter following conversion of native forests to continuous cultivation in Ethiopia	After conversion the proportion of water-stable macro-aggregates was significantly reduced compared to forest soils
Barral et al.	2007	Comparison of the structural stability of pasture and cultivated soils	Promotion of aggregate stability requires adding organic matter to cultivated soils, or by adopting lower impact cultivation practices such as reduced tillage.
Barreto et al.	*2009*	*The impact of soil management on aggregation, carbon stabilization and carbon loss as CO2 in the surface layer of a Rhodic Ferralsol in Southern Brazil*	*Larger aggregates and larger proportion of the soil in greater aggregate size classes in no-till compared to conservation tillage. Total organic carbon stocks higher under no-till and higher emission rates of CO2*
Bissonnette et al.	2001	Interactive effects of management practices on water-stable aggregation and organic matter of a Humic Gleysol	Conservation tillage and manure applications led to improvement in surface soil conditions when used in a rotation system rather than in a monoculture

Table 3.13, cont.: Summary of the literature dealing with aggregate stability as an outcome of management intervention

Author	Date	Title	Outcome
Blanco-Canqui & Lal	2009	Extent of soil water repellency under long-term no-till soils	Water drop penetration test was more strongly correlated to SOC conc., aggregate stability, and soil texture and R index
Blanco-Canqui et al.	2007	Aggregate disintegration and wettability for long-term management systems in the northern Appalachians	Long-term management altered aggregate disintegration, but its effects on aggregate wetting within agricultural practices were small.
Bouajila and Gallali	*2010*	*Land use effect on soil and particulate organic carbon, and aggregate stability in some soils in Tunisia*	*Soil where the organic matter was the principal aggregation agent showed greater degradation sensitivity to soil organic carbon loss. Soil aggregate stability and soil organic carbon fraction could be used as indicators to apply the most appropriate management practices to increase soil sustainability or productivity.*
Carter	*1992*	*Influence of reduced tillage systems on organic matter, microbial biomass, macro-aggregate distribution and structural stability of the surface soil in a humid climate*	*Minimum tillage systems in humid climates can improve structural stability at the soil surface of fine sandy loams over a relatively short time frame.*
Castro Filho et al.	*2002*	*Aggregate stability under different soil management systems in a red latosol in the state of Parana, Brazil*	*The no-tillage system had the best aggregation indices. The greatest quantities of organic carbon were found in the 2 mm aggregate size class. The crop rotations studied did not affect the aggregate stability.*
da Veiga et al.	*2009*	*Aggregate stability as affected by short and long-term tillage systems and nutrient sources of a hapludox in southern brazil*	*The stability index in the surface layers was greater in treatments where crop residues were kept in the field, which is associated with soil organic matter content.*
Dufranc et al.	*2004*	*Physical, chemical and biological soil attributes related to aggregate stability of two oxisols under no-tillage in the state of Sao Paulo, Brazil*	*The clayey Oxisol showed higher aggregate stability compared to the sandy loam Oxisol, mainly because of its higher clay and organic matter content.*
Emasi et al.	2009	Effect of land-use change on soil fertility characteristics within water-stable aggregates of two cultivated soils in northern Iran	Cultivation significantly led to 71% and 6% reductions in total exchangeable bases
Ernst and Siri-Prieto	2009	Impact of perennial pasture and tillage systems on carbon input and soil quality indicators	Including pastures in the rotation, or switching from CT to NT improved soil quality properties (protection from soil erosion).
Filho et al.	*2002*	*Aggregate stability under different soil management systems in a red latosol in the state of Parana, Brazil*	*No-tillage system had the best aggregation indices. The greatest quantities of organic carbon were found in the 2 mm aggregate size class. The crop rotations studied did not affect the aggregate stability indices.*
Gerzabek et al.	1995	Response of soil aggregate stability to manure amendments in the ultuna long-term soil organic-matter experiment	Humus content had significant impact on Soil aggregate stability. Increasing C_{org}-content enhanced aggregation.
Gomez et al.	2001	Changes in some soil properties in a Vertic Argiudoll under short-term conservation tillage	Reduction in the soil structural stability was observed as related to the undisturbed soil. However, the C-W/S sequence under NT resulted in lower soil degradation with respect to the other treatments.
Hajabbasi and Hemmat	2000	Tillage impacts on aggregate stability and crop productivity in a clay-loam soil in central Iran	Direct drilling improved soil structural stability, its lower yield potential indicate reduced tillage systems may be the alternative compared to conventional practice (MD).
Haynes	1999	Labile organic matter fractions and aggregate stability under short-term, grass-based leys	The positive effects that a short-term (5 yr) pasture can have on soil organic matter quantity and quality and its attendant benefits on N fertility and soil structure.
He et al.	2009	Effects of 10 years of conservation tillage on soil properties and productivity in the farming-pastoral ecotone of Inner Mongolia, China	Ten-year mean crop yields increased by 14.0% and WUE improved by 13.5% compared to traditional tillage due to greater soil moisture and improved soil physical and chemical status.
Kasper et al.	2009	Influence of soil tillage systems on aggregate stability and the distribution of C and N in different aggregate fractions	Tillage type influences both aggregate stability and aggregate chemical composition. Minimum tillage has the highest potential to sequester C and N in this agriculturally used soil.
Li et al.	2007a	Effects of 15 years of conservation tillage on soil structure and productivity of wheat cultivation in northern China	No-till and residue cover is a more sustainable farming system, which can improve soil structure, and increase productivity with positive environmental impacts in the rainfed dryland farming

Table 3.13, cont.: Summary of the literature dealing with aggregate stability as an outcome of management intervention

Author	Date	Title	Outcome
Li et al.	2007b	Soil physical properties and their relations to organic carbon pools as affected by land use in an alpine pastureland	The current land use and management changes had - besides depleting SOC adversely affected important soil physical properties, potentially accelerating erosion and reducing soil infiltration and water retention
Liang et al.	2010	Short-Term Impacts of No Tillage on Aggregate-Associated C in Black Soil of Northeast China	No-tillage practices did not lead to the increase of average SOC content at 0-30 cm depth, but it did significantly increase SOC at the top soil
Marcolan et al.	2007	Recovery of physical attributes of an ultisol as affected by soil tillage and sowing time in no-tillage	4 ys under no-tillage were necessary to recover the original aggregate stability condition
Miao et al.	2009	Aggregation stability and microbial activity of China's black soils under different long-term fertilisation regimes	Microbial activity increased larger fractions (>0.5 mm), but decreased the smaller fractions (<0.5 mm). Microbial synthesis products serve as binding agents for aggregate formation. The combination of chemical and organic fertilisers was most effective for increasing macro-aggregate stability.
Pinheiro et al.	*2004*	*Aggregate distribution and soil organic matter under different tillage systems for vegetable crops in a Red Latosol from Brazil*	*Adoption of no-tillage led to a decline in aggregation compared with grass reference, but did significantly alter soil organic concentration*
Quiroga et al.	2009	Grazing effect on soil properties in conventional and no-till systems	Grazing had a negative effect on bulk density, but had no effect on aggregate stability
Razafimbelo et al.	2008	Aggregate associated-C and physical protection in a tropical clayey soil under Malagasy conventional and no-tillage systems	C protection might occur in aggregates via physico-chemical protection mechanisms by association of organic matter to clay and silt fractions, or by protection due to chemical composition.
Roldán at al.	*2003*	*No-tillage, crop residue additions, and legume cover cropping effects on soil quality characteristics under maize in Patzcuaro watershed (Mexico)*	*Conservation tillage practices can provide an alternative technology contributing to sustainable agriculture*
Saber and Mrabet	*2002*	*Impact of no-tillage and crop sequence on selected soil quality attributes of a vertic calcixeroll soil in Morocco*	*Better stability of aggregates was demonstrated by a significantly greater aggregation index. Hence, combined use of no-tillage and 3-yr rotation helped to improve soil quality in this experiment.*
Salton et al.	*2008*	*Soil aggregation and aggregate stability under crop-pasture systems in mato grosso do Sul State, Brazil*	*The formation of macro-aggregates seems to be related to the presence of roots, which are more abundant under grass pastures.*
Singh and Malhi	2006	Response of soil physical properties to tillage and residue management on two soils in a cool temperate environment	Despite firmer soil, no-tillage and residue retention are recommended to improve aggregation
Taboada-Castro et al.	2006	Dynamics of aggregate stability influenced by soil management and crop residues	Aggregate stability showed temporal variation as a function of organic matter contents and sampling period
Vestberg et al.	2002	Cropping system impact on soil quality determinants	Arbuscular Mycorrhizal spore density correlated positively with high amounts of extractable Ca & P which were a result from excessive liming
Whalen et al.	2003	Compost applications increase water-stable aggregates in conventional and no-tillage systems	Rapid improvements in aggregation of a silt-loam in the first 2 yr after compost application and the adoption of no-tillage practices.
Williams and Petticrew	2009	Aggregate stability in organically and conventionally farmed soils	For cultivated soils, it was not possible to differentiate aggregate stability for soils managed under organic or conventional farming practices, but aggregates of soils that only received artificial fertilizers consistently exhibited less stability.
Yang et al.	2009	Effects of forest conversion on soil labile organic carbon fractions and aggregate stability in subtropical China	Labile fractions were more sensitive indicators of SOC change resulting from the forest transition.

The apparent benefits of no-till over conventional cropping practices on levels of soil carbon, may however, be questionable, given the recent evidence reviewed by Baker et al. (2007), who have argued that previous studies have failed to measure soil carbon throughout the entire profile. Lal et al. (2008), have found no difference between conventional and reduced tillage systems.

The studies identified in Table 3.13 generally support the more general conclusions of the recent review by Bronick and Lal (2005) on the influence of management on soil structure (see also Amezketa, 1999; Pagliai et al., 2004). These authors argue that aggregate stability is a good indicator of soil structure, and indeed soil quality, and that broadly any management practice that increases productivity and reduces disturbance enhances aggregation and better soil structure. It should be noted, however, that it may be difficult to use aggregate stability as an indicator of quality. A study undertaken for the Environment Agency of England and Wales on *The Development and Use of Soil Quality Indicators for Assessing the Role of Soil in Environmental Interactions* (Environment Agency, 2006) suggested that any index based on aggregate stability would have to show clear interpretable differences between and within soil and land use types. Unfortunately, they found that there is no accepted method for the assessment of aggregate stability. They also observed that aggregate stability testing has mainly been carried out for arable soils.

However, although no simple index of soil quality based on measures of aggregate stability are currently available, the Environment Agency study noted that a change in aggregate stability does suggest important modifications in a range of basic soil properties. The study highlighted that many factors may bring such changes about, including a change in crop type, a change in management practice, a change in soil pH or a change in SOC. The review by Bronick and Lal (2005) found that aggregation is correlated with root-mass, root morphology, fungal mass, additions of organic matter to soils, and that cover crops in no-till systems can significantly promote aggregation over tilled soils. These conclusions are confirmed in the study by Gregory et al. (2009) identified in the CSM set, which has looked at the effect of long-term management on the physical and biological resilience of a range of soils in England.

Gregory et al. (2009) tested the hypothesis that soil organic matter is a fundamental control of resilience and how this affected the response of soil to physical and biological stresses. They argued that since organic matter content is affected by the long-term management of soils, it is particularly important to better understand the strengths of these kinds of relationships. Their study included soils from a range of different arable and grassland sites, at which management practices had been in place for between 45–160 years, and included the long-term experiments at Rothamsted. The soils were subjected to physical or biological stresses in the laboratory, and the effect monitored over a recovery period of up to 28 days. The disturbance factors considered were physical compaction, transient heat stress, and persistent copper stress. Using a set of resistance and resilience indices they found that grassland soils recovered faster from the effects of compaction than arable soils, and that they were less sensitive to heat and copper stress than cultivated soils. They also found that there was a significant correlation between the indices of resilience and the organic matter content of the soils. The resistance and resilience indicators used were based on the ratio of the absolute value of the measured soil function at maximum stress and after the recovery period. The authors concluded that the greater levels of particulate organic matter in grassland soils probably enhanced their physical resilience over arable soils, and that their increased resistance to heat and copper stresses was probably due to greater organic matter content, as well as higher microbial diversity. It should also be noted, however, that the experimental sites differed in terms of their clay content, which also had a large impact on soil resilience. The earlier study by Gregory et al. (2007) also emphasises the importance of the physical texture of soils as a determinant of resilience.

On the basis of the observed differences that different management practices can have on a range of soil properties, Idowu et al. (2009) have recently proposed an ‘integrative soil health test’ for evaluating the impacts of different management options. Van Eekeren et al. (2010) have sought to use biotic soil parameters to predict soil quality characteristics and the ability of these soils to provide ecosystems services, but it appears that further work is required before such indices are available.

The impact that particular types of agricultural practices can have on levels of soil carbon and other associated aspects of soil quality, suggest that management of the carbon content of soils is important in terms of restoring and protecting the general resilience of systems, and, given the earlier discussion, a potential starting point for any discussion of the ways management interventions might mitigate the impacts of climate change on the supporting services provided by soils. A review of the two sets of literature identified here suggests that while warming might increase rates of soil respiration, there are a number of management interventions that might be considered to ensure that the soil represents a carbon sink. Smith (2004), for example, argues that the carbon sinks resulting from sequestering activities are not fixed and will persist only as long as suitable management practices are maintained.

An inspection of the components of resilience considered by the papers in the MSR set suggests that in the context of soil management, the issues related to ‘resistance’ and ‘recovery’ are treated more equally than in the set of literature dealing with climate. An issue to emerge from the review of papers in the management set is the extent to which there is an upper limit to the amount of carbon that can be stored in mineral soils. For example, Gulde et al. (2008), who found in an experimental study involving long-term (>20years) manure application to agricultural soils in Canada that, as carbon input increases, the mineral fraction of a soil saturates. Thus additional inputs will only accumulate in labile soil carbon pools that have a relatively faster turnover. Stewart et al. (2007) have also investigated the threshold effect experimentally, also finding that for agricultural soils saturation does occur. They suggest that in terms of achieving the greatest efficiency in soil carbon sequestration, we should focus on those soils that are further from carbon saturation.

The general implications of a threshold (*sensu* saturation) effect, and therefore the contribution that the management of soil carbon might make as a climate mitigation strategy has been discussed with particular reference to the UK by Smith (2004), Smith et al. (2009) and Ostle et al. (2009). Smith et al. (2009) point out that while management can be effective in promoting soil carbon sinks, the strength of those sinks as measured by the rate of carbon uptake, will diminish over time as they become saturated. Although the time taken to achieve saturation is variable, and dependent on the type of ecosystem being considered, Smith (2004) notes that the IPPC good practice guidelines generally assume about 20 years for soil carbon to approach a new equilibrium. It should be noted, however, that this is a guideline only, and that temperate soils may around 100 years to reach equilibrium; as a result it the interpretation of results from different climatic zones may be difficult to interpret. Smith (2004) emphasises that while soil carbon sequestration could meet around a third of the current annual global increase in atmospheric carbon its effect would be limited in duration. Nevertheless, it is clear that soil management practices are important for enhancing and protecting existing soil carbon stocks and creating new opportunities for sequestration (Ostle et al., 2009), and that in policy terms one clear strategy is to look for ‘win-win’ options that serve both to increase carbon stocks and at the same time improving the capacity of soils to provide ecosystem services in terms of their maintaining their fertility, their ability to resist erosion and other disturbances, and their contribution to sustaining yields.

The review by Schils et al. (2008) also provides an analysis of literature on the impact of management on soil carbon (see also Ostle et al., 2009). This work confirms the importance of distinguishing between organic and mineral soils in developing future strategies, and the need to separate issues of carbon storage and sequestration. Thus for peat and organics soils they key management goal should be to preserve existing stock; historically the most serious losses from these important carbon stores has been due to the drainage of peats for forestry and agriculture. In the case of mineral soils, evidence suggests that changes in land use can significantly affect the stocks of soil carbon which can be reduced when grasslands and forests are converted to croplands; there may, however, be some recovery if forests or grasslands are re-established. These authors also summarise the effect of a range of land management mitigation measures on carbon sequestration.

Table 3.14: Effect of a selection of mitigation measures on carbon sequestration in agriculture (after Schils et al., 2008)

	Potential implementation cost	Probability of implementation (Based on potential uptake by farmers)	Global mitigation potential (Smith et al., 2008) (tCO_2 eq./ha/yr)
Catch crops	Low	High	0.29 -0.88
Reduced tillage	Low	Medium (low in some areas)	0.15 -0.70
Residue management	Low	High	0.15 -0.70
Extensification	Medium	Low	1.69 -3.04
Fertiliser application	No	Medium (already done in some areas)	0.26 -0.55
Fertiliser type	Low	Medium (already done in some areas)	0.26 -0.55
Rotation species	No	Medium	0.29 -0.88
Adding legumes	Low	High	0.26 -0.55
Permanent crops	Variable	Low (reduces flexibility)	1.69 -3.04
Agroforestry	Medium	Low (reduces flexibility)	0.15 -0.70
Grass in orchards & vineyards	Medium/high	Low	1.69 -3.04
Optimising grazing intensity	Low / medium	Medium (already done in some areas)	0.11 -0.81
Length and timing of grazing	Medium	Medium	0.11 -0.81
Grassland renovation	Low	High	0.11 -0.81
Optimising manure storage	Medium / high	Medium	
Manure application techniques	Medium	Medium	1.54 -2.79
Application of manure to cropland versus grassland	Low	Medium	1.54 -2.79
Organic soil restoration	Medium / high	Medium	36.67 – 73.33

Soil Resilience and Economic Values

The secondary objective of this study was to examine the question: are management interventions for soil resilience or soil resistance cost-effective? While it was recognised from the outset that this issue could be the subject of a systematic review in its own right, it was felt that it would be useful to examine the included studies in order to explore the extent to which the topic had been addressed or the implications considered.

We therefore combined the initial CRS and MSR sets and extracted all papers that included reference to some economic issue. Thirteen papers were identified and a reading of them suggested that the majority considered the issue mainly in terms of crop production and the vulnerability of ecosystems generally, rather than from a soil perspective. Only one, namely the study of Capalbo et al. (2004) which dealt with sensitivity of carbon sequestration costs to economic and biological uncertainties on US northern Great Plains considered soil issues explicitly. Using simulation modelling techniques these authors suggest that for robust estimates of the contribution that agriculture could make, more accurate measurement of the key variables, including the rate of carbon sequestration and the productivity impacts of increasing soil carbon are needed.

The limited number of papers included within our search set probably **does not** reflect the true volume of material on this topic. Although a test using Scopus and the search string for soil resilience and climate without the empirical requirement found no additional papers, the modified version dealing with management and tillage found around 60 articles. A scan of them suggested that a key widely cited reference was that of Brussaard et al. (2007), who have reviewed soil biodiversity for agricultural sustainability. These authors discuss the estimates provided by Pimentel et al. (1997) and van der Putten et al. (2004), that services provided annually worldwide by soil biota exceed 1.5 trillion US dollars, and suggest that about 50% of this is derived from recycling of organic materials. However, this article does not discuss resilience as an issue, and concludes that generally more work is required to determine economic values. Haygarth and Ritz (2009) have also suggested that specifically within the UK context, soil 'remains an undervalued and underappreciated resource'.

The volume of literature on the economic benefits of strategies for soil carbon management in the face of climate change is potentially large and relevant (see for example Schils et al., 2008) but it was not investigated in detail here, since current debates do not appear to link explicitly to notions of resilience.

3.4.5 Quantitative synthesis

No quantitative syntheses have been prepared at this stage. Although the set of studies dealing with soil resilience and climate change (CSR) was useful in giving an overview of the current debate, they were considered too heterogeneous to be used in any meta-analysis. As noted above, a meta-analysis for the impacts of warming on soil respiration, mineralisation, soil moisture and productivity is already available (Rustad et al., 2001), and Jastrow et al. (2005) provides a further meta-analysis for the effects of CO_2 on carbon stocks. While these analyses could be extended and updated, there is little to suggest from the literature extracted that the broad conclusions of these earlier analyses must be modified. The establishment of the global database for soil respiration studies provides the opportunity to regularly update the meta-analysis in this topic area (Bond-Lamberty and Thompson, 2010 a, b, & c).

The set of included studies dealing with soil resilience and management (MSR) was both larger and less heterogeneous than the soil-climate collection, and there is, perhaps greater potential here for a meta-analysis to be undertaken. However, the qualitative analysis suggested that recent work seems to confirm the general conclusions that have been advanced by earlier, traditional reviews (particularly in relation to tillage practices) and that a quantitative meta-analysis would add little at this stage.

We recognise, however, that quantitative analysis is an essential part of the systematic review process, and that the identification of where these techniques can best be used to provide the most robust insights about the resilience of soils in relation to climate and management is essential. Both qualitative reviews seem to suggest that while the broad impacts of climate and management are now understood, the complexities arising out of the interaction of different factors needs to be examined more closely. A profitable next step would be to examine whether there was sufficient literature available to look at these more subtle effects.

3.5 Outcome of the review

Conclusions

The review has looked at the intersection of the literatures on the relationship between soil resilience and climate and soil resilience and management to explore the question: *can soil management enhance, restore or protect the resilience or resistance properties of soils, given the likely impacts of climate change?* Although the question is an open-framed one, not ideally suited to a systematic review, the study had identified a number of important insights. These can be summarised as follows:

- There is good evidence to suggest that a number of key soil properties linked to soil carbon are vulnerable to soil warming, and that increasing temperatures could lead to reduced levels of carbon sequestered in the soil; this conclusion is supported by existing, published meta-analyses.
- While there is considerable uncertainty as to whether increased soil respiration under a warmer climate will lead to a net, global transfer of carbon to the atmosphere, there is good evidence to suggest that in localities where there is a loss of soil carbon, soil quality would be reduced, making them potentially more vulnerable to extreme events and physical disturbances.
- There is good evidence to suggest that management interventions can increase the resilience of soils to disturbance by increasing soil carbon content and enhancing soil structure. Although management practices based on 'reduced' or 'conservation' tillage have been regarded as particularly effective the evidence that this leads to additional carbon storage is now being challenged.
- There is good evidence to suggest that as soil carbon levels are increased, there is a saturation effect, and that while the benefits of improved soil quality would persist, the strength of the carbon sink provided by soils would diminish.
- There is limited evidence as to the economic benefits of investing in soil management ***from a resilience perspective***.

Thus in terms of the review question it can be concluded that there is good evidence to support the assertion that soil management can enhance, restore or protect the resilience or resistance

properties of soils, given the likely impacts of climate change. However, the economic benefits of maintaining or enhancing soil resilience in the face of climate change cannot easily be estimated.

This conclusion must, however, be qualified in terms of the **limitations associated with this study**. Namely:

- That in terms of the impacts of climate change on the resilience of soils, the effects of increasing concentrations of CO_2 on soil processes is probably under-represented in the set of studies included in this review.
- More information is needed on the way different soil properties interact and mediate the effects of warming on soil micro-biological activity and soil respiration.
- The studies identified here provide only limited information on the way different soils respond to management inputs, particularly in relation to those in the UK.

Implications for management, policy and research

Although the literature available of the topic of soil resilience that makes specific reference to the UK is limited, these general conclusions do have implications for policy. The *Soil Strategy for England and Wales* notes, for example, the importance of understanding the state of our carbon stocks and the processes that affect them. This study confirms the central role that management of soil carbon plays, not just in terms of carbon sequestration for climate change mitigation, but also in protecting the supporting ecosystem services that soils provide. The conclusions thus support an approach to soil policy and management that recognises their multi-functional nature. Although the *Soil Strategy* rightly places emphasis on the conservation of our peat lands, a more balanced treatment of the soil carbon issue in relation to ***all*** soils is probably required.

The advantage of focusing on the multi-functional character of soils in relation to the carbon management issue is that there are a number of measurable, scientifically credible indicators that could be monitored to assess changes in soil resilience. These indicators can be used to evaluate the effectiveness of agri-environmental schemes, and may provide the basis for monitoring novel payment schemes that focus more directly on ecosystem services. The importance of monotirn has been emphasised by Schils et al. (2008), who have considered how a range of EU policies (namely, Common Agricultural Policy (CAP), the Nitrates Directive, the Renewable Energy Sources Directive, the Biofuels Directive, Waste policy and the EU Thematic Strategy for soil protection) are likely to impact on soil carbon. They found that the requirements under the Cross Compliance within CAP can be used to maintain soil organic carbon, and that the requirements of the Soil Framework Directive would not appear to adversely impact on soil C. They concluded, however, that EU policy on renewable energy may not secure appropriate management for soil carbon.

This review has also highlighted a number of knowledge gaps and wider scientific issues that could form the basis of further work. Certainly much more research is needed on the interactions between the various climatic and management drivers and what effects they might have on soil resilience. A particular focus should be the micro-biological mechanisms that underpin the dynamics of carbon in soils and the implications that these changes have for the other dimensions of soil quality.

In terms of wider questions about the resilience of ecosystems, this review suggests that while questions about the sensitivity of soils to various independent factors are central to current debates, the ‘resilience’ paradigm is **not** widely applied. In the literature reviewed here, resilience as a term is more frequently used as a synonym for ‘stability’, ‘recovery’ and ‘sensitivity’ etc. rather than as a way of making reference to a specific theoretical framework. In the literature considered, there was, for example, little reference to the kind of ‘threshold’ effects or ‘regime shifts’ widely debated in the resilience literature, nor was there any obvious analysis of the kind of hysteresis effects that are seen in aquatic systems, where the trajectories that characterise degradation and recovery differ significantly. In this respect, the conclusion of Loveland and Webb (2003), that the *quantitative* evidence for such thresholds is slight, remains valid.

4. Biodiversity

By Pam Berry, Paula Harrison and Richard Mercer

4.1 Background

2010 is the International Year of Biodiversity, which aims to promote action worldwide to reduce the continuing loss of biological diversity, and although biodiversity has long been a focus of public policy in the UK, it is clear that more needs to be done. The England Biodiversity Strategy seeks to ensure that biodiversity is considered in all main sectors of public policy and at the national level we need to consider what disturbances, such as climate change, might have, as well as understanding the effects of other types of environmental change. Climate change raises a number of challenges concerning impacts on ecosystems and how we manage them. Most notable amongst these is the challenge of understanding the resistance and resilience of ecosystems to external pressures, both from more gradual changes in climatic conditions and rapid shocks of extreme events. The question of the vulnerability and resilience of habitats to pressures from various drivers is, therefore, very relevant. The IPCC (2007) defines vulnerability to climate change as 'the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes' and is seen as a function of its exposure, sensitivity and adaptive capacity, with the latter embracing elements of resistance and resilience.

Some of the above issues have been considered most recently in relation to how efforts to conserve biodiversity in the UK fit with the emerging strategies for adapting to climate change. The England Biodiversity Adaptation Principles for climate change (Smithers et al., 2008) have as one their five adaptation principles "to maintain and increase ecological resilience". Ecological resilience was seen as depending on "a dynamic relationship within species and among species and between species and their abiotic environment...." (Convention on Biological Diversity, 2000). There are four actions in the England Biodiversity Adaptation Principles thought necessary to maintain and increase ecological resilience: conserve range and ecological variability of habitats and species, maintain existing ecological networks, create buffer zones around high quality habitats and take prompt action to prevent the spread of invasive species. This review, therefore, is both timely and relevant to current biodiversity policy development.

4.2 Objectives

Given the concern about managing the impacts of climate change on biodiversity, an initial question of "Which ecosystems are most vulnerable to climate change and what can be done to protect the biodiversity and ecosystem services associated with them?" was posed for discussion. This is clearly a very broad question and it would be useful to consider how it might be refined to ensure that the outcomes of the review are as useful as possible. There is a wide literature on the effects of biodiversity on a range of ecosystem properties (e.g. productivity) and indeed resilience (see Balvanera et al., 2006), and the interest in RECCE was on the extent to which potential interventions might buffer ecosystems against the impacts of climate change. It was noted that this perspective views 'biodiversity' (e.g. species richness of habitats, ecosystems) more as a cultural service and focuses on the question of how resilient they are to drivers of change and what could be done to reduce their vulnerability. Thus the resilience of biodiversity could be framed as the ability to maintain species richness and heterogeneity under external interventions, such as climate change or habitat loss.

4.2.1 Primary Question

In order to refine the review and to increase its policy relevance, the four actions in the England Biodiversity Adaptation Principles thought necessary to maintain and increase ecological resilience were considered, with ecological networks being considered inappropriate for further investigations as there is a review of them and connectivity being carried out at the moment. The Broad Habitats were chosen as the context for this review, as they form the basis of UK biodiversity strategy. The primary question, therefore, was refined to:

> **Can management interventions mitigate the impact of environmental change on biodiversity characteristics of UK Broad Habitats?**

The components of this question are outlined in a systematic review format of subject, intervention outcome, with driver added as a fourth component in Table 4.1 and the details of how each of these was used in the search is given in Section 4.3.2.

Table 4.1: Definition of components of the primary systematic review question

Subject	UK Broad Habitats but also including analogous habitats and ecosystems from Europe and/or North America
Driver	Environmental change, specifically climate change
Outcome	Change in biodiversity characteristics
Intervention	Management interventions that would mitigate impacts
Comparators	Degrees of environmental change (with or without intervention), including extreme events and other indirect results of climate change

4.2.2 Secondary question

While much research has been undertaken on the potential impacts of climate change on species and habitats in the UK (Berry et al., 2003; 2007; Mitchell et al., 2007), little or no explicit assessment has been undertaken of their resilience, thus the second question was formulated as:

> **How resilient are the biodiversity characteristics of the UK Broad Habitats to environmental change?**

The search components were similar to those for the primary question.

4.3. Methods

4.3.1 Question formulation

The question was developed as part of the search protocol to address the overarching RECCE question: how do management interventions impact on the resilience of ecosystems under environmental change? (see Chapter 1). Biodiversity is one of the key components of an ecosystem and one of the main determinants of an ecosystem's resilience to environmental change.

The initial question was refined through discussion on the RECCE website forum, through a consultation with Defra and with the input of expert opinion.

One of the suggestions received through the RECCE eforum was that it might be useful to examine the extent to which the study by Mitchell et al. (2007), on the vulnerability of broad habitats to climate change, could be underpinned by the systematic review. Although this could be the primary question of another systematic review, it is believed that the secondary question within this review would go part way to exploring the literature that could support the Mitchell et al. (2007) study.

4.3.2 Search strategy

Relevant published research articles were identified through searches of the following electronic databases:

1. ISI Web of Science
2. Scopus
3. Science Direct

Search string and term development

The primary question was the starting point for the development of the search string. The question was broken down into subject, driver, outcome and intervention categories and combined into the following format:

- broad habitats **AND** biodiversity characteristics **AND** climate change **AND** management.

In order to further focus the search we included a category describing resilience and finally applied a filter to exclude certain topics. The final search format was this:

- broad habitats **AND** biodiversity characteristics **AND** climate change **AND** management **AND** resilience **AND NOT** terms to be excluded.

The development was iterative and we aimed to capture as much of that process as we could in the notes and descriptions. Each of the categories in the search string is discussed in more detail below.

UK Broad Habitats

The UK Broad Habitat terms were used to describe the different habitats within the UK since they have already been used in the National Ecosystem Assessment. Although the UK Broad Habitat[7] terms have been in circulation for some time there are few researchers who use these terms to describe their study sites.

We tested the suitability of using the UK Broad Habitats and Priority Habitats as search terms, by searching for the habitats individually in Web of Science (details are presented in Appendix 2.1). This simple test returned quite small numbers and revealed that strict usage of the UK Broad Habitat terms would be restrictive to the systematic review. Twenty four of the habitat-terms tested were noted as recording less than 20 hits in the search, with only 106 publications combined!

We also tested the number of UK Broad Habitats publications recorded within the results from an early iteration of the search string: **broad habitats AND biodiversity characteristics AND climate change.**

[7] For a full list of the UK Broad Habitats that were covered please refer to Appendix 2.1

The publications that had been found for the 24 habitats mentioned previously (those with less than 20 hits) were filtered using the **biodiversity characteristic** and **climate change** synonyms strings. Many of the remaining UK Broad Habitat terms were reduced to returning publication numbers in single digits (see Table 4.2). Only calcareous grasslands returned more than 26 publications for this test. What was interesting to note was that if we only used these terms (without the more general habitat terms also noted in the table) then there would have been no results from subsequent searches when more categories were added to the search string (e.g. categories on management and/or resilience).

It was for this reason that we decided to broaden the scope of the habitat terms to include terms like *grassland* and *forest*. Since this approach would capture international habitats outside of the scope of this study (e.g. tropical savannah grasslands) it did necessitate a filtering process at the end of the search.

Table 4.2: A test of how the UK Broad Habitats perform as search terms. The number of publication attributed to each UK Broad Habitat within an early search of: broad habitats AND biodiversity characteristics AND climate change.

acid grassland*	0
arable field margin*	1
blanket bog*	2
hedgerow*	3
mixed woodland*	2
broadleaved woodland*	2
wood pasture*	5
calcareous grassland*	26
coniferous woodland *	0
dwarf shrub heath*	14
lowland heathland*	1
fens	11
reedbed*	0
improved grassland*	0
coastal grazing marsh	1
coastal grassland*	0
limestone pavement*	3
chalk river*	0

mesotrophic lake*	0
coastal sand dune*	1
machair	0
woodland*	176
meadow*	108
heathland*	23
peatland*	50
bog*	47
marsh*	82
swamp*	51
grassland*	477
river*	461
river flood*	21
floodplain*	81
saltmarsh*	8
salt marsh*	36
forest*	1584

The subject Expert noted that the results from this search indicate the way that research is being done/not being done at a specific habitat level. The majority of climate change studies are national or international in their scope and might not be looking at particular habitats, or they are concerned with very general habitat types (e.g. uplands) – which then makes it more difficult to extract specific management interventions. It was suggested that there is a risk that the number of publications returned from the search would be a reflection on the scale of the studies concerned, rather than the subject matter. If the scale of the study is more extensive then it is less likely that they will use habitat specific terms to describe the study area.

Biodiversity Characteristics

The *a priori* selected search terms for the subject are based on the *England Biodiversity Strategy – adaptation to climate change* (Mitchell et al., 2007).

Biodiversity or 'biological diversity' is a very broad concept and can be defined as the "totality of genes, species and ecosystems of a region" and "the variation of life at all levels of biological organisation". As such biodiversity includes: species diversity, ecosystem diversity, morphological diversity and genetic diversity. It is also a term that can stretch across many different scales; from a regional scale pertaining to ecosystem diversity, down to a local scale when examining the genetic diversity within a small isolated population.

Using such a broad definition will by default provide a hugely diverse and broad set of results in a literature survey.

The following terms were included to represent the range of synonyms relating to the concept of biodiversity: biodiversity, species richness, geographic distribution, genetic diversity, species diversity, ecological diversity, species evenness, alpha diversity, beta diversity, gamma diversity, community composition, species composition, functional group, functional trait, and homogenisation*.*

The expert consultation stressed two areas as being of particular importance:

i. Species Composition

Composition is a critical measure, especially when some broad habitats might be characterised by particular species. For example, we could lose one species from a species-rich habitat and the measure of species richness wouldn't change much. But if the species lost was a key species (either from an ecological or cultural value standpoint) then there would be a large change to the resilience of that habitat / ecosystem to provide certain services. The term *homogenisation* was seen as covering some of the issues associated with species composition. If you have the same species appearing in more and more habitats then you are essentially losing the special species – those ones that are unique to those habitats and provide a cultural service.

ii. Functional Traits

Functional traits can be viewed in two ways: An ecosystem that has lost one species to be replaced with another species with a similar function then this can be taken as an indication of a resilient ecosystem. However, functional traits are probably less important from the perspective of cultural services, since people will not be interested in the replacement of a rare habitat specific species with another common one that performs the same function. This distinction could be important if we are looking at the resilience of two different aspects of an ecosystem – the cultural and the regulatory aspects.

Climate Change

Although the scope of the RECCE programme covered environmental change, in terms of brevity it was decided to narrow this topic and focus just on climate change. The following terms were included to represent the range of synonyms relating to the concept of climate change: *climate change, climatic change, global warming, environmental change, drought,* and *warming.*

Management

There are general terms such as “management regime” and “land management” that describe an intervention strategy for maintaining, enhancing or studying the resilience of subject systems. Although the subject systems have different requirements and have been subject to measures adapted to that system, a series of general intervention terms were applied to the general search string. Subject specific intervention terms could then be applied subsequently to narrow down the results within each subject specific section. Since this study also aims to identify evidence for conditions that enhance or maintain ecological resilience the natural conditions that contribute to a resilient system can also be included in the evidence base.

The following terms were included to represent the range of synonyms relating to the concept of “intervention”: manage, management, restoration, restore, conserve, conservation, protect, protection, remediate, remediation, intervene and intervention.

Resilience The term resilience has been refined in literature and research concerning ecological resilience and can be described specifically by two ideas as detailed by Brand and Jax (2007):

> The **magnitude** of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour; and,
>
> The **capacity** of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity.

Other terms that represents the first idea of the magnitude of disturbance that can be absorbed, are *threshold, limit,* and *resistance*. The second idea of retaining essentially the same identity of a system is well characterised by the terms vulnerability, recovery, stability, variability, and adaptation. This second group of terms is a description of the integrity of the system and its susceptibility to change. Different disciplines represent the theme of resilience differently. For example the three parallel and overlapping knowledge domains identified by Janssen et al. (2006), and Janssen (2007) use the terms *adaption, resilience* and *vulnerability* in research on the human dimensions of global environmental change. These three terms originate from different disciplines and their legacy is indicated by the category of journals that publish them, although there is an increasing overlap between the knowledge domains in recent years.

Original disciplines using the terms (adapted from Janssen et al., 2006):

> **Resilience:** population ecology and later social ecological systems
>
> **Vulnerability**: impact of natural hazards on person or groups and recently climate change
>
> **Adaptation**: anthropologic study of response to environmental variability and subsequently specifically to climate change

The following terms represent the range of synonyms relating to the concept of ecological resilience and how this is presented in the literature: *resilience, resilient, adaptation, adaptability, adaptive, resistant, resistance, threshold, vulnerable, vulnerability, recover, recovery, stability, variability, tipping points* and *sustainability.*

Exclusion terms

Geographic exclusion terms were developed in conjunction with the UK Broad Habitat terms to help focus attention back onto Eurocentric and other relevant studies that would contribute to the scope of this study. The exclusion terms were compiled by examining the first 100 and last 100 publications returned from an earlier search and noting geographic regions (e.g. Australia, tropical) that were not directly relevant to UK ecosystems.

The full list of exclusion terms is included in Appendix 2.2.

4.3.3 Study inclusion criteria

References retrieved from the databases were exported directly into EndNote prior to assessment. Duplicate references from the searches were removed. Only studies reported in English were used to conduct this review.

Articles were screened for relevance by assessing the title and abstract of each paper. Due to time constraints the inclusion of studies was not verified by a second reviewer. However, during the scoping phase of the project an assessment was done that showed the two reviewers *agreed moderately* on their assessment of relevance (Cohen's Kappa = 0.46).

The following criteria were used to assess the papers as suitable for inclusion:

- Is the study within our geographic scope (UK, Europe or North America[8])
- Is an element of climate change studied (either direct or indirect)
- Is there a change in one or more biodiversity parameters?
- Does the paper contain quantitative data?

4.3.4 Study quality assessment

Usually study data are accepted for further analysis (or possibly meta-analysis) when the study's criteria are fulfilled and appropriate comparators and variance measures exist (e.g. Smith et al., 2010). Given the small number of papers meeting the criteria, all papers were examined to explore the set questions.

4.3.5 Data extraction strategy

A tiered data extraction strategy was adopted due to limitations on time and also on the availability of relevant publications. The initial extraction focused on extracting descriptive information for each publication that would enable us to profile the database of publications. This was vital because the breadth of potential subjects, outcomes and drivers (habitats, biodiversity characteristics and climate change parameters) meant that it was not possible to know beforehand the sorts of data

[8] It was decided that there would be sufficient overlap in some of the habitats within North America that we could successfully explore extracting some of this information for the study. It was decided to maintain focus and to reduce the number of possible publications returned in a search, to exclude all other geographic areas.

that could be reliably extracted, and that would contribute to a meta-analysis around the primary question. No data has subsequently been extracted beyond this initial stage.

Once papers had been identified for inclusion in the study the following data were extracted into a spreadsheet:

Design: Whether the study was experimental, observational or modelling in design or a review.

Dependent variable: The habitat and biodiversity characteristics measured.

Independent variable: The climate parameter or management intervention used.

Comparator: The type of comparison being considered, defined in terms of the independent variable.

Space or Time Perspective: The scale of the study and whether the study looked at differences in responses of biodiversity characteristics over time.

Time-span considered: If time comparisons were involved, how long the time span being used to track the response was.

Resilience perspective: Whether the study provided insights into the resilience of biodiversity or the ability of the system (habitat) to resist disturbance or to recover from disturbance.

Ecosystem and Location: The geographical context of the study.

4.3.6 Data synthesis

Given the diversity of the wider set of papers and the relatively few papers considered relevant to all components of the search, only a qualitative synthesis was undertaken. This can help the appreciation of current research into the contribution of management to mitigating climate change impacts on UK Broad Habitats, and their resilience to climate change.

4.4 Results

4.4.1 Primary Question

Can management interventions mitigate the impact of environmental change on biodiversity characteristics of UK Broad Habitats?

Searches were conducted on the 21/07/2010 and all references identified during the searches were exported to EndNote X2. A total of 558 references were exported from the three search engines: WoS (239), Scopus (278), SD (41). Duplicate references were removed in EndNote (177) leaving a database of 411 references for assessment. The contribution of unique references by each search engine can be broken down to: WoS (239 refs or 58%), Scopus (163 refs or 40%), Science Direct (9 refs or 2%). These 411 references were then assessed on their titles and abstracts.

The first round of assessment produced 62 (15%) references that were deemed to be potentially suitable to answering the question. We downloaded the full text for each of these references (where possible) for subsequent assessments and for data extraction. Only 54 references had access to full text and these were used for the next stage of assessment (see Appendix 2.3).

Description of studies

The second assessment, based on a closer examination of the full text of the 54 references (not just the Title and Abstract), was attempted before the extraction of any data deemed suitable for the meta-data analysis component of the review. The reason for this was that although there were 54 references with the potential to answer the question, it was believed that the majority of these would not contain all the elements we needed to answer the initial question. The second assessment eliminated all but five references that contained the three components most needed for the question to be answered: (i) a climate change component (direct or indirect); (ii) a measure of change in one or more biodiversity characteristics; and (iii) a management intervention that could mitigate the climate change impact on the biodiversity characteristic.

The following habitats / ecosystems were covered in the five references:

- calcareous fens (Switzerland);
- moorland / heathland (Peak District, UK);
- semi-natural grassland (SE France); and
- commercial forests (Austria and Germany).

Closer examination of the management component of these references showed that:

- three were model-based studies (one of which was not relevant and two were deemed as partially relevant[9]);
- one was an observational study (deemed relevant); and
- one was an experimental study (deemed relevant).

Qualitative study quality assessment

The lack of suitable references coming through the assessment phase of the review meant that it was not possible to extract any data that would be able to contribute to a meaningful meta-analysis. Only two studies (0.5%) from the initial extraction of 411 were deemed relevant to answering the primary question and the findings within the papers are discussed below.

Synthesis of primary question

Both the papers that were deemed relevant (Lindner et al. 2000; Lexer & Seidl 2009) related to climate change and forest management (Table 4.3). Lindner et al. (2000) used a forest succession model (FORSKA) to examine forest development in 488 forest inventory plots in the federal state of Brandenburg, Germany, under two climate and three management scenarios, while Lexer et al. (2002) used a hybrid forest patch model (PICUS) to examine how the vulnerability of nine different site types in commercial forests of the Austrian Federal Forests (AFF) would alter under climate change scenarios and different sustainable forestry management objectives.

Table 4.3: A comparison of the relevant components of the biodiversity papers for Question 1

9 Partially relevant for their ability to potentially contribute to the second question.

	Lindner et al., 2009	Lexer & Seidl, 2009
Subject	Natural and managed forests	Managed forests
Driver	Climate change: current climate and with a temperature increase of 1.5^{o}K	Climate change: baseline A1B, A2 and B1 scenarios
Intervention	Management 1: traditional management; 2: favour climatically well adapted species; 3: maximise species diversity.	Management: 1 current AFF management preference; 2: biodiversity maximised 3: 1 and 2 given equal weight
Outcome	Changes in forest type	Vulnerability to climate change, established through indicators
Comparators	Forest type (dominant species)	% forest area

Lindner et al. (2000) showed that using current climate 71% of the forests under traditional management were still pine-dominated forests in the year 2100, but the management scenarios 2 and 3 led to a 98% and 61% respectively increase in proportion of deciduous species. There was a higher share of oak and birch dominated stands in the second scenario (49% and 30% respectively) and of oak (18%) and other hardwoods (25%) in scenario 3. Under the climate change scenario, there was a shift in simulated species composition towards more drought tolerant species, including a decrease in beech from a maximum of 10% under current climate, to less than 1%. Under traditional management 50% of the plots were simulated as pine-dominated and a further 28% as mixed pine-broad-leaved dominated. Under the adaptive and species diversity management scenarios, oak and oak-pine forest types were simulated as more dominant. As this is a modelling study it is subject to a number of limitations and while many aspects of the FORSKA model have been validated, the authors are less certain about its current ability to handle the different management routines.

Lexer et al. (2009) used indicators to assess how different components of the forest could be vulnerable to climate change. The indicators were chosen to be sensitive to climate change and to reflect the AFF management objectives and were: productivity, timber and carbon stocks, biodiversity and disturbances. Biodiversity has two sub-indicators – standing deadwood and tree species diversity (expressed as the Shannon H' index, calculated from species' basal area shares). The state of the system was represented by the following indicators: species composition, silvicultural flexibility and economics (cost intensity). The modelling showed that vulnerable forest area increased during the 21st century, and also that under the conservation scenario the percentage vulnerable area was less than under the management scenarios 1 or 3. The biodiversity indicators seemed insensitive to climate change and were more affected by the management regimes. This is because disturbance increased with climate change, while timber stock, carbon pools and productivity decreased primarily due to drought stress, mediated by an intensified bark beetle disturbance regime. The vulnerability assessment framework was shown to be sensitive to the biodiversity indicators, and thus indicates the importance of integrating biodiversity into future management regimes.

These two papers have shown, in a modelling context, the importance of management. In the first case, it can be inferred that management can be used to affect future forest types in order to achieve desired objectives, including ensuring that species which are more adapted to climate change are promoted (Lindner et al. 2000). In the second (Lexer et al. 2009), resilience could be associated with low vulnerability or no change and this could be achieved, in this example, by the promotion of the biodiversity indicators and/or by reducing the negative changes in the other indicators. Neither authors use the term resilience in relation to their studies, although both do imply it.

4.4.2 Secondary Question

Description of studies

The same 54 full text publications were then assessed with regard to their suitability to answer the secondary question of the project:

> How resilient are the biodiversity characteristics of the UK Broad Habitats to environmental change?

Publications were assessed on firstly on whether they contained two components that were needed to answer the question: (i) a climate change component (direct or indirect); and (ii) a measure of change in one or more biodiversity characteristics. At this stage of the review we took a broad approach to assessing these two components.

Only 18 of the 54 papers assessed had both a climate change and a biodiversity component. A summary of the relevancy, habitats covered and the climate change components are summarised in Table 4.4. Only 12 of the publications were deemed to be relevant (six) or partially (six) relevant. The majority of the studies that were relevant covered an aspect of water stress (e.g. drought). The most numerous of these were grassland habitat types of which all the studies were experimental. Of the 18 publications, only two were conducted in the UK, 10 in the rest of Europe and six in North America.

Table 4.4: Number of papers recorded that contained both a climate change component and a measure of change in one or more biodiversity characteristics. Superscript numbers indicate the number of papers in each category that were deemed to be relevant to answering the question.

Habitats	GCM	Temperature	Water stress	Other
river / stream	11			water contributions
forests / woodland	73	11	1	
Grassland			33	
Riparian				Flooding1
Various (ECN sites)			22	
limestone pavement			11	
Relevance (full / part)	4	1	6	1

Qualitative Study quality assessment

The lack of suitable references coming through the assessment phase of the review meant that it was not possible to extract any data that would be able to contribute to a meaningful meta-analysis. Only six studies (1.5%) from the initial extraction of 411 were deemed relevant to answering the secondary question and the findings within the papers are discussed below.

Synthesis of the second question

Forests

The three papers all use models to assess the impacts of climate change on different biodiversity components and thus they are not directly comparable, although they all comment to various extents on species composition. One paper is concerned with how genetic diversity and ecophysiology affects species' adaptation to climate change (Kramer et al., 2008), another addresses changes in ecosystem composition (Nitschke and Innes, 2007) and the third, species turnover (Vennetier and Ripert, 2009).

Kramer et al. (2008) integrated field and experimental information on the genetic and ecophysiological functioning of beech (*Fagus sylvatica*) from two 2ha plots in five beech forests in Western Europe (Austria, France, Germany, Italy and The Netherlands) into a coupled genetic-ecophysiological model for trees to assess the adaptive response of beech stands to climate change. They found that if recruitment intervals are short and many mother trees contribute to the next generation, then beech has a high adaptive potential. These findings are important for future management regimes which can influence these critical factors.

Nitschke and Innes (2007) used a tree and climate assessment model (TACA) in the interior Douglas-fir (IDF) ecosystem, British Columbia to model the resistance and resilience of 17 tree species to climate change scenarios, based on the sensitive regeneration stage. It also used changes in phenological and biophysical variables to examine potential changes in ecosystem composition. The model used the following variables to determine species presence/absence: growing degree day thresholds, species-specific temperature thresholds, minimum temperature, chilling requirements, bud break, drought and frost.

Table 4.5: Changes in biophysical variables by 2085 (Nitschke and Innes, 2007)

Biophysical variable	Current	By 2085
Growing degree day threshold exceeded	41%	88%
Chilling requirement not met (average)	0%	38.00%
Budburst		42-52 days earlier
Frost damage (average but considerable variability)	32%	51%
Drought threshold exceeded	71%	94%

The projected changes in climate and thus biophysical variables (Table 4.5) could lead to the IDF ecosystem becoming dominated by ponderosa pine. Thus the IDF is viewed as not resilient to climate change, as under increased temperatures and drier conditions it cannot successfully compete in its regenerative phase with the ponderosa pine.

Vennetier and Ripert (2009) used a bioclimatic model, validated with historical plot data, to simulate the turnover of flora in French Mediterranean forests under several climate change scenarios. The turnover over the last 30, 20 and 10 years has been simulated as 11.5, 14 and 25% and projected changes are summarised in Table 4.6. This turnover was not equally distributed across the plant types, with more than 50% of the mesophilous plants, which require more water and a cooler climate, losing ground, while more xero-thermophilous plants arrived or increased in cover and abundance.

Table 4.6: Projected changes for the Vennetier and Ripert (2009) bioclimatic model

Increase in annual temperature (^{o}C)	Change in spring rainfall (%)	Change in summer rainfall (%)	Simulated % turnover
1	-10	-10	10
2	-10	-10	20
1.4	-18	-32	25

This paper thus showed how climate change could lead to a considerable turnover in forest flora, but the turnover in the last decade was only half that predicted by the model and equal to that for the last 20 years, thus there was some resistance to climate change and adapting to new climate conditions may take about 20 years. This may allow for more sensitive (mesophilous) species to take advantage of favourable conditions to reproduce. Management however may be necessary as many of the plants in the areas with the highest plant species richness lose their suitable climate space by 2050.

__Grasslands__

All three papers examined the impact of drought from an experimental perspective and although none were undertaken in the UK, their findings could be considered relevant to the response of Broad Habitat grasslands. The earliest paper, Tilman and Downing (1994), examined the resistance to drought as expressed by the relative rate of change of plant biomass. They found that drought species-rich communities produced about half their pre-drought biomass, whereas the species-poor communities produced only one eighth. Their analysis suggested that drought resistance was a consequence of the species-rich communities being more likely to contain some drought resistant plants. They also calculated resilience as the ratio of post-drought biomass to average pre-drought biomass. This showed that the species-poor communities were further from their pre-drought biomass in all of the post-drought years, whereas four years after the drought the species-rich plots had regained their biomass. There was a significant partial correlation between this drought recovery and the natural logarithm of 1989 species richness (the year after the peak of the drought), with species-poor plots taking longer to recover. Their results suggest that ecosystem drought resistance has an increasing, but non-linear relationship with species richness, thus each extra species lost has a progressively greater impact on drought resistance. This work, therefore, supports the diversity-stability hypothesis.

Pfisterer and Schmid (2002) used artificial drought in field experiments to also explore the resistance and resilience of ecosystems, and while they agree with Tilman and Downing (1994) that autotrophic biomass is a good response variable associated with species richness, they found that species-poor systems had more resistance to the drought perturbation, and a greater initial resilience, with the original relationship between diversity and productivity being restored faster (after one year). They suggest that while biodiversity increases biomass production, such a diversity-production association may lead to an inverse relationship between biodiversity and the stability of ecosystem functioning. Pfisterer and Schmid (2002) also found that the presence of particular species e.g. *Poa pratensis* or groups e.g. legumes could affect plot biomass production due to their different sensitivity to drought. These varying responses of individual species to perturbation led to decreased species evenness in perturbed subplots when compared with unperturbed subplots. They conclude that while ecosystem resistance and resilience decreased with increasing diversity in their experiments, the relationship between diversity and biomass production was still positive, even under perturbed conditions. Thus, the perturbation was not strong enough to completely remove the positive diversity-dependence of ecosystem functioning.

Zavalloni et al. (2008) focused on the single and combined effects of temperature and increasing species richness levels (1, 3, 9 species) on the resistance of grassland communities to an imposed drought period. The communities were grown for three years at either ambient (unheated) or ambient +3°C (heated) air temperatures and the relevant biodiversity characteristics measured were green vegetation cover and above ground biomass. The green vegetation cover was significantly reduced by the drought in both temperature treatments, although the decrease was higher in heated than unheated communities, indicating their lower resistance to the drought. The decrease, however, was similar for the different species richness levels, suggesting that this does not affect ecosystem resistance. After only 13 days of recovery, the green vegetation cover of both temperature treatments approached values similar to those observed before the imposed drought, suggesting similar resilience in both treatments.

Above-ground biomass was reduced by increased temperature, consistently for all species richness levels showing that the drought period did not change the biomass production patterns. This suggests that the heated communities had not developed mechanisms to better cope with extended summer droughts. The biomass of dominant species, such as *Medicago sativa*, *Rumex acetosa* and *Dactylis* glomerata, however, was positively influenced by the species richness level. In this study, therefore, increasing species richness did not enhance drought resistance and the communities exposed to warming and short drought events did not show a higher resistance to the imposed severe drought.

There has been a long running debate in the literature about species richness and its relationship with resistance and resilience, and for some reason many of the papers have not come through to this stage of the review or have not been picked up, including papers by the above authors (e.g. Tilman et al., 2006). This may be because they have not contained a specific environmental change term. The above papers illustrate some of this debate, with contrasting findings on the aforementioned relationships in the context of imposed drought.

4.4.3 Outcome of the review

Conclusions

It is not possible to critically assess "How resilient are the biodiversity characteristics of the UK Broad Habitats to environmental change?" based on three papers for two habitats, even with cautious extrapolation of these examples, especially as none of the them was undertaken in the UK.

This is not a function of the level or kinds of research being carried in the UK (or elsewhere), but rather, that it is premature for studies on the efficacy of (adaptation) management strategies governing the mitigation of biodiversity impacts to be measured. In essence we are asking a question that the body of current research is unable to answer. Expert opinion was that since climate change impact research is focused on future changes, most of the empirical data would be either modelling or experimental, a pattern that has been shown in this review. This would also make it difficult to say anything with certainty and this leads to a problem with the 2nd question (Watt, 2010, pers. comm.).

An initial contributory factor to the lack of papers is that, as discussed earlier, the use of UK Broad Habitats may be restrictive, as the terms are not widely used by ecologists (Watt, 2010, pers. comm.). This was addressed by using a wider set of search terms which was at least partially successful in increasing the number of papers for the review.

A second possible explanation for the low numbers of research publications identified is that the terms associated with a search this broad may be too complicated to be accommodated in a systematic search of this nature. For example, there are few specific terms that describe resilience throughout the literature and there are instances, as noted in this review, that although authors suggest the concept of resilience they sometimes do not use terms that explicitly state what they are referring to.

Implications for management, policy and research

The question(s) raised in this systematic review may be premature and it is believed that current research is probably not able to provide an answer at this stage. It is also noted that management is mostly undertaken by Statutory Agencies, NGOs and private landowners and thus may not be documented or published in a way that is picked up by these searches. The reviewers believe that a more flexible search approach to the question, or a more refined question could have helped. Alternative search engines such as those on www.conservationevidence.com could also have helped[10] and made use of the grey literature. Also, it could, however, be argued that systematic reviews are not designed for such complicated search strings. In terms of informing current and future policy, other systematic reviews should be designed such that the questions are more specific and/or there are only three search components. This review also points to the need for more long-term research and monitoring to support answering such complex questions, although there could be an issue in that responses due to climate change measures may be combined with mitigating other aspects of environmental change, or that climate change is only one of a number of drivers of biodiversity characteristics. Thus extra care will be needed to separate out the responses from these

[10] However, these types of search engines are not intended to be used with the elaborate search strings that were developed during the course of this review.

different drivers. Long-term data can also be used in model validation, for, as this review has shown, many of the relevant studies are based on modelling.

Although the review has not been able to effectively address the questions through a meta-analysis of research findings, it has thrown up a number of interesting issues that provides some insight into the process of systematic reviews and also into how future research is conducted.

5. Water

By Richard Mercer, Pam Berry and, Paula Harrison

5.1. Background

The document Future Water (Defra, 2008) sets out a strategy for ensuring the sustainable delivery of water supplies in England by 2030, and what steps are needed to improve and to protect the water environment. The strategy deals with a number of issues affecting both supply and demand. Defra is interested in understanding how increased variability in water availability and changes in abundance will affect the quantity and quality of future water provisioning. Rivers, lakes and wetlands fulfil key regulating functions with respect to the quantity and quality of freshwater and Defra are also currently investigating the impact of creating wetlands to reduce flow variability. It is widely accepted that climate change poses severe threats to freshwater ecosystems. A review of the scientific basis for adaptively managing vulnerable habitats and species found that adaptation planning is constrained by uncertainty about evolving climatic and non-climatic pressures, by difficulties in predicting species- and ecosystem-level responses to these forces, and by the plasticity of management goals (Wilby et al., 2010). Different ecosystems are known to be of varying importance in the provision of water regulating services and a review of the status and trends globally (Millennium Ecosystem Assessment, 2005; Carpenter et al., 2009) and in Europe indicates that for most of them their service provision is declining (Harrison et al., 2010), due to human pressures and climate change. Thus in order to ensure sustainable delivery of such services it is important to know how ecosystems could be managed most effectively.

5.2. Objectives

These ideas formed the starting point for identifying a question relating to water and the issue of resilience in the light of climate change. It was suggested that a primary focus for review might be the resilience of ecosystems at the catchment scale, and how different land management strategies might best deliver a range of ecosystem services, including water quantity and quality. It was also suggested that in general terms, policy makers needed to understand better the 'connectivity between environmental compartments', and that land and water managers needed better tools for understanding the interactions between ecosystems. This led to the following broad question being suggested as the basis for discussion:

> ***How can we best protect the capacity of England's major ecosystems to supply and regulate the quantity and quality of water?***

Two contrasting perspectives were then considered in terms of the direction that the *RECCE* water review might take. Firstly, the resilience of aquatic and wetland systems to environmental change or secondly the resilience of the water regulating services associated with ecosystems could be studied. Given the current interest in ecosystem services, for example in the Millennium and UK National Ecosystem Assessments, the systematic review focused on the ability of water ecosystems to regulate quantity, such as flood prevention and quality of fresh water.

5.2.1 Primary objective

The primary question therefore was:

> ***Can management interventions mitigate the impacts of environmental change on the water regulating characteristics of ecosystems?***

This is a very broad question that does not specify the type of management interventions, environmental changes or water regulating characteristics needed for a systematic review. It also is different from other systematic reviews in that it includes issues about both interventions and external drivers, thus adding an extra level of complexity to the review. Table 5.1 separates the initial question using the formal elements of a potentially reviewable question, that is some permutation of *'does intervention/exposure I/E applied to populations of subjects P produce outcome O?'* (Centre for Evidence-Based Conservation, 2010).

Table 5.1: Definition of components of the primary systematic review question

Subject	UK Broad Habitats but also including analogous habitats and ecosystems from Europe and/or North America
Driver	Environmental change, specifically climate change
Outcome	Regulation of water quantity and quality (regulatory services)
Intervention	Management interventions that would mitigate impacts – e.g. restoration
Comparators	degrees of environmental change (with or without intervention), including extreme events and other indirect effects of climate change

A quality control element of the review requires studies to have a baseline or control in order to identify the effect of management interventions and to be quantitative in order to establish their effectiveness. This introduces a further restriction on the inclusion of papers in the review.

The primary objective of this review is the investigation of the contribution of management to the mitigation of climate change impacts on the resilience of water regulating services of ecosystems.

5.2.2 Secondary question

As discussed in the introduction there is concern about the condition and trend of ecosystems services, including water regulation, with climate change being seen as one of the key negative drivers of service provision. Studies have indicated that often there is little or geographically patchy information on which to base these assessments of status and trends and particularly any quantification of them (e.g. Harrison et al., 2010). Thus the secondary objective of this study is to examine the question: ***How resilient are the water regulating characteristics of ecosystems to environmental change?***

5.3 Methods

5.3.1 Question formulation

The question was developed as part of the search protocol to address the overarching RECCE question: *how do management interventions impact on the resilience of ecosystems to environmental change?* Water regulation is an important ecosystem service, particularly with projected greater water demand in the future and with more variable precipitation. Understanding how these regulatory services will be impacted by climate change is a pressing question with examples including questions like: will increased variability in rainfall and groundwater impact on the ability of riparian habitats to slow flood waters?

The initial question was refined through discussion on the RECCE website e-forum, through a consultation with Defra and with the input of expert opinion. There was only one response via the RECCE website and this suggested the question: "How can we understand and value the resilience of an ecosystem at the scale of a river catchment so as to better manage land and water in a more integrated way to provide optimum goods and services?". This question was modified through the other discussion mechanisms, such that rather than seeking to understand resilience in order to inform management of water goods and services, management was used as a means to understand ecosystem resilience (in the light of climate change). This was mirrored in the Defra Project Steering Group, where discussion revolved around whether the resilience of aquatic and wetland systems to environmental change should be considered, or rather the resilience/vulnerability of the water regulating services associated with ecosystems more generally to environmental change, with the latter being decided upon as the relevant issue for investigation. The expert consulted agreed that the question posed is relevant to policy, with the two main hydrological concerns at the moment being (1) changes in run-off speed and volume and (2) diffuse pollution and these could be essentially covered by the posed questions.

5.3.2 Search strategy

Relevant published research articles were identified through searches of the following electronic databases:

1. ISI Web of Science
2. Scopus
3. Science Direct

Proceedings were not included in the search and were removed from the final output.

Search string and term development

The primary question was the starting point for the development of the search string (Table 5.2). The question was broken down into subject, driver, outcome and intervention categories and combined into the following format:

> *Hydrological unit **AND** water parameters **AND** vegetation unit **AND** management **AND** climate change*

In order to focus the search further we included two additional categories, the first describing resilience and the second describing quantitative studies. Finally, we applied a filter to exclude certain topics. The final search format was:

hydrological unit **AND** water parameters **AND** vegetation unit **AND** management **AND** climate change **AND** resilience terms **AND** quantitative terms **AND NOT** terms to be excluded

The development was iterative and we aimed to capture as much of that process as we could in the notes and descriptions. Each of the categories in the search string is discussed in more detail below.

Table 5.2: The results of the development of the search string

Search	Search Strings – WoS	Hits
1	TS=(catchment* OR river* OR stream* OR watershed* OR landscape*)	>100,000
2	TS=(flood* OR "run off*" OR runoff OR eutrophication OR drainage* OR "flow regime" OR erosion* OR siltation OR pollut* OR discharg* OR "overland flow*" OR "particl* load*" OR sediment* OR "suspend* load*" OR pH OR DOC OR "dissolved organic carbon" OR "flow regime*" OR retention OR "ecosystem service*" OR "water quality" OR "water quantity" OR "water storage*" OR "regulat* service*" OR "low flow*" OR "environmental flow*" OR "land drainage*" OR "flow regulation*")	>100,000
3	TS=("land cover" OR "non structural" OR vegetation OR woodland* OR forest* OR tree* OR wetland* OR meadow* OR heathland* OR peatland* OR bog* OR marsh* OR swamp* OR grassland* OR river* OR "river flood*" OR floodplain* OR saltmarsh* OR "salt marsh*" OR wetland* OR riverine* OR riparian* OR moorland OR machair OR "chalk river*" OR fens OR reedbed* OR "soft engineering*")	>100,000
4	TS=("climat* change*" OR "global warming" OR "environment* change*" OR drought OR warming OR temperature*)	>100,000
5	TS=(manage* OR restor* OR conserv* OR protect* OR remediat* OR interven* OR rehabilitat* OR "land use" OR abstraction OR "program* of measure*")	>100,000
6	#1 AND #2 AND #3 AND #4 AND #5	3,750
7	Exclusion terms – straight from Biodiversity #14	
8	#1 AND #2 AND #3 AND #4 AND #5 NOT #7	1,651
9	TS=(sampl* OR experiment* OR measur* OR data OR monitor* OR meter*)	
10	TS=(resilien* OR adapt* OR resistan* OR threshold* OR vulnerab* OR recover* OR stability OR variability)	
11	#8 AND #9 AND #10	324
12	Removal of 77 proceedings papers	245

Hydrological Unit

The "hydrological unit" segment of the search string was intended to ground the rest of the search segments to the core aspect of the primary and secondary questions. Many of the terms within the other string segments are widely used in other research fields and we felt that we needed to control the breadth of the search. For this reason the "hydrological unit" segment was inserted to focus attention on the components of the landscape where we would see the water regulatory effects of ecosystems: rivers and streams. This segment also provides some sense of scale to the search. The regulatory role of ecosystems and habitats is generally measurable at larger scales. We believe that these are covered by the terms catchment and watershed.

The following terms were included to represent the range of synonyms relating to the concept of the hydrological unit: catchment, river, stream, watershed, and landscape.

Water Parameters

The water regulating characteristics of ecosystems were covered by searching for terms within the literature that relate to the quantity and quality of water within aquatic systems. The terms selected were deemed to be quantifiable, meeting one of the main aims of RECCE, and were chosen to include those that may be used by a range of different disciplines (e.g. ecologists, land managers, engineers).

The following terms were included to represent the range of synonyms relating to measurable water parameters: flood, flooding, run off, runoff, eutrophication, drainage, flow regime, erosion, siltation, pollution, pollutant, discharge, overland flow, particle load, sediment, sedimentation, suspended load, pH, DOC, dissolved organic carbon, retention, ecosystem service, water quality, water quantity, water storage, regulatory service, low flow, environmental flow, land drainage, and flow regulation.

Vegetation Unit

The primary and secondary questions focused on UK Broad Habitats, but it was thought necessary to expand the terms describing the habitat component of the search to include more generic terms. It was also noted that different disciplines would use different terms to describe habitats, and in some cases riparian habitats providing an ecosystem service might not be described in line with the UK Broad Habitats or be comparable. For example, trees may be planted in riparian areas to provide structure to slow flood waters, but these habitats might not be described as woodlands or forests.

The following terms were included to represent the range of synonyms relating to the vegetation unit: land cover, non structural, vegetation, woodland, forest, tree, wetland, meadow, heathland, peatland, bog, marsh, swamp, grassland, river flood, floodplain, saltmarsh, salt marsh, riverine, riparian, moorland, machair, chalk river, fens, reedbed and soft engineering.

Management

There are general terms such as "management regime" and "land management" that describe an intervention strategy for maintaining, enhancing or studying the resilience of systems. We used the terms that were developed for the Biodiversity section of the RECCE (Chapter 4), with the addition of some subject specific terms after expert consultation.

The following terms were included to represent the range of synonyms relating to the concept of "intervention": *manage, management, restoration, restore, conserve, conservation, protect,* *protection, remediate, remediation, intervene, intervention, rehabilitation, rehabilitate, abstraction, land use* and *program of measure.*

Climate Change

Although the scope of the RECCE programme covered environmental change, in terms of brevity it was decided to narrow this topic and focus just on climate change. The following terms were included to represent the range of synonyms relating to the concept of climate change: *climate change, climatic change, global warming, environmental change, drought, warming* and *temperature.*

Resilience terms

The term resilience has been defined in the literature and research concerning ecological resilience and can be described specifically by two ideas as detailed by Brand and Jax (2007):

1. The **magnitude** of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour; and,
2. The **capacity** of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity.

Other terms that represent the first idea of the magnitude of disturbance that can be absorbed, are *threshold, limit,* and *resistance*. The second idea of retaining essentially the same identity of a system is well characterised by the terms vulnerability, recovery, stability, variability, and adaptation. This second group of terms is a description of the integrity of the system and its susceptibility to change. Different disciplines represent the theme of resilience differently. For example, the three parallel and overlapping knowledge domains identified by Janssen et al. (2006) and Janssen (2007) use the terms *adaption, resilience* and *vulnerability* in research on the human dimensions of global environmental change. These three terms originate from different disciplines and their legacy is indicated by the category of journals that publish them, although there is an increasing overlap between the knowledge domains in recent years.

Original disciplines using the terms (adapted from Janssen et al., 2006):

Resilience: population ecology and later social ecological systems;

Vulnerability: impact of natural hazards on person or groups and recently climate change; and,

Adaptation: anthropologic study of response to environmental variability and subsequently specifically to climate change.

The following terms represent the range of synonyms relating to the concept of ecological resilience and how this is presented in the literature: *resilience, resilient, adaptation, adaptability, adaptive, resistant, resistance, threshold, vulnerable, vulnerability, recover, recovery, stability, variability.*

Quantitative terms

RECCE is focussed on quantitative studies that can provide data that could ultimately be incorporated into a meta-analysis. This search segment was included to focus the studies on those that actually contained measurable data as opposed to those publications discussing the qualitative impacts of ecosystems on water regulation.

The following terms represent the range of synonyms relating to quantitative studies: *sample, experiment, measure, data, monitor* and *meter*.

Exclusion terms

The geographic exclusion terms developed in the Biodiversity section were transferred across to this section. They were developed to help focus attention onto Eurocentric studies, which are most likely to provide transferable studies to the UK context, as well as other relevant temperate areas, such as the U.S. and ecosystems that would contribute to the scope of this study.

The full list of habitat terms is included in Appendix 2.2.

5.3.3 Study inclusion criteria

Papers to include in the review had to meet the following criteria:

Relevance: studies that were in very hydrologically and/or ecologically different parts of the world were omitted as results were considered not to be sufficiently transferable to the UK context, which was the prime focus of this review. Also, only journal articles with titles and abstracts in English and PDFs available for full analysis were included.

The following criteria were used to assess the papers as unsuitable for inclusion:

- Examining or modelling potential impacts of climate change on water, where the focus was on the modelling methodology
- Exploring how changes in hydrological parameters would impact on biodiversity (mostly on single species)
- Toxicology experiments dealing with small sets of species
- Historical studies with limited environmental reconstruction, such that it is not possible to quantify hydrological changes

Types of intervention: a wide range of interventions were considered and after consultation with an expert this was widened to include terms such as, soft engineering and flow regulation, as they were thought to be appropriate to the engineering community concerned with the water resource management.

Types of outcome: these should reflect the regulation of water quantity and quality and thus included a wide range of terms to cover the physical, chemical and biological properties of water, as well as those relating to the magnitude and timings of flows.

Types of comparators and designs: experimental, observational and modelling studies where there was a control (baseline) were considered appropriate for inclusion. Studies in the first two categories, were of necessity based on smaller spatial scales, and usually shorter time-scales than modelling studies.

References retrieved from the databases were exported directly into EndNote X2.0.1 prior to assessment. Duplicate references from running identical searches on the three search engines were removed. Only studies reported in English were used to conduct this review. Searches were conducted on the 26/07/2010 and all references identified during the searches were exported to EndNote X2. A total of 586 references were exported from the three search engines: WoS (245), Scopus (285), SD (56). Duplicate references were removed in EndNote (198) leaving a database of

388 references for assessment. The contribution of unique references by each search engine can be broken down to: WOS (245 refs or 63%), Scopus (128 refs or 33%), Science Direct (15 refs or 4%). These 388 references were then assessed on their titles and abstracts.

Articles were initially filtered by title and abstract and any that were obviously irrelevant were excluded. The abstracts of the remaining articles were then examined to assess relevance and viewed at full text of it appeared that contained information pertinent to the review questions. Due to time constraints the inclusion of studies was not verified by a second reviewer. However, during the scoping phase of the project an assessment was done that showed the two reviewers *agreed moderately* on their assessment of relevance (Cohen's Kappa = 0.46).

5.3.4 Study quality assessment

Usually study data are accepted for further analysis (or possibly meta-analysis) when the study's criteria are fulfilled and appropriate comparators and variance measures exist (e.g. Smith et al., 2010). Given the small number of papers meeting the criteria, all papers were examined to explore the set questions, but only a qualitative, more descriptive analysis was possible (Section 5.4).

5.3.5 Data extraction strategy

A tiered data extraction strategy was adopted due to limitations on time and also on the availability of relevant publications. The initial extraction focused on extracting descriptive information for each publication that would enable us to profile the database of publications. This was vital in that with the breadth of potential subjects, outcomes and drivers it was not possible to know beforehand the sorts of data that we could reliably extract, and that would contribute to a meta-analysis around the primary question.

Once papers had been identified for inclusion in the study the following data were extracted into a spreadsheet:

Design: Whether the study was experimental or observational in design or a review.

Dependent variable: The water or river variables measured

Independent variable: the climate parameter or management intervention used

Comparator: The type of comparison being considered, defined in terms of the independent variable.

Space or Time Perspective: the scale of the study and whether the study looked at differences in water response time.

Time-span considered: if time comparisons were involved, how long the time span being used to track the response was.

Resilience perspective: whether the study provided insights into the ability of the hydrological system to resist disturbance or to recover from disturbance.

Ecosystem and Location: the geographical context of the study.

5.3.6 Data synthesis

Given the diversity of the wider set of papers and the relatively few papers considered relevant to all components of the search, only a qualitative synthesis was undertaken. This can help the appreciation of current research into water regulating services, especially the contribution of ecosystems to this.

5.4 Results

5.4.1 Primary Question

Can management interventions mitigate the impacts of environmental change on the water regulating characteristics of ecosystems?

The first round of assessment produced 105 suitable papers but only 78 were used due to journal access restrictions. No assessment is available of the possible contribution of the excluded 27 papers.

Description of studies

Examination of the full text of the 78 references was undertaken to reveal how many references contained the three components needed to answer the primary question: (i) a climate change component (direct or indirect); (ii) a measure of change in one or more water regulating characteristics of ecosystems; and (iii) a management intervention that could mitigate the climate change impact on the water regulating characteristic (Table 5.3).

Table 5.3: Frequency of the selected components of the search terms

Component	Number of studies
Climate change	17
Measure change in one or more water regulating characteristics of ecosystems	11
Management intervention	22

Of those with a climate change component, two were using historical records to reconstruct or infer past climate, while others were concerned with using future climate scenarios. Only 11 studies referred to the water regulating properties of their study habitats, while many others were measuring variables, such as land cover, which could influence regulation. The management interventions included changes in land cover, especially forest, and flood management and it is the latter which were more directly related to the mitigation of the climate change impact on the water regulating characteristics.

Study quality assessment

Only four references were quantitative studies which had all three components (Table 5.1). All four papers were modelling studies. The studies were all based in different locations and considered different hydrological units as follows:

- Whitehead et al. (2006): lowland chalk stream in England

- Hu et al. (2005): stream in USA
- Oltchev et al. (2002): catchment in Russia
- Diodato (2006): catchment in Italy.

Table 5.4 compares the relevant components of the water regulating papers for Question 1. Two studies considered the regulation of water quantity (total runoff in Oltchev et al. (2002) and stream discharge in Hu et al., (2005)) and two considered the regulation of water quality (N-load in Whitehead et al. (2006) and catchment erosion in Diodato (2006)). Management interventions in three papers were all related to forest habitats (Hu et al. (2005); Oltchev et al. (2002) and Diodato (2006)), whilst Whitehead et al. (2006) considered management related to arable and wetland habitats.

Table 5.4: Comparison of the relevant components of the water regulating papers for Question 1

	Whitehead et al. 2006	Hu et al. 2005	Oltchev et al. 2002	Diodato 2006
Subject	Lowland chalk streams.	Stream within a watershed.	Catchment.	River basin.
Driver	Climate change: 3 GCM (CGCM2, CSIRO, HadCM3) and 2 emission (A2, B2) scenarios up to 2100.	Climate change: 2 precipitation scenarios (wet and dry conditions).	Climate change: 2 scenarios (ECHAM4 GCM and C-HRM regional model).	Historic climate variability over past 400 years (1675-2004).
Intervention	Management: (i) reduce N fertilization in arable; (ii) reduce N deposition; (iii) introduce water meadows.	Management: 6 land use change scenarios related to different amounts of conversion of forest to grassland.	Management: (i) reforestation; (ii) deforestation.	Historic land use change: deforestation.
Outcome	Regulation of water quality.	Regulation of water quantity.	Regulation of water quantity.	Regulation of water quality.
Comparators	Stream-water nitrate-N and ammonium-N concentration.	Change in stream discharge from river basin.	Change in surface runoff and groundwater recharge.	Change in annual net erosion.

Qualitative synthesis

Only four studies from the initial extraction of 388 were deemed relevant to answering the primary question. The open-ended and multi-component nature of the primary question meant that there was a lack of suitable references coming through the assessment phase of the review, such that it was not possible to extract any data that would be able to contribute to a meaningful quantitative analysis.

Whitehead et al. (2006) modelled the impacts of climate change on nitrogen (N) in a lowland chalk stream (the River Kennet, a major tributary of the River Thames) using the INCA-N model. Daily hydrology and water quality were projected under three GCMs (CGCM2, CSIRO and HadCM3) and two greenhouse gas emission (A2 and B2) scenarios for the period 1961–2100. Stream-water N concentrations increase over time by up to 33% for nitrate-N and 122% for ammonium-N in the 2080s as higher temperatures enhance N release from the soil, and lower river flows reduce the dilution capacity of the river. Particular problems are shown to occur following severe droughts when N mineralization is high and the subsequent breaking of the drought releases high nitrate loads into the river system. Extended periods of high nitrates could create problems for the water industry because of the need to maintain public water supplies with nitrate-N below EU legal limits. Also, there are implications for export of nitrate to coastal ecosystems and downstream impacts such as enhanced eutrophication. Three management interventions for reducing climate-driven N loads were modelled individually and in combination: (i) reductions in N applications of fertilisers or organic manures or taking land out of production; (ii) reductions in N deposition from atmospheric pollution; and (iii) the introduction of water meadows adjacent to the river system to enhance natural denitrification processes. In all cases, the management interventions result in water quality improvements relative to the non-intervention (control) situation. Furthermore, the benefits may be realised as early as the 2020s. The most effective strategy was found to be to change land use or reduce fertiliser use, followed by water meadow creation, and atmospheric pollution controls (Figure 5.1). Uncertainty about the future emission pathway had a modest effect on water quality even for the 2080s. However, different GCMs yield very different water quality projections and, by implication, different levels or timing for management interventions.

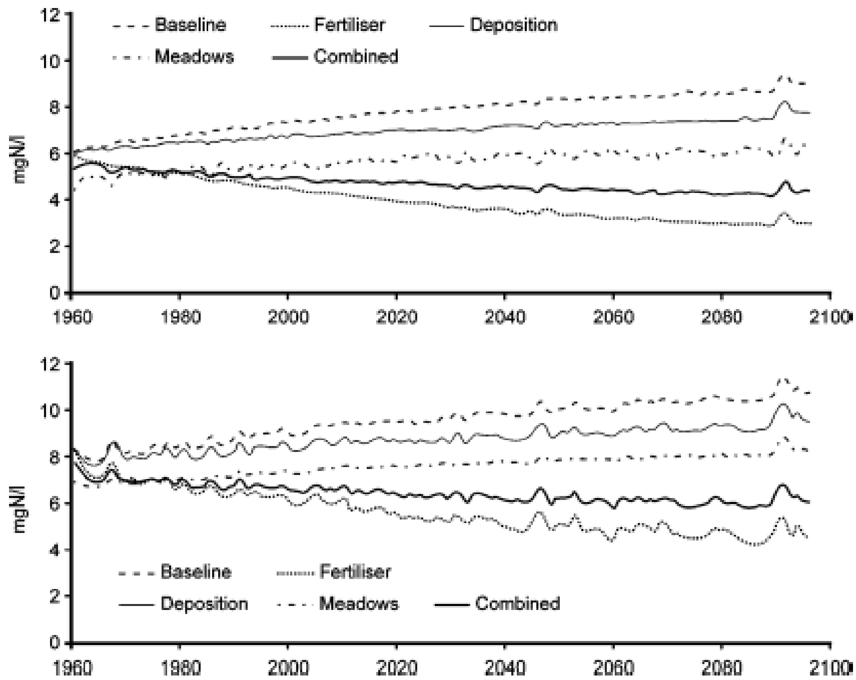


Figure 5.1: Adaptation runs using HadCM3 and A2 emissions showing nitrate impacts in the upper 'natural' reach (top graph) and in the lower 'effluent affected' reach (bottom graph) in terms of mean annual stream water nitrate concentrations for 1961–2100. The runs represent baseline conditions, fertiliser reduction, N deposition reduction, water meadow creation, and a combined strategy (Whitehead et al., 2006).

This paper clearly shows how management interventions can mitigate the projected increases in N due to climate change, and the third intervention shows how water meadows can help regulate water quality in this catchment, although the authors point out that the water meadow strategy has to be considered carefully. This is because during drought years it might not be possible to divert river flows across wetlands due to lower in stream volumes, and increased stress on river ecology. In addition, flow paths may alter, bypassing the water meadows and, therefore, management would be required to keep them operating to maximise denitrification. Wetlands, however, could act as a sink for first flush of nitrates from terrestrial systems when droughts end.

Hu et al. (2005) modelled the effect of climate and land cover change on stream discharge for the Jacks Fork River basin in the Ozark Highlands of the south-central United States using different independent and combined climate and land cover change scenarios. Six land cover change scenarios were constructed based on forest conversion to pasture or cropland: (i) change forest to grass in the north- and east-facing slopes (29% forest reduction), (ii) in south- and west-facing slopes (36% forest reduction), (iii) in west- and north-facing slopes (26% forest reduction); (iv) in north-, east-, and south-facing slopes (48% forest reduction); (v) change all grass to forest; and (vi) change all forest to grass. Climate change scenarios only considered changes in precipitation and were based on an analyses of the region's climate in the last 104 years. Two precipitation scenarios were constructed representing wet and dry climate conditions.

The results show that the more forest reduction (less forest coverage), the larger the stream discharge in the basin. The maximum change in stream discharge resulting from land cover change, from a grassland to a fully forested basin, is 0.7 mm day^{-1}. This change is about a half of the 1.3 mm day^{-1} caused by climate change alone from the extremely wet to extremely dry climate scenarios. Furthermore, when land cover change occurred simultaneously with climate variation, the basin discharge change amplified significantly and became larger than the combined discharge changes caused by the climate and land cover change alone. This indicates a synergistic effect of land cover and climate change on basin discharge variability related to the non-linear nature of evaporation and transpiration and related surface as well as soil hydrological processes in reaction to different climate conditions.

Oltchev et al. (2002) use a combination of the historical record of range of temperature and precipitation variables from the Upper Volga catchment and recent field data to construct a terrestrial water balance of the catchment as a function of external factors, such as climate and land-use, and examine the response of forest ecosystems to these external factors, as well as build and validate models for projecting the impacts of climate change.

The response of runoff to changes in temperature and precipitation over the last 20 years is shown in Table 6.5. Using a global scale general circulation model (ECHAM4) with a doubling of CO_2, climate change could lead to a 61mm increase in total runoff, while a regional model projects a 43mm increase and that the contribution of snowmelt to total runoff could decrease from 78% to 61% and 69% to 33% under the global and regional models respectively.

Table 5.5: Changes in mean annual and seasonal air temperature, precipitation and runoff in the Upper Volga catchment (from Oltchev et al., 2002).

Parameters	Period	Year	Winter	Summer
Air temperature (^{o}C)	Last 50 years	1.2	2.9	0
Precipitation (mm/period)	Last 50 years	14	92	-18
Runoff (mm/period)	Last 20 years	0	10	-5

A reforestation scenario which assumes a 13% increase in forest in the catchment is projected to lead to a decrease in surface runoff by 2-3% and of groundwater recharge by 1-2%, while for a deforestation scenario (5% decrease in cover made up of a decrease of 10% conifers and 3% mixed and deciduous) projected a 1-2% increase in total runoff and no change in groundwater recharge. These results imply that forest management in this case could have a minor impact on water regulation under climate change. Other studies on the effects of forestry management (especially deforestation) on runoff, which were not identified in this study, possibly as they did not include a climate change component, have suggested that the management impact in the above case study is relatively small compared with changes in temperate forests (e.g. Eiserbies et al., 2007).

Diodato (2006) modelled erosion responses to climate and land cover changes by reconstructing annual net erosion for the period 1675-2004 for the Calore River basin in southern Italy. The author argues that the modelling and reconstruction of the response of a river basin to past environmental changes is vital for developing scenarios of future response. This assumes that if the erosion model gives adequate results for the twentieth century, then it will also give acceptable results when run with changed climate and land-cover. However, the climate of the study region is Mediterranean, which may have limited applicability to the UK situation.

Results from Diodato (2006) show the effects of deforestation and rainstorm frequency on erosion over the past 400 years. Forest clearance began between 1780 and 1810 resulting in increased erosion (annual rates were about 20–100 MG km^{-2}). Continued deforestation between 1811 and 1860 caused an exponential increase in soil erosion (exceeding 300 MG km^{-2}). From 1861, erosion continued to increase at a slower rate due to greater aridity in the region, fluctuating at around an average annual rate of 550 MG km^{-2} after 1970. Pulses of natural sedimentation in the pre-deforestation period were related to Vesuvius volcanic activity and changes in rainstorm frequency. After deforestation, the basin system became unstable with sudden fluctuations in the hydrogeomorphological regime contributing significantly to increased erosion and reduced water quality in the river systems draining towards the Tyrrhenian coast. The results show that land-use had a more dramatic impact on erosion rates than natural climatic variability and suggest that the response of the Calore river basin to climate change is highly contingent upon local land-use and land management practices.

Hu et al. (2005), Oltchev et al. (2002) and Diodato (2006) all consider elements of how deforestation could affect the regulation of water flow, demonstrating the importance of forest in performing this service. Hu et al. (2005) also establish that there is a synergistic relationship between land cover and climate in the provision of this service, thus making it difficult to extrapolate across case studies.

Diodato (2006) also show the importance of forest (and other land use) for the regulation of water quality.

5.4.2. Secondary Question

Description of studies

The same 78 full text publications were then assessed with regard to their suitability to answer the secondary question of the project:

> ***How resilient are the water regulating characteristics of ecosystems to environmental change?***

Publications were assessed firstly on whether they contained two components that were needed to answer the question: (i) a climate change component (direct or indirect); and (ii) a measure of change in one or more water regulating characteristics of ecosystems. Only one additional paper (Westwood et al., 2006) had a climate change and water regulating component.

Westwood et al. (2006) used extensive monitoring of six chalkland streams in southern England to examine the effects of the cessation of drought conditions between 1989-1992 and 1996-1998 on the rate and extent of recovery of in-channel aquatic and wetland macrophytes and also developed, a system for hindcasting/forecasting the nature of the macrophyte community on the basis of antecedent flow records. In term of the drought recovery, all communities generally showed recovery only 1 year after the cessation of dry conditions, with further, slower reinstatement throughout the second year. Sites which were affected by inflows or poor habitat conditions took longer to recover or did not recover at all. High flows (e.g. in 2001) particularly affected one stream, the Lambourn, and these led to increasing homogeneity of community types. This part of the study, therefore, demonstrated the current resilience of these streams to droughts, where the water and or habitat quality is good and also showed how high flows may have an adverse impact on community diversity. While climate change was not specifically mentioned here, south-east England is projected to experience more drought events in summer and higher flows in winter (Murphy et al., 2009) and thus this resilience is important, as the macrophyte community will contribute to water quality.

The effects of a range of physical, hydroclimatic variables at the catchment scale, such as rainfall, percolation and soil moisture conditions, as well as topographical, land use and rates of abstraction variables were tested using canonical correspondence analysis and other mulitvariate techniques, to establish their effect on the vegetation. This showed the importance of antecedent flow conditions, thus it was possible to use these to predict the nature of the macrophyte community, with a current accuracy level of 72% for any of 13 community types and 90% for any of four community groups. The paper contains flow thresholds needed to sustain specific communities in the Lambourn, as well as community types related to flow (m^3 sec^{-1}). These results were seen as important in the context of climate change, although no attempts were made to undertake any forward predictions and they have a caveat that the relationships will only be maintained as long as other site parameters do not change.

5.4.5 Qualitative comments

This one paper has relevance to the question of the resilience of water regulating services, as if the role of the different macrophyte communities in maintaining or enhancing water quality can be established, then it would be possible to use the predictions to explore how climate change could affect this service. This aspect of contribution to water regulation and resilience, however, was not directly acknowledged in the paper and was only inferred by the reviewer.

5.4.6 Outcome of the review

Conclusions

This review has sought to explore the evidence from the scientific literature for the potential contribution of management to the mitigation of the impacts of environmental change on the water regulating characteristics of ecosystems and, secondarily the resilience of the water regulating characteristics of ecosystems to environmental change. As with biodiversity, the review has not been able to effectively address either of the questions through a quantitative analysis of research findings, and the possible explanations for the low numbers of research publications are similar. Firstly, while there a number of studies investigating the impacts of climate change on aspects of hydrology, many of them do not contain either the necessary biodiversity or the management component. It may be that with a greater focus on catchment-based management as a consequence of the Water Framework Directive and the desire of Defra and other organisations to adopt an ecosystem approach or an ecosystem-based approach to climate change adaptation and mitigation, that this deficit may be addressed. It is possible that the search criteria and questions were too broad and more results may have been obtained by investigating specific topics, such as tree planting impacts on water quality or runoff or particular wetland management impacts on water quality, thus breaking down the components of change (Orr, 2010, pers. Comm.). Also, many of the management terms refer to those used by conservation to obtain a positive outcome and thus potentially detrimental management practices could have been included, such e.g. grazing, drainage, planting, sowing etc. This might mean that research from agricultural disciplines may be omitted (Orr, pers. comm).

Secondly, it may be that not all studies had the necessary climate change component, or, as with historical studies, did not provide sufficient measures for assessing the effect of any management intervention. Thirdly, having four categories of search terms may make the search too complicated to be accommodated in a systematic search of this nature and as has been seen above very few papers contain a term from each of the categories. Also, as with biodiversity, the resilience term or its synonyms are rarely used, although in some cases they can be inferred.

The question(s) raised in this systematic review, however, are important to the future management of water resources, but it appears that research is currently unable to provide a clear, quantifiable answer at this stage. The reviewers believe that a more flexible search approach to the question could have helped, as there is (plenty of) research on aspects of management impacts (especially deforestation) on hydrological parameters relevant to water regulating services (both quantity and quality) which were not captured for the final analysis because of their lack of an explicit (rather than inferential) climate change component. The combination of just three of the search components, with management or climate change as alternatives might have enabled more information to be captured about the role of ecosystems in water regulation.

Implications for management, policy and research

It is unwise to draw strong management or policy implications from the limited papers extracted in this study, but the importance of ecosystems in the regulation of water quality and quantity can be clearly seen.

Wilby et al. (2010) advocate more multi-disciplinary field and model experimentation to test the cost effectiveness and efficacy of adaptation measures applied at different scales. They suggest that in particular, there is a need for a major collaborative programme to: examine natural adaptation to climatic variation in freshwater species, identify where existing environmental practice may be insufficient, review the fitness of monitoring networks to detect change; translate existing knowledge into guidance and implement best practice within existing regulatory frameworks. Such a programme would enable elements of the primary question to be addressed and if these components were integrated they could make a significant contribution to the questions posed for this review.

6. Air Quality

By Roy Haines-Young and Marion Potschin

6.1 Background

The background to the issue of air quality and ecosystem resilience was provided by the recent document *Air Pollution: Action in a Changing Climate* (Defra, 2010a). It notes that while concerns about air quality have largely focused on the impacts for human health, the consequences of pollution for ecosystems are significant. Although emissions of nitrogen and sulphur have decreased significantly since the 1970s, currently 58% of sensitive habitats in the UK exceed critical loads for acidity, and 60% exceed critical loads for eutrophication.

The *Defra document* largely focuses on the need to link the separate policy frameworks that have evolved for managing air pollution and climate change, and while there are clear benefits for the wider environment if both are addressed effectively, the potential benefits for ecosystems are not dealt with in any depth. While falling pollution loads may reduce the rate of biodiversity loss, and climate mitigation and adaptation measures leave room for nature, the impacts of interactions between climate and air quality are less well understood. Thus a key focus for this study is to examine whether ecosystems might be more or less resilience in the context of global warming. This kind of understanding is needed so that we can be sure that pollution targets are set appropriate for the future.

It should be noted, however, that given the wide-ranging nature of the impacts of changes in air quality on ecosystems, the time available for this study did not permit a comprehensive review of the topic. Rather the intention is a more modest one, namely to examine the extent to which the concept of resilience and the ideas that are closely associated with it have been *explicitly* debated in this literature.

6.2 Objectives

The question identified in this topic area was:

> ***How resilient are England's major ecosystems to changes in air quality and how might this change under future climates?***

It clearly concerns the impacts of changes in air quality on ecosystems, rather than the regulation of air quality by ecological structures and processes. This perspective was suggested by the discussions at the initial project kick-off meeting[11] and the more general policy concerns expressed in the recent document *Air Pollution: Action in a Changing Climate* (Defra, 2010a). The latter noted that while compared to human health effects, the damage caused by air pollution on ecosystems may be less obvious and more difficult to quantify and monetise, but it nevertheless remains important. Issues potentially identified for inclusion in the review were the impacts of sulphur and/or nitrogen deposition when critical loads for acidity are exceeded, and ozone, and particular how responses to changes in air quality might change under future climates. An underlying concern in the initial discussions was the extent to which ecosystems would be more or less resilient to changes in air

[11] Kick-off meeting with project Steering Group and RECCE members on February 15th, 2010 in Defra Office, London.

quality and whether any management or policy interventions could be effective in ensuring more sustainable outcomes.

6.2.1 Primary Objective

As with the other topic areas considered in this study, the question initially was very 'open-framed' and unsuitable as it stands for a systematic review. The question does not, for example, specify what aspects of air quality might be considered, nor does it specify what particular ecological aspects need to be considered, other than that the focus is at the community, habitat or whole system level. In addition it does not conform to the usual format of a systematic review question because it combines several independent variables or drivers, namely air quality itself and climate change. There is also the problem that the issue of how management or policy interventions might change these relationships is not considered explicitly.

To cope with these complexities, and at least scope out what air quality issues are being considered actively in the current literature in relation to the UK Broad Habitats, it was decided that the review could proceed most effectively by regarding the sub-question about management as a secondary objective, and making the inter-relationships between air quality and climate the primary focus. Table 6.1, therefore sets out the initial question using the formal elements of a potentially reviewable question, that involves a permutation of *'does intervention/exposure I/E applied to populations of subjects P produce outcome O?'* (Centre for Evidence-Based Conservation, 2010). Table 6.1 also indicates the kinds of experimental or observational design that might potentially yield evidence to answer the question.

Table 6.1: Definition of generic components of a potential systematic review question for air quality

Subject (Population, P)	Communities, habitats or ecosystems
Intervention	Changes in air quality, climate change or management
Outcome	Response of communities, habitats or ecosystems to changes in air quality
Comparators	Changed pollution levels and interactions with other factors
Designs	Any studies comparing response of communities, habitats or whole ecosystems to changes in air quality, or any studies comparing outcomes in context of changes in climate or management

One of the major tasks in exploring this question is to identify what kinds of air quality issues are being considered and how these relate to the UK Broad Habitats and the more general discussions about resilience of ecosystems. This in taking the review forward the 'response' cited in the outcome component of the review question will involve looking at the extent to which the Broad Habitats differ in their resistance to changes in air quality or vary in their speed of recovery following damage from particular pollution events or episodes. Thus, while the initial review question is not as specific as a conventional systematic review would require, it does provide a mechanism for mapping out some of the key areas of knowledge that surround this topic.

6.2.2 Secondary Objective

From the initial discussions two secondary objectives emerged in relation to the issue of air quality. First the extent to which recent literature has considered whether management interventions might usefully increase the resilience of ecosystems given the challenges they face in relation to air quality under a changing climate. Second, the economic values associated with the resilience of ecosystems in the context of air quality.

Unlike the review for soils, it was decided to consider management as a secondary objective, because it was less clear how interventions might operate at the habitat level. Management and policy in the area or air quality tends to be achieved through regulatory mechanisms, and it was felt that inclusion of these issues within this review would add an unwanted layer of complexity. Thus in considering management the intention was a more narrow one, namely of considering whether there is any evidence that particular management practices that might impact on the resilience of the Broad Habitats.

It was recognised from the outset that consideration of the economic valuation of resilience in relation to air quality might add a significant additional dimension to the study, but that given the time available, it was unlikely that any useful analysis could be made. There secondary objectives set for this study were therefore to understand the extent to which management interventions might mediate the impacts of changes in air quality on ecosystems.

6.3. Methods

6.3.1 Question formulation

The broad question on ecosystem resilience and air quality was considered as part of the wider discussions surrounding the project initiated through the RECCE website, consultations with the Project Steering Group established by Defra and via invited experts.

The initial guidance from the Steering Group was that the work might look at the impacts of air quality parameters on ecosystems, rather than the ability of ecosystems to regulate air quality. Of particular interest were the sub-lethal effects that air pollutants might have, causing subtle changes in ecosystems function that might be exacerbated by climate change, and the interactions between pollutants and other controlling factors. From the topic expert advice we received the importance and relevance of this approach was confirmed.

It was suggested by the expert advisor that the impact of climate change in particular is a relevant and urgent area to study. Controlling pollution emissions at source remains a major international challenge. Strategies to reduce emissions adopted by European countries, for example, may not be sufficient to reduce total reactive N because the increase in emissions from developing countries, as with CO_2, continues to increase. In terms of climate change and critical loads, the expert suggested that the impact will be related to atmospheric chemistry which in turn is affected by meteorological conditions including precipitation, temperature and mixing. However, it is highly likely that sensitivity of the vegetation and ecosystems will also change under global warming thus causing greater sensitivity such that it will be necessary to amend critical loads. Changes in temperature, precipitation rates (particularly reduced effects from drought), humidity, frost etc. might have serious effects on ecosystem productivity causing stress that could lead to much greater sensitivity to pollution (synergistic and antagonistic) as well as direct impacts on the ecosystems from climate change. These effects can change plant community structure, affect sensitivity species and also substratum (soil, tree pH etc.) and lead to loss of sensitive species and habitats. Finally, it was suggested that pollutants are often long-lived and trans-boundary in character, and that this might need to be considered. Moreover, pollutants under consideration would need to be assessed individually if the review were to be effective.

To constrain the review it was decided to focus on a selected number of air quality parameters. Defra's *Air Pollution: Action in a Changing Climate* emphasises the importance of obtaining a better understanding of eutrophication (caused by deposition of pollutants such as nitrogen oxides and ammonia) and acidification (caused by deposition of pollutants such as sulphur dioxide and nitrates). Ozone (and its precursor compounds including Volatile Organic Compounds, VOC), and particulate matter (including black carbon) are also highlighted as important issues.

6.3.2 Search strategy

Relevant published research articles were identified through searches of the following electronic databases:

- ISI Web of Science
- Scopus
- Science Direct

To standardise the review with other parts of this study, we used the generic strings discussed in the introduction to cover the concepts related to 'resilience' and the Broad Habitats. These were used together with more specific set of terms designed to identify empirical papers to explore the set of papers identified as being relevant to air quality. The initial search strings for air quality included the terms 'air quality, 'pollution', 'particulate matter, VOC, ozone, 'black carbon' and 'critical load*'. Papers dealing with UV-B effects that appeared in the search sets were subsequently *excluded* from the analysis on the advice of the expert panel. The results are summarised in Table 6.2.

The three search engines identified large numbers of documents using a search string that combined the air pollution terms with strings designed to identify empirical papers dealing with resilience concepts. It was thus decided to restrict the searches to papers that dealt with the resilience concepts more explicitly by extracting only those where it was mentioned in the keywords or title. This strategy reduced the number of papers significantly but the set for review was till potentially large (~2000 references). Thus the additional search string dealing with habitats was used.

Searching for habitats within the initial set of papers where more general reference to resilience concepts was made produced subsets for Scopus, Web of Science and Science Direct of 162, 271 and 51 papers respectively. Inclusion of resilience concepts as key words appeared to be too restrictive. The three subsets (S3, WS3 and SD3) were therefore downloaded into EndNote; duplicates and publications other than journals were eliminated, a combined set of 297 records was produced.

The selected set was screened for relevance, first on the basis of title, then by a reading of the abstract. Given that the 'empirical' search terms were only intended to produce a 'first cut' the manual screening was designed to eliminate papers which were not empirical (i.e. reviews) and to categories papers according to whether they were based on experimental or observational evidence. Using these procedures a provisional set of 119 empirical papers that made reference to some aspect of ecosystem resilience and air quality was constructed. A more detailed scan of the full text reduced this to a final target set of 49; we will refer to this subset as AQRS (Air Quality Review set).

To determine whether there was any material in the initial sets that might be suitable in terms of the secondary objectives of the review, the set of 119 papers was screen to identify those which made reference to a management or economic issues; 27 and 17 papers were identified respectively. Although they were not empirical investigations as such, they were flagged for further analysis.

During the data extraction process, any relevant review studies were noted. The web was also searched for any relevant meta-analyses dealing with air pollution topics.

Table 6.2: Search strategies to identify papers dealing with resilience in the context of changes in air quality

ID	Strategy	Search string	Number
	Scopus		
S1	*All papers using terms related to air quality, resilience and likely to be empirical in approach, based on their abstract.*	ABS("air quality" OR "pollution" OR "particulate matter" OR voc OR ozone OR "black carbon" OR "critical load*") AND ABS(recover* OR stab* OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") AND ABS(evidence OR empirical* OR assessment* OR quantification* OR sampl* OR experiment*)	10,250
S2	*All papers using terms related to air quality, and likely to be empirical in approach, based on their abstract and where resilience concepts are mentioned in keywords*	ABS("air quality" OR "pollution" OR "particulate matter" OR voc OR ozone OR "black carbon" OR "critical load*") AND (KEY(resilien* OR recover* OR stab* OR vulnerab* OR sensitiv* OR resist*)) ABS(evidence OR empirical* OR assessment* OR quantification* OR sampl* OR experiment*)	2,999
S3	*Search S1 qualified by reference to Broad Habitats*	Plus habitats (only 40 were found with resilience concepts in keywords)	162
S4	*Search S1 qualified by reference to climate change*	S3...And ABS("climate change" OR "global warming" OR "environment* change" OR "chang* environ*")	38
S5	*Search S1 qualified by reference management*	S3...And ABS(management)	82
	Web of Science		
WS1	*All papers using terms related to air quality, resilience and likely to be empirical in approach, based on their abstract.*	TS= ("air quality" OR "pollution" OR "particulate matter" OR voc OR ozone OR "black carbon" OR "critical load*") AND TS=(recover* OR stab* OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") AND TS=(evidence OR empirical* OR assessment* OR quantification* OR sampl* OR experiment*)	12,147
WS2	*All papers using terms related to air quality, and likely to be empirical in approach, based on their abstract and where resilience concepts are mentioned in TITLE*	TS= ("air quality" OR "pollution" OR "particulate matter" OR voc OR ozone OR "black carbon" OR "critical load*") AND TI=(recover* OR stab* OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") AND TS=(evidence OR empirical* OR assessment* OR quantification* OR sampl* OR experiment*)	1497
WS3	*Search W S1 qualified by reference to Broad Habitats*	Plus habitats (only 40 were found with resilience concepts in title)	271
WS4	*Search WS1 qualified by reference to climate change*	WS3.... AND TS=("climate change" OR "global warming" OR "environment* change" OR "chang* environ*")	12
WS5	*Search WS1 qualified by reference management*	WS3...AND TS=(management)	33
	Science Direct		
SD1	*All papers using terms related to air quality, resilience and likely to be empirical in approach, based on their abstract.*	ABS("air quality" OR "pollution" OR "particulate matter" OR voc OR ozone OR "black carbon" OR "critical load*") AND ABS(recover* OR stab* OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") AND ABS(evidence OR empirical* OR assessment* OR quantification* OR sampl* OR experiment*)	2968
SD2	*All papers using terms related to air quality, and likely to be empirical in approach, based on their abstract and where resilience concepts are mentioned in TITLE*	ABS("air quality" OR "pollution" OR "particulate matter" OR voc OR ozone OR "black carbon" OR "critical load*") AND (specific-authkey("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*") OR specific-otherkey ("recover*" OR "stab*" OR "resist*" OR "vulnerability" OR "sensitiv*" OR "resilienc*")) AND ABS(evidence OR empirical* OR assessment* OR quantification* OR sampl* OR experiment*)	329
SD3	*Search SD1 qualified by reference to Broad Habitats*	Plus habitats (none were found with resilience concepts in keywords)	51
SD4	*Search SD1 qualified by reference to climate change*	SD3...And ABS("climate change" OR "global warming" OR "environment* change" OR "chang* environ*")	4
SD5	*Search SD1 qualified by reference management*	SD3...And ABS(management)	5

6.3.3 Study inclusion criteria

For a study to be included in the review it was required to meet the following criteria:

Relevance: empirical studies from any part of the world dealing with some aspect of ecosystem resilience (resistance to change or recovery from disturbance) were to be considered, where there was some impact due to air quality or air pollution. Only studies designated as 'journal articles' by the search engines with titles and abstracts in English, were included. No geographical restriction was applied. Ecosystems were defined using the terms for the UK Broad Habitats (See Part 6.2).

Types of intervention: as noted above, the topic selected for review was a complex one, involving an investigation of the extent to which ecosystem resilience might be impacted upon by a range of air quality parameters. To constrain the analysis air quality was defined in terms of atmospheric concentrations of nitrogen or sulphur compounds, ozone and particular matter, or relevant papers identified if, where appropriate, they made reference to discussions about critical loads in relation to these topics. Thus papers were included if involved experimental manipulation of pollution loads or were based on temporal or spatial observations of changes in air quality parameters.

Types of outcome: quantitative measurements of the degree a structural or functional property of an ecosystem or ecological community was either buffered against changes in air quality, was sensitive to changes in air quality, or recovers following some pollution event. Outcomes had to be measurable in terms of some biotic or abiotic characteristic of an ecosystem, habitat, community, population or species; physiological responses of individual plants or animals were included.

Types of comparators and designs: both experimental (manipulative) or observational studies were considered relevant providing they made a controlled comparison of relevant outcomes under either different pollution loads (simulated or actual). Observational studies based on spatial comparisons between sites having different climate or management regimes were included, as well as studies that looked at the impact of changes over time at a single site.

These selection criteria were used to identify the 49 papers in the final 'included set' (AQRS) described above. They were then downloaded from EndNote to Excel for further coding and analysis.

6.3.4 Study quality assessment

Information relating to the quality of the individual studies was extracted for the articles in the AQRS subset. Although these studies had already met the inclusion criteria described it was considered important to examine them more closely to determine what kinds of experimental or observational design underpinned the evidence that they provided. Although evidence generated from Randomised Controlled Trials (RCTs) is to be preferred in any systematic review, as noted in the soils review these types of experimental designs cannot always be used in the environmental sciences. Investigations are often confined to observational studies involving comparisons over space or time against some assumed baseline.

For consistency the same a priori quality assessment criteria used in the soils review were applied here. Given that the investigation of ecosystem resilience implies an understanding of some response parameter over time (e.g. how sensitive it is to disturbance, or how quickly does it recover), it was felt that the way the study dealt with the temporal dimension was important.

Moreover, given that the ability to devise experimental interventions is more limited in the environmental sciences, it was also felt that it was important to distinguish between studies that used some kind of controlled manipulation from those that observed responses across over space or time. As before, it was felt important to identify studies that involved site comparisons as distinct from those that track the characteristics of sites over time. Any reference to threshold effects in the sense of 'regime shifts' were also considered.

Table 6.3: General of potential resilience studies based on experimental and observational designs

	Experimental	Observational
Time comparisons	*Studies that manipulate some independent variable in a controlled way within a laboratory or field situation, and which follow the dynamics of some response variable over time.*	*Studies based on artificial of 'natural' experiments, in which the management history of study sites is know and that the present day state can be compared with some known or inferred base-line from the past.*
Space comparisons	*Studies that simulate changes in independent driving variables by the translocation of an experimental systems in a controlled way.*	*Studies based on artificial of 'natural' experiments, in which the management history of study sites is known and that the effects of treatments can be inferred from a spatial comparison.*

The four-fold classification of papers in the soils review was therefore applied here (Table 6.3); papers in the AQRS set were classified according to whether they were experimental or observational and whether they followed some ecosystem response over time or space comparisons. While generally experimental studies are to be preferred to over observational ones, they are often limited in terms of the time span that can be considered, compared to observational studies. Within the observational group, however, those that consider the changes of individual sites over time are probably superior to those that simply make spatial comparisons. In the case of soils, the length of time over which changes were studied was felt to be an important factor in the quality assessment. In the case of air quality, while long term observations are also important, many more of the studies were found to be short-term experimental ones; thus time span was not used as a quality measure.

6.3.5 Data extraction

For each study that met the inclusion criteria the following basic data were extracted and assembled in an excel spreadsheet:

Design: Whether the study was experimental or observational in design.

Dependent variable: The ecosystem property or properties used to assess the resilience response. A note was made of whether the response was measured at the habitat, community, population or individual species level.

Independent variable: The air quality parameter manipulated or observed.

Comparator: The type of comparison being considered, defined in terms of the independent variable, generally concentration levels.

Space or Time Perspective: whether the study looked at ecosystem response over space or time.

Resilience perspective: whether the study provided insights into the ability of the ecosystem response measure to resist impacts of changes in air quality or to recover from pollution events.

Ecosystem and Location: how the authors described the geographical context of the study, including the ecosystem type.

6.3.6 Data synthesis

The open-framed character of the review question meant that it could not be determined at the outset whether a quantitative data synthesis could be undertaken. The decision was also dependent on whether any relevant meta-analyses were available. However, to determine whether such an investigation was possible in principle, as part of the qualitative synthesis the text of each the included article was read in more detail. The papers were inspected to determine whether they contained sufficient information to make them suitable for a more detailed quantitative synthesis using the Comprehensive Meta-Analysis V2.0 programme[12]. The latter was available to the review team and provides a typology of 100 treatment formats that can be used to capture the statistical outcomes of experimental or observation studies. The typology was used to classify the treatment formats of the included studies. Following other recent systematic reviews we chose a threshold value of four studies measuring the same outcome to decide whether to pursue a meta-analysis for a particular ecosystem attribute.

6.4. Results

6.4.1 Review statistics and descriptions of studies

Of the 297 papers chosen through the search protocol and the three search engines, 49 (16%) were identified as relevant. The basic data extracted from the final 'included subset' (AQRS) are shown in Tables 6.4 and 6.5

Table 6.4 a&b summarise the characteristics used to assess the ecosystem response to a given air quality parameter. The data have been grouped in two ways: first, in terms of the specific topic extracted from the original paper; the terminology used follows that used by the original authors (Table 6.4a); second by grouping of these measures into broader categories, interpreted by the study team to indicate whether the study focused at the habitat, community, population or individual level (Table 6.4b). Table 6.4a suggests that a wide range of measures were used to assess the impact of changes in air quality; the most frequently measured related to growth response, tissue damage and community composition. Grouping the individual measures suggests that the major of studies were framed at the individual species level, followed by more aggregated, responses relevant the community level measures. The latter included seed bank composition of the composition of, say, lichen communities in different areas. Habitat level responses used measures that look at wider ecosystem properties such as surface pH.

Table 6.5 summarises the relationships between the air quality drivers considered by the included studies and the level at which ecosystem responses were assessed. Ozone was the most frequently factor investigated, this topic accounting for nearly half of the studies, which mostly considered responses at in individual species level. Thus species growth rates, phenology and reproductive successes were used as response measures. However, some community level responses to ozone were also investigated.

[12] http://www.meta-analysis.com/

Table 6.4 a & b: Types of ecosystem response identified in review set

(a) Response measure

Type of response measure	Number
Arbuscular mycorrhyzal community composition	1
Biomass, community composition	2
Bog re-vegetation	1
Butterfly populations	1
Cell ultra structure	1
CH4 emissions	1
Community composition	**3**
Community sensitivity	1
Competition and reproductive ability	1
Epiphyte communities	1
Eutrophication	1
Foliar injury in wood species	1
Growth and reproduction	1
Growth rate	**4**
Growth, flowering and litter production	1
Larvae feeding activity	1
Lichen communities	1
Lichen growth	1
Ozone uptake	1
Peat sensitivity to acid deposition	1
Phenology and flower weights	1
Phenology and reproduction	1
Photosynthetic rate	2
Physiological and molecular response	1
Physiology, growth and seed production	1
Pioneer species	1
Plant resistance to pathogens	1
Population genetics	1
Primary productivity	1
Productivity, community composition	2
Seed bank composition	1
Species richness	1
Sphagnum productivity, and peat formation - threshold	1
Stomatal flux	1
Stress sensitivity of Calluna	1
Surface PH	1
Tissue damage	**3**
Twig growth	1
Wetland sensitivity to desiccation	1
Grand Total	**49**

(b) Level of response

Response level	Number
Individual response	21
Population response	2
Community response	19
Habitat response	7
Grand Total	**49**

Table 6.6a&b show what aspects of resilience were considered in the studies and what kind of experimental or observational designs were used. The overwhelming majority considered the sensitivity of the response parameter to changes in the air quality parameter, and have been categorised as measuring ‘resistance’. The recovery aspect is either under-represented in the set or it may be a gap in the literature. One study (Aerts et al., 1992) identified a threshold effect in relation to the balance between carbon sequestration and decomposition in a sphagnum-dominated ecosystem, although the regime shift was not discussed from a theoretical perspective. Most of these studies were experimental (manipulative) in design.

Table 6.5: Cross tabulation of air quality drivers and the ecosystem level at which responses are measured

Air quality driver	Habitat response	Community response	Population response	Individual response	Grand Total
Acid deposition	2			1	3
Air pollution		3			3
Air pollution plus other drivers		1			1
N deposition	1	6	1	2	10
Ozone	2	5	1	14	22
Ozone, CO2 conc				1	1
Ozone, N	1				1
Ozone, SO2				2	2
Pesticide spray drift and vehicle emissions				1	1
SO2		2			2
SO2 and NO2				1	1
SO2 and warming	1				1
Grand Total	**7**	**19**	**2**	**22**	**48**

Table 6.6 a & b:Study designs and resilience perspectives (E = experimental, O = observation)

(a) Resilience perspective

Resilience Perspective	Design		Grand Total
	E	O	
Recovery		2	2
Resistance	32	12	44
Resistance and recovery		2	2
Threshold	1		1
Grand Total	**33**	**16**	**49**

(b) Study design

Design	Comparison		Grand Total
	Space	Time	
E	4	28	32
O	11	5	16
Grand Total	**15**	**33**	**48**

The dominance in experimental studies seems to suggest that the set of include studies is towards the top end of the quality spectrum, although the problem of scaling up from microcosms to communities and habitats is one that is discussed widely in this literature (Kolb et al., 1997; Fuhrer et al., 1997).

6.4.2 Qualitative synthesis

At the outset it was recognised that the focal question was an open-framed one, which was unlikely to be answered simply through the process of a systematic review. Instead the strategy adopted was one that allowed the identification of which air quality parameters were currently being considered in the literature in the relation to the question of ecosystem resilience, and then determine whether there was sufficient material for the individual topics to make a more rigorous quantitative assessment. Although some studies considered more than one air quality factor, the data in Table

6.5 suggest that a useful grouping of topics might be: ozone, the combined effects of N and S deposition, and finally acidification effects. This grouping of studies seemed to be more effective than one based on habitat, which seemed to be biased towards grasslands and bogs (Table 6.7). Of the studies framed at habitat level, 11 focused on a type of grassland and 4 on a bog or mire. Only one study explicitly dealt with forests.

Table 6.7: Habitats covered by included reference set

Habitats and location	Acid deposition	Air pollution	Air pollution input plus other drivers	Air pollution plus other drivers	N deposition	Ozone	Ozone, N	SO2	SO2 and warming	Grand Total
Alpine dry meadows, Colorado, USA					1					1
Bog, Britain	1									1
Bog, Finland		1								1
Calcareous dune grasslands, Netherlands					1					1
Chalk grassland, Britain						1				1
Coastal sage scrub, California					1					1
Global data			1							1
Grassland communities, Europe						1				1
Grasslands, Switzerland						1				1
Juniper scrub, UK				1						1
Laboratory						1				1
Lichen communities Britain					1					1
Lichen communities, SE USA		1								1
Low alpine heaths, Cairgorms. Scotland					1					1
Ombrotrophic bogs, Britain	1									1
Ombrotrophic bogs, Sweden					1					1
Pasture communities, Spain						1				1
Peatlands									1	1
Pioneer grasslands, Oregon, USA						1				1
Ruderal grasslands, Chalk, Germany		1								1
Secondary forests, Taiga, Urals								1		1
Semi-natural communities, Switzerland					1					1
Semi-natural grasslands, UK						1				1
Sub-alpine grasslands, Switzerland							1			1
Wet meadow Netherlands								1		1
Grand Total	**2**	**3**	**1**	**1**	**7**	**7**	**1**	**2**	**1**	**25**

Ozone

Ozone is produced by photochemical reactions in the atmosphere involving carbon monoxide, methane and other hydrocarbons in the presence of oxides of nitrogen. Naturally, the highest rates of production tend to occur when temperatures and solar radiation inputs are high, especially when stagnant high pressure systems dominate in summer. The ozone problem has, however, been exacerbated in industrialised regions as a result of emissions of oxides of nitrogen and VOC. Ground ozone can therefore be a significant pollutant, and particular high concentrations can occur down-wind of urban areas. Felzer et al. (2007) note that background levels of ozone in unpolluted air can be within the range 50-60ppb, while affected areas can experience concentrations as high as 400ppb.

High concentrations of ozone can have a damaging effect on human health. It can also have significant impact on ecological systems. The review by Felzer et al. (2007) summarises the main ecosystem effects (Table 6.8), which include the increased incidence of visible injury, reduced photosynthetic rates and stomatal conductance, and increased dark respiration. As a result reduction in above and below ground growth rates can occur, decomposition rates may decline and there may be reduced nitrogen uptake by vegetation.

Table 6.8: Summary of ecosystem effects of ozone exposure (after Felzer et al., 2007)

Variable	O_3 Effect
Visible injury	⇧
Photosynthesis	⬇
Stomatal conductance	⇩
Dark respiration	⇧
Tree biomass	⬇
Crop yield	⬇
Root growth	⇩
Decomposition	⇩
Nitrogen uptake	⇩

Note: arrows indicate the direction of change with increasing O3; solid arrows indicate more certain effects and open symbols.

The search protocol identified the largest number of papers dealing with air quality issues to be concerned with ozone; 26 of the 55 papers included looked at ozone impacts at the individual species, community or habitat levels (Table 6.7). At the individual level 17 papers were identified. They reported effects on tissues, reproduction and phenology (e.g. Rinnan and Holopain, 2004; Bermejo et al., 2003; Meszaro et al., 2009; and Novak et al., 2005). In contrast to most of the studies at the individual level, which were experimental in character, the study by Stribley and Ashmore (2002) concerned the observation of the twig growth patterns in the upper canopy of 40 year old beech trees in two compartments at Wytham Wood near Oxford, over the period 1987-1996. These authors found that while the growth responses in one compartment were significantly correlated with soil moisture deficit, in the other ozone exposure showed stronger correlations. They concluded that the study provided evidence that the annual primary growth of mature beech was sensitive to seasonal ozone exposure (AOT40) below the critical level set by UNECE, derived from on open-top chamber experiments with beech saplings. The results, they suggest, support the interpretation that drought and ozone pollution are important factors in the long term decline of beech trees in southern Britain. Other workers citing the Oxfordshire study have confirmed that beech growth can be affected by ozone concentrations (Ferretti et al., 2007), with damage exacerbated through the interaction with other pollutants, such as nitrogen. The experimental study reported by Thomas et al. (2006) showed a combined effect of the two pollutants using measures based on leaf area and the shoot elongation, with ozone fumigation appearing to amplify the effects of nitrogen treatment. Bussotti and Ferretti (2009) report more general crown damage in forests, and Bassin et al. (2007) have provided a recent overview of the literature relating to the factors affecting the ozone sensitivity species from of temperate European grasslands (Table 6.9)

These individual level studies identified here appear to confirm the general conclusion that susceptibility to ozone damage is often species specific and dependent upon particular conditions and circumstances (Lovett et al., 2009 after US EPA, 2006). While the effects at the individual level are important, it is towards understanding their consequences at the population, community and habitat levels that mainly concern us here.

Table 6.9: Included references dealing with impacts of ozone

Author	Date	Title	Outcome
Ashmore et al.	1995	Effects of ozone on calcareous grassland communities	Ambient levels of ozone in southern Britain can cause changes in species composition of semi-natural calcareous grasslands
Bassin et al.	2007a	Nitrogen deposition but not ozone affects productivity and community composition of subalpine grassland after 3 yr of treatment	The results suggest that effects of elevated O3 on the productivity and floristic composition of subalpine grassland may develop slowly, regardless of the sensitive response to increasing N
Bender et al.	2006	Responses of biomass production and reproductive development to ozone exposure differ between european wild plant species	Significant differences between species in the sensitivity of different end points toward ozone exposure. Ozone caused a significant reduction in leaf biomass of more than 20% in six species, and a significant increase in leaf biomass in three species.
Bergmann et al.	1999	Ozone threshold doses and exposure-response relationships for the development of ozone injury symptoms in wild plant species	Native herbaceous plant species with contrasting patterns of ozone sensitivity can be used for biomonitoring in the field to distinguish between short- and long-term effects of ozone.
Bermejo et al.	2003	Assessment of the ozone sensitivity of 22 native plant species from Mediterranean annual pastures based on visible injury	*Trifolium* species were particularly sensitive since foliar symptoms were apparent in association with O3 accumulated exposures below the current critical level for the prevention of this kind of effect
Bungener et al.	1999	Growth response of grassland species to ozone in relation to soil moisture condition and plant strategy	Specific relative growth rate is an important determinant for the potential sensitivity of grassland species to long-term effects of ozone, and that reduced irrigation causes no general protection from the effects of ozone on growth.
Carlson	1979	Reduction in the photosynthetic rate of Acer, Quercus and Fraxinus species caused by sulfur dioxide and ozone	Photosynthetic rate in leaves exposed to SO2 plus O3 at high relative humidity and either intermediate or low light intensity was reduced with visible symptoms in some, but not all, replicates.
Evans and Ashmore	1992	The effects of ambient air on a semi-natural grassland community	Impact of air pollution on plant communities cannot be readily predicted from laboratory ozone treatments of individual species or artificial two-species mixtures.
Franzaring et al.	2000	Growth responses to ozone in plant species from wetlands	While no significant ozone effects on flowering date and flower numbers were detected, flower weights were significantly reduced in *E. cannabinum* and *P. lanceolata.*
Gimeno et al.	2004	Assessment of the effects of ozone exposure and plant competition on the reproductive ability of three therophytic clover species from Iberian pastures	An increased flower biomass was found in the CFA monoculture mesocosms of *T.cherleri* when compared with the remaining mesocosms, once the plants were exposed in the open for 60 days.
Jones et al.	2007	Predicting community sensitivity to ozone, using Ellenberg Indicator values	Provides a regression-based model for predicting changes in biomass of individual species exposed to ozone (RSp), based on their Ellenberg Indicator values
Kolliker et al.	2008	Elevated ozone affects the genetic composition of Plantago lanceolata L. populations	Micro-evolutionary processes could take place in response to long-term elevated O-3 exposure in highly diverse populations of outbreeding plant species
Meszaros et al.	2009	Measurement and modelling ozone fluxes over a cut and fertilized grassland	Results demonstrate the importance of canopy structure and non-stomatal pathways on O_3 fluxes
Novak et al.	2005	Seasonal trends in reduced leaf gas exchange and ozone-induced foliar injury in three ozone sensitive woody plant species	The timing and severity of the reductions in leaf gas exchange were species specific and corresponded to the onset of visible foliar injury
Nussbaum and Fuhrer	2000	Difference in ozone uptake in grassland species between open-top chambers and ambient air	extrapolation of ozone flux-response relationships from OTC experiments must be based on canopy-level ozone concentrations, and that these relationships should be applied only to single species under microclimatic conditions similar to those prevailing in the experiment
Pfleeger et al.	2010	Response of pioneer plant communities to elevated ozone exposure	The Effects Of Ozone on Individual Species, Both Direct And Indirect, In A Community May Be Detrimental, Insignificant, Or Positive.
Plazek et al.	2000	Effects of ozone fumigation on photosynthesis and membrane permeability in leaves of spring barley, meadow fescue, and winter rape	Plants show a large adaptation to ozone and prevent loss of membrane integrity leading to ion leakage

Table 6.9. cont.: Included references dealing with impacts of ozone

Author	Date	Title	Outcome
Plazek et al.	2001	The influence of ozone fumigation on metabolic efficiency and plant resistance to fungal pathogens	Positive effect of ozone on resistance of all plant species to fungal infection. Pathogen resistance increased in the plants that were acclimated to the enhanced ozone level.
Rinnan and Holopainen	2004	Ozone effects on the ultrastructure of peatland plants Sphagnum mosses, Vaccinium oxycoccus, Andromeda polifolia and Eriophorum vaginatum	Reduced photosynthesis in dwarf shrubs by low concentrations; O_3 sensitivity only under cool autumn conditions
Sanz et al.	2007	Ozone sensitivity of the Mediterranean terophyte Trifolium striatum is modulated by soil nitrogen content	Significant O_3×N interactive effects; N fertilization counterbalanced O_3 effects at moderate O_3 levels
Shimizu et al.	2005	Response O-3 and SO2 for five Mongolian semi-arid plant species	O_3 significantly reduced leaf number of Carex spp., biomass and root/shoot ratio of Polygonum alopecuroides, root/shoot ratio of Sanguisorba officinalis, but had no effect on other growth parameters. SO2 significantly reduced leaf number and biomass of Carex spp., but there was no effect on other spp.
Stribley and Ashmore	2002	Quantitative changes in twig growth pattern of young woodland beech (Fagus sylvatica L.) in relation to climate and ozone pollution over 10 years	Drought and ozone pollution are important factors in the long term decline of beech trees in southern Britain
Tjoelker et al.	1993	Light environment alters response to ozone stress in seedlings of acer-saccharum marsh and hybrid populous L.1. in-situ net photosynthesis, dark respiration and growth	Shade-grown sugar maple and unshaded poplar may experience reductions in carbon gain and growth under elevated levels of ozone
Volk et al.	2006	Grassland yield declined by a quarter in 5 years of free-air ozone fumigation	Moderately elevated O_3 level reduces the productivity of grasslands during a 5-year exposure under field conditions
Whitefield et al.	1998	The effects of nutrient limitation on the response of Plantago major to ozone	Low-N treatment plant more sensitive to ozone than those grown under the high-nutrient regime.
Wustman et al.	2001	Effects of elevated CO2 and O-3 on aspen clones varying in O-3 sensitivity can CO2 ameliorate the harmful effects of O-3?	CO_2+O_3 treatment resulted in a slight reduction of leaf injury, harmful effects of O-3 not ameliorated.

Table 6.10: Overview of studies showing inter-specific differences in ozone sensitivity of herbaceous species
(after Bassin et al. 2007a)

Vegetation type or origin	Species number	%of species showing visible injury	%of species showing reduced above-ground productivity	%of species showing reduced below-ground biomass	%of species showing changes in root/shoot ratio	Reference
UK native	32	19	44	Not tested	28-19 +	Reiling & Davison, 1992
Swiss mesic grassland	33	70	Not tested	Not tested	Not tested	Nebel & Fuhrer, 1994
German native	12	42	8	Not tested	Not tested	Bergmann et al., 1995
Calcareous grassland	5	40	20	Not tested	20-0 +	Warwick &Taylor, 1995
Swedish native	27	11	67	Not tested	Not tested	Pleijel et al. 1997
Danish grassland	8	87	75	Not tested	Not tested	Mortensen 1997
Swiss native	24	96	21	Not tested	Not tested	Bungener et al., 1999
German native	25	32	Not tested	Not tested	Not tested	Bergmann et al., 1999
Wetland	10	10	30	40	10-10 +	Franzaring et al., 2000
Fen-meadow	12	75	25	17	40- 0 +	Power & Ashmore, 2002
Mediterranean annual grassland	22	72	42	32	16-16+	Bermejo et al., 2002 Gimeno et al., 2004
UK upland vegetation	33	24	15	Not tested	Not tested	Hayes et al., 2007

Population level responses are appear to be relatively rare in the literature, although Kolliker et al. (2008) suggest on the basis of their experimental study that that micro-evolutionary processes could take place in response to long-term elevated O_3 exposure in highly diverse populations of out breeding plant species. They worked with old semi-natural grasslands exposed to elevated ozone over five years using a free-air fumigation system. They found that the genetic diversity of populations of *Plantago lanceolata* that were exposed to elevated ozone was slightly higher than in populations sampled from control plots. The observed changes could have relevance in the resilience debate, in that the changes may indicate a slow adaptation of this species to elevated ozone levels. However, the study did not examine if this change was associated with greater resistance of the species to this pollutant and so the proposition is untested.

Pfleeger et al. (2010) note that although there has been a considerable research effort directed towards understanding the effects of ozone on crop plants, there is relatively little experimental work that has looked at the effects on natural vegetation communities. Eight studies were identified using our search protocol.

The Pfleeger et al. (2010) study sought to determine how a plant community responds over several generations to elevated ozone exposures using open topped chambers. They looked at response in terms of changing seed bank composition over time. The experimental material was soil whose seed back reflected the populations of naturalized plants common to the Willamette Valley in Oregon. They found that sixty plant species from 22 families emerged in the chambers over the four years of the experiment. High seedling mortality rates were detected in the elevated ozone plots, and this allowed more resistant individuals to survive. Overall they suggested that at the community level, there was a trend of decreasing biomass with increasing ozone exposure. At elevated levels of ozone, premature senescence of taller species could be detected, and this resulted in increased light for understory species. Thus while this study confirmed considerable variations in susceptibility at the individual species level, with responses detected ranging from detrimental, insignificant, through to positive, the changes are likely to modify the overall community dynamics in terms of competitive relationships and competitive interactions between the original species set.

All of the community and habitat level studies for ozone impacts concerned grassland communities. Working with sub-alpine grasslands in Switzerland, Volk et al. (2006) describe the results of a long-term experiment involving exposing intact grasslands to moderately elevated ozone levels over five years under real field conditions. Their results were consistent with the proposition that ozone damage reduces plant productivity. They found that compared with the ambient air control, there was a loss in annual dry matter yield of 23% over five years, and suggest that ozone stress could therefore have negative implications for the maintenance of biological diversity in rural landscapes across large areas of Europe. In a later study from the Alps, Bassin et al. (2007b) looked at the interaction effects with nitrogen, which might act to stimulate productivity and mitigate the ozone effects. They found no significant interaction effects, however, and conclude that the impacts of higher ozone levels on these the productivity and composition of these grasslands may develop slowly, regardless how sensitive the species are to increasing N inputs.

Two studies have looked at the impacts of ozone on grasslands in Britain. The study by Evans and Ashmore (1992) confirms the impact that ozone exposure can have in terms of reducing productivity, but concluded that the impact of air pollution at the community level could not easily predicted from laboratory studies on individual species or mixtures. The later experimental study

(Ashmore et al., 1995), which also involved calcareous grassland communities, confirmed that ambient levels of ozone in southern Britain can cause changes in species composition of semi-natural calcareous grassland communities.

Although some of the papers identified using our search protocol made reference to interaction effects, few looked at the implications of climate change explicitly, and this may suggest a significant knowledge gap. Wustman et al. (2001) did, however, look at the sensitivity of aspen clones to ozone under elevated levels of carbon dioxide and whether there might be any mitigating effect. Felzer et al. (2007) argue that it is important to understand this issue, because we might expect increasing CO_2 to partially counter act the impacts of ozone, by stimulating productivity. They report that the few experimental studies that have been conducted to suggest that there is, in fact, a negative interaction between them. The study by Wustman et al. (2001) also found this to be the case. The combined elevated carbon dioxide and ozone treatment only resulted in a small reduction of tissue damage, and that over all the damaging effects of ozone were exacerbated.

The conclusions based on the papers identified through the present search on the mitigating effects of ozone at higher concentrations of CO_2 may not, however, be fully representative of the wider evidence-base. For example, the review on the implications of increasing troposphere background ozone concentration for vegetation in the UK (Ashmore et al. 2002) concluded that evidence that ozone damage is reduced at higher CO_2 concentrations is strong (see also Ashmore, 2002). In his review of the impacts of air pollution effects and climate change Runeckles (2002) caution that the evidence for the mitigating is indicative but not consistent. In general terms he suggests that 'for *most* species, elevated CO_2 reduces *many* of the effects of O_3' (Runeckles, 2002: 444, italics in the original). The fact that little recent material on this issue was identified using our protocol suggests that it may not therefore have been adequate in identifying a comprehensive or representative body of material on this topic.

Nitrogen and sulphur deposition

Twenty-two of the papers included in the review set dealt with aspects of nitrogen and sulphur deposition and air pollution more generally (Table 6.10), three at the individual level, one in terms of population effects, and 18 at the scale of communities or habitats. Thus the classic study of Power and Ashmore et al. (1995) involved making experimental additions of ammonium sulphate to nitrogen poor dry heathland in southern Britain, and tracking its impact on *Calluna* over a five year period. The study found that the application of nitrogen at rates that were only marginally above the critical load produced small but non-significant increases in shoot nitrogen content. However, there was a large and significant positive effect on shoot growth, flowering, litter production, resulting in higher canopy densities of *Calluna*. Such an effect could transform the competitive relationships within the community. Weiss (1999) described how eutrophication as a result of nitrogen inputs to nutrient poor serpentine soils in California lead to the invasion of annual grasses when grazing pressure was relaxed, and declines in associated butterfly species.

At the community and habitat levels, the impact of eutrophicaton of lichen communities continues to be widely reported (e.g. McCune et al., 1997; Ellis and Coppins, 2009). From their study of terricolous alpine lichens, Britton and Fisher (2009) conclude that this species group has the potential to be used as indicators of deposition and impact in northern and alpine ecosystems because they are highly sensitivity to extremely low loads and concentrations of N. They found that the concentrations of N commonly encountered in UK cloud water may be having detrimental effects on the growth of sensitive species and the communities they form.

Aerts et al. (1992) have reported the effects of increased nitrogen or phosphorus supply on the productivity of Sphagnum-dominated ombrotrophic bogs in northern and southern Sweden. In an experimental study, productivity of the sphagnum layer was increased significantly by the addition of nitrogen but not phosphorus. However, there were significant interactions, especially at higher the nitrogen levels indicating that in areas with a high atmospheric nitrogen supply, plant productivity may be more limited by phosphorus than nitrogen. The study by Aerts et al. (1992) is particularly interesting in the present context because their results indicate that these effects can have quite profound consequences for the dynamics of these communities, resulting in something resembling a regime shift. These authors suggest that high atmospheric nitrogen supply may affect the carbon balance of these ombrotrophic bogs, because while productivity under these conditions is not limited by N decomposition is probably increased by these high loads, and this may switch the these habitats from sinks to sources for carbon.

Interaction effects have also been reported in relation to nitrogen, phosphorous and CO_2 levels in relation to mycorrhizal communities by Treseder (2004), who presents a meta-analysis of recent work. She found that current evidence suggests that while standing stocks of mycorrhizal fungi may increase under elevated CO_2 levels, they appear to decline under additions of phosphorous. The effects of nitrogen were more difficult to predict, however, although the results also appeared to indicate a negative effect of increasing loads. The implications of such effects are that shifts in the mycorrhizal communities may trigger corresponding shifts in other ecosystem processes, such as nutrient uptake, trace gas emissions, carbon sequestration and soil aggregate stability. However, evidence for these knock-on effects is limited.

Significant interaction effects have also been reported for other types of sensitive habitat. Britton and Fisher (2007), for example, have undertaken a 5-year fertilization experiment to examine the interactive effects of nitrogen deposition, fire and grazing on low alpine heaths, in the Cairngorm Mountains, Scotland. At the end of the trial significant reductions in species diversity were observed, even for the lowest nitrogen treatment, mainly as a result of loss of lichen species. The effect of nitrogen additions on higher plants was mainly seen as a result of interactions with other factors. Thus while fire had a significant effect on the diversity and composition of the community the control plots recovered relatively quickly; species richness was observed to its former level with four years and by extrapolation vegetation composition was predicted to recover within about seven years. However, significant interactions were detected between nitrogen deposition and fire treatments. The burnt plots showed no significant effect of nitrogen treatment on species diversity, but the diversity of unburned plots was significantly reduced only one year at the highest input levels for N.

As the recent reviews of upland communities by Holden et al. (2007) and Orr et al. (2008) demonstrate how complex the interactions between the various drivers of change can be in these areas. The issues surrounding the emissions of methane are particularly problematic. It is widely acknowledged that methane emissions from peatlands, for example, can contribute significantly to global warming but that this may be reduced by sulphate reduction stimulated by increasing aerial sulphur deposition. However, as Pester et al. (2010) point out the biology behind these processes is not well understood. As a potential contribution in this area, these authors report on how

Desulfosporosinus species can be identified using genetic markers and how despite their rarity in peat communities they can make a significant contribution to the biogeochemical process that diverts the carbon flow in peatlands from methane to CO_2.

Bobbink and Lamers (2002) provide a detailed review of the effects of nitrogen deposition at the species and habitat level, and note that it is possible to make reliable estimates of the sensitivities of a large number of ecosystems to increased nitrogen deposition. In the conclusion of their review, they note that future research challenges include the need to look in more detail at the interaction effects with other pressures associated with climate change, such as warming and increased CO_2 concentrations. The absence of papers dealing specifically with how deposition impacts might be modified in future may indicate that this remains an important research gap. The more recent review Lovett et al. (2008) also appears to support this conclusion.

A further apparent gap the material identified by our search protocol was literature dealing with the recovery of habitats following reductions in pollution inputs. NEGTP (2001) report on trans-boundary air pollution notes that there while there is a large body of evidence to suggest that nitrogen inputs can modify the structure and composition of plant communities in the UK, there is little evidence at present of the extent to which reduction of nitrogen loads have lead to any recovery. This the authors suggest that recovery may take decades, and in some situations may not be fully reversible

Acidification

The search protocol identified only three papers dealing with acidification effects or the recovery of habitats from them. This result suggested again that the search strategy may have been too restrictive, given the volume of material that the expert panel indicated that may be available. The NEGTAP (2001) report also notes, the results of modelling studies, which give some insights about the sensitivity of soils to acidification and their likely speed of recovery. Such material is clearly relevant in the context of discussions of resilience, but our search has failed to identify any significant and more recent material. The NGTAP (2001) report concluded that there is some evidence for the chemical recovery of soils from the effects of acidification; much of the evidence supporting this conclusion has been provided by Countryside Survey. The modelling studies discussed in the NEGTAP study suggest, however, that while trends indicating recovery are detectable, the process may be slow, taking place over decades. However, in some cases modelling studies suggest that a return to conditions prior to acidification may not be possible for some upland soils.

Ecosystem resilience and management

The secondary objective set for this part of the review was to examine the extent to which recent literature suggests any management strategies that might mitigate the effects of changing pollution loads on ecosystems, particularly those effects arising from climate change. However, few of the papers identified using the search protocols dealt with management impacts directly, although it is clear that, given some of the observed interaction effects, management interventions could either to mitigate or exacerbate the effects. Since pollution loads may act to change the competitive balance between species, management interventions can potentially affect outcomes.

As noted in the recent study of Britton and Fisher (2007), species and community responses can be affected by fire in heathlands. Bassin et al (2007) suggest that in the case of grasslands, the timing of cutting and grazing could also have important implications for the balance in the sward. These authors note that cutting or grazing is often used to maintain temperate grasslands. As a result, the phases of intensive growth and leaf development are distributed more evenly across the growing season and his may increase the chances that sensitive phases in growth cycles may coincide with peak ozone events; for example, species occupying lower canopy layers may as a result of cutting or grazing become exposed to higher ozone levels and more light during the initial phase of re-growth.

The limited volume of material identified in relation to management suggests that this remains probably an important evidence gap. The extent to which management interventions might be used to mitigate climate change impacts also appears to be an area where further work is required.

6.4.3 Quantitative synthesis

No quantitative syntheses have been prepared for the impacts of air quality on ecosystem resilience have been made. As in the case of soils, although the set of included studies dealing with the topic gave a useful overview of the current debate, they were considered too heterogeneous to be used in any meta-analysis.

6.4.4 Outcome of the review

This review has looked at the literature dealing with relationship changes in air quality and ecosystem function. As noted at the outset, the review question was an open-framed one, not ideally suited to a systematic review, and so we sought to break it down into more manageable subtopics. Thus we have focused the impacts of ozone and atmospheric deposition of nitrogen and sulphur and acidification effects. Although the heterogeneity of the studies meant that a quantitative synthesis of the material was not possible the identified studies do provide some important insights. These can be summarised as follows:

a) There is evidence to suggest that currently exposure to ozone can impact at the individual and habitat levels. Although species vary in their responses to elevated ozone levels, changes in growth patterns and reproductive performance can shift the competitive balance within communities, potentially resulting in biodiversity loss. The evidence for habitat level transformation is more extensive for grassland communities, although effects on growth and performance have been detected in forests. The evidence linking the effects of ozone exposure to components of climate change is more limited, but it seems to indicate that elevated concentrations CO_2 increase the damaging effects of ozone rather than offsetting them.

b) There is a considerable body of evidence to suggest that atmospheric inputs of nitrogen and sulphur can have chronic damaging effects on vegetation, soils and drainage waters. Effects have been detected at sub critical-load concentrations, and can result in significant community level changes. The extent to which these effects may be exacerbated or mitigated under conditions of climate change is, however, less clear.

c) Similarly while there is a considerable body of evidence to suggest that acidification has modified ecosystem structure and function, fewer studies have considered how these effects might be modified under future climatic conditions.

d) The limited volume of material identified in relation to the extent to which management interventions can mitigate the effects of changes in air quality suggests that this is an important evidence gap. The extent to which management interventions might be used to mitigate climate change impacts also appears to be an area where further work is required.

In relation to the more general issue of resilience a number of other conclusions can be drawn from the review of air quality issues. First, that as a theoretical construct it is not widely applied in this literature. In the main, the work related to air quality looks at sensitivities in the form of dose-response relationships, and there appears to be much less attention to the dynamics of recovery or threshold effects in the form of regime shifts. This is not to say such patters of response cannot be imputed from the work, but rather that this kind of conceptual framework is missing from this segment of the literature. A more careful analysis of the way different concepts align across these different discipline areas is probably required.

7. Ecosystem resilience, environmental change and the role of a systematic review

By Roy Haines-Young and Marion Potschin

7.1 Introduction

This study has explored two issues. First, a substantive scientific question concerning how policy action might help to sustain ecosystems in the face of environmental change or be designed to protect their capacity to recover following disturbance. Second, a methodological question, concerning the extent to which a 'systematic review' can be used to explore how policy and management interventions might promote ecosystem resilience. Given the brief for this study (see Appendix 1), and the way it has been constructed, it is essential that these two points are taken together to fully evaluate the contribution that this study is attempting to make.

While we have presented the material on soils, biodiversity, water and air quality as four 'stand-alone' reviews, their design was based on a common underlying motive: namely to examine whether the general ideas that surround notions of resilience can usefully connect up current evidence *across* different discipline areas in ways that can inform policy debates concerned with managing the impacts of climate change on ecosystems. The requirement that the analysis should be based on systematic review methods, rather than more informal review approaches, clearly constrained the nature of the task. As a result the outputs of the reviews must be considered from this perspective. Thus while the reviews have sought to identify and report on the available empirical literature in systematic and repeatable way, their coverage was clearly controlled by the need to seek out material that explicitly dealt with the resilience concept or ideas closely associated with it. The reviews are 'stand-alone' but they may not be as comprehensive as one might expect if one considered stability and recovery of ecosystems in relation to soils, biodiversity water and air quality as separate topics. In other words, the purpose of this study is mainly to help understand the contribution that systematic reviews can make in relation to general policy questions about resilience, rather than to explore ecosystem dynamics across these four thematic areas in isolation.

We begin this critical reflection on the results of this study first from the resilience perspective, and then for the systematic review process. The discussion continues with the presentation of a knowledge map for resilience that synthesises the study outputs across the four topic areas, and then concludes with our recommendations for further work.

7.2 Framing resilience

In the introduction to this study we noted the difficulties that surround the notion of resilience. These initial discussions summarised the key aspects of resilience that would be considered, namely the resistance of ecosystems to disturbance and their speed of recovery following some disruptive event, but the wider semantic and theoretical debates were largely avoided. It is now appropriate to consider them in more detail.

Brand (2009) has recently presented an extensive review of resilience and sustainable development, and has argued that currently the idea of resilience is 'in jeopardy' as a result of a number of conceptual and theoretical difficulties. On the one hand there is the problem of 'conceptual vagueness'. This has come about, he suggests, since the concept was first introduced into ecology in the 1970s as a result of interest being taken up in a number of different discipline areas. Increasingly the word is being used with a number of different intentions and understandings, including both the *description* particular ecosystem characteristics or dynamics (e.g. in terms of 'stability in the face of disturbance' and 'ability to recover following impact') as well as representing some kind of *normative* proposition about what kinds of ecosystem characteristics are desirable or necessary in the context of sustainable development, say. It also appears to reflect particular cultural and philosophical assumptions. As a result we see in the literature usages based on fairly well defined measures, closer to the original 'engineering' formulation derived from systems theory, through to more open-ended treatments of the idea[13]. Brand (2009) interprets the transformation as suggesting that resilience has become more of a 'boundary object', helping to transmit and coordinate thinking between disciplines even though there is no commonly accepted or precise definition of the term. The very fact that it can be open to interpretation and debate is, Brand (2009) adds one of its advantages, because it can help bridge between different areas of knowledge. On the other hand it can equally become a drawback because the very 'malleability' of the idea can frustrate scientific progress since it is not easily operationalized.

Brand (2009) concludes that as resilience is increasingly used as a perspective rather than a clear well defined concept, the original ecological dimension of the idea is about to disappear. His analysis suggest that recent studies tend to emphasis more the social, political and institutional asperities of resilience, or deal with notions of resilience from the integrated or holistic perspective of socio-ecological systems, while focused ecological studies become increasingly rare.

The results and difficulties encountered by this study clearly reflect some of the wider issues identified by Brand (2009). For example, part of the stimulus to this work has been the need to deliver the Public Service Agreement (PSA) to *"...secure a diverse, healthy and **resilient** natural environment, which provides the basis for everyone's well-being, health and prosperity now and in the future...",* with policies based on 'evidence', but used in this way the notion of resilience is much more all-encompassing and normative than that envisaged in the original ecological formulation. In fact, if we unpack the way in which the idea of resilience is used in discussions surrounding the PSA target, we can appreciate just how multi-faceted and malleable the idea can be. Thus it can be interpreted from the perspective of *conservation*, namely in terms of finding ways to protect important aspects of our natural capital base, by designing, say, an appropriate network of marine protected sites. It can also be interpreted and applied in the sense of *restoring* ecological function by, for example, reducing the fragmentation of habitats and building functional ecological networks or reducing the impacts of pollutants. Finally, it can be looked at from the perspective of ensuring that ecosystems can *transform* and *adapt* in the face of climate or other environmental changes involving long term directional change in some external driver. Clearly in the context of sustainable development we need all these different types of thing. Moreover, to secure them we would probably need to pay attention to social and institutional arrangements as well as the characteristics of ecological systems. However, while these goals are worthy and important, it seems unlikely that they can be bound together unambiguously in a single, *operational* concept.

[13] In fact Brand (2009, p. 201) outlines 10 different meanings of ecological resilience that can be derived from the current literature.

Brand (2009) argues that to accommodate the different usages surrounding the notion of resilience, more precise terminology is required. As noted in our introduction, the distinction he suggested between *ecological* or *ecosystem resilience* and *socio-ecological resilience* is a useful one that captures the spectrum of intentions. However, the outcomes of this study suggest that it may not alone be sufficient. Even though we have focussed on the more easily defined idea of ecological resilience, the experience we have gained from our review in the four different topic areas is that resilience *per se* is not central to current debates which are much better understood in terms of the more distinct ideas of stability, the ability to recover following some transient disturbance, and the extent to which these systems might be transformed under longer-term changes in some set of exogenous or external controlling factors.

The concept of resilience, we suggest, is therefore more useful in policy debates if we recognise that principally it is a normative concept, valuable in identifying the types of range of ecosystem characteristics that might be promoted through management and policy designed to secure 'sustainability'. Equally we should avoid the temptation of thinking that the design of particular aspects of policy or management can be unambiguously underpinned with evidence as to their effectiveness, without more clearly stating what particular aspects of ecosystem dynamics are being considered. To make progress, we clearly need to find ways of mapping or translating the normative aspects of 'resilience' onto more precisely defined concepts that can be used to explore the available empirical literature.

7.3 Systematic Review and Knowledge Mapping

The difficulty of undertaking a systematic review on resilience was discussed in the introduction to this Report (Section 1.3). Given the 'open-framed' nature of the questions about ecosystem resilience implied by the study brief, we suggested that a two stage approach was more appropriate. Following the 'Guidelines for Systematic Review in Environmental Management' (Centre for Evidence-Based Conservation, 2010, p.19) it was proposed that this would involve the construction of a '**knowledge map**' describing the main areas of concern in the present literature, which could then be used to undertake more focused analysis using systematic review methods.

Although the idea of knowledge mapping fits well with the suggestion that resilience thinking has to be refined around a more specific and measurable set of characteristics, techniques for knowledge mapping are much less well-developed than those for systematic review. This situation meant that the current study was somewhat exploratory in nature, and it is useful to reflect now on how successful this strategic approach was, since ultimately it must control the quality of subsequent outputs.

All systematic reviews have to start with a scoping phase to ensure the structure and relevance of the review question, and the robustness of the search protocols. Knowledge mapping is a much broader and wide-ranging process, which involves more interpretation than systematic review. Although knowledge mapping seeks to identify the specific topic areas within which unified or coherent bodies of evidence exist, difficulties arise in deciding the boundaries of the mapping process when the field itself is poorly defined, or there is little consistent usage of terminology. This problem was particularly acute in the case of resilience. While there is a considerable body of literature dealing with the resilience concept in general terms, this study found that empirical studies that explicitly explored the idea in an analytical way are far fewer in number; this was particular apparent in the case of biodiversity and water, for example. To overcome this difficulty an attempt was made to expand the body of potentially available material by identifying additional terms that captured different aspects of 'resilience thinking' such as 'stability', 'vulnerability' or 'recovery'. Although this strategy was successful it resulted in the selection of a number of sources whose relevance to the overall topic of ecosystem resilience had to be established. As far as it is possible, the systematic review process tries to eliminate bias by making the selection process as transparent and repeatable as possible. Knowledge mapping is, it seems, more open to an interpretation because the links between concepts and terms are not there in the literature, waiting to be discovered or revealed, but involve a process based on judgement. Thus in the case of soils, soil quality was used as a way of framing aspects of resilience thinking, but much of the soil quality literature makes little reference to the term resilience. More generally, while many papers dealt with the effects of changing moisture and temperature regimes on soils, they did not always link this explicitly to the issue of climate change. Clearly decisions about what to include in the knowledge map are therefore critical because they will define the geometry or configuration of the systematic reviews that are then undertaken within each area of knowledge.

The need to identify more specific or focused sets of review questions that nested within the general resilience topic was recognised in the design of this study, and the team sought to develop a consultation process to achieve this. However, experience suggests that the study team probably attempted to move too quickly to the review stage without exploring fully what resilience itself implied from a policy perspective. Once the topic areas of soils, biodiversity, water and air quality had been identified, the team then sought to consult with 'subject' and 'policy' experts within each of the thematic areas. Their concerns linked more to the issues in each field rather than on the general utility of the resilience concept for policy or management. Their involvement bought insights, but the process did not achieve an integrated framework for the analysis of *resilience*. Moreover, by constructing a set of stand-alone analyse they have in a subsequent round of consultation, tended to be considered in terms of their individual adequacy as a review of the 'state-of-the-art' in each field, rather than as an examination of whether a body of cross-cutting evidence existed that might support the use of 'resilience' as an idea in policy debates. Possible alternative approaches are discussed below (see 7.4. & 7.5).

When contemplating the requirements of a systematic review, the 'situational logic' suggests a reductionist approach, in which perspectives are gradually refined and focused so that precise questions can be asked. Although knowledge mapping may help this process, our experience indicates that it cannot simply be viewed as a means of identifying where effort might subsequently be directed without any regard as to how the results of those individual reviews would contribute to some overall conclusion. A shortcoming of the present study was, perhaps, that the decision to identify four distinct topic areas as a framework for review was made without any clear understanding of how the separate findings could subsequently be linked to each other in some final analysis of the overarching notion of *resilience*. For example, while the focus of the investigation of air quality was on the impacts of changing atmospheric inputs on ecosystem function, that for water looked at how the evidence on how the water regulating characteristics of ecosystems changed under future climates. A more integrated picture of ecosystem resilience might have been achieved if, instead, the impacts of changing moisture regimes on ecosystem function had been looked at.

These findings could then have been aligned more easily with those for soils, biodiversity and atmosphere to determine the vulnerability of ecosystems to environmental change.

Given the need to base policy on the best available evidence, any study what seeks to inform discussions surrounding the aspiration of, say, securing *a diverse, healthy and* ***resilient*** *natural environment* must start with a clear understanding of what appropriate policy outcomes might be *vis à vis* resilience. In relation to the impacts of climate change, for example, is it that that ecosystems should be resistant to such change or is it that they should be adaptable and capable of adapting to new conditions while maintaining the ecosystem service we currently enjoy or might need in the future? Should management or policy intervention seek to buffer the effects or promote adjustment? The answers depend on the situation one is looking at, and if context matters it seems unlikely that any single body of evidence can determine whether or not building resilience *per se* is an appropriate or relevant policy goal. Anderies (2006) has argued that the notion of resilience is best thought of a set of ideas about how to interpret complex systems. For those who seek to apply those interpretations through policy or management action, a knowledge map that describes qualitatively the different ways the concept has been constructed and used, could possibly be more helpful than a specific quantitative meta-analysis that deals with only one ecosystem component.

By moving too quickly to the review stage, without refining what was embedded in the resilience concept from a policy or management perspective, the literature searches generated a rather narrow range of material that neither usefully extend thinking about resilience, nor completely reflect the current state of knowledge in each topic area. Instead of trying to discover whether there was evidence across different topic areas that systems showed some kind of 'resilience' in the face of climate change, a more fruitful approach might have been to examine how the multiple ideas embedded in the resilience thinking are reflected or constructed in different discipline areas. This would involve building up a rich picture of equivalences between different concepts and terms in different subject areas. It is unlikely that this could be achieved by literature searches alone, and probably requires a more extensive use of experts than was possible in this study.

The lesson from this project is that when seeking to use the methods of systematic review to ensure that policy is based on evidence, the importance of an initial phase of knowledge mapping should not be overlooked. It is particularly important when addressing open-famed questions involving concepts like resilience which may be used in a normative rather than analytical way in policy debates. The systematic review process can deliver insights, but as this study illustrates to make progress we have to be clearer from the outset about the kinds of evidence would support the assertion that resilience, for example, is an *appropriate* and *achievable* policy or management goal.

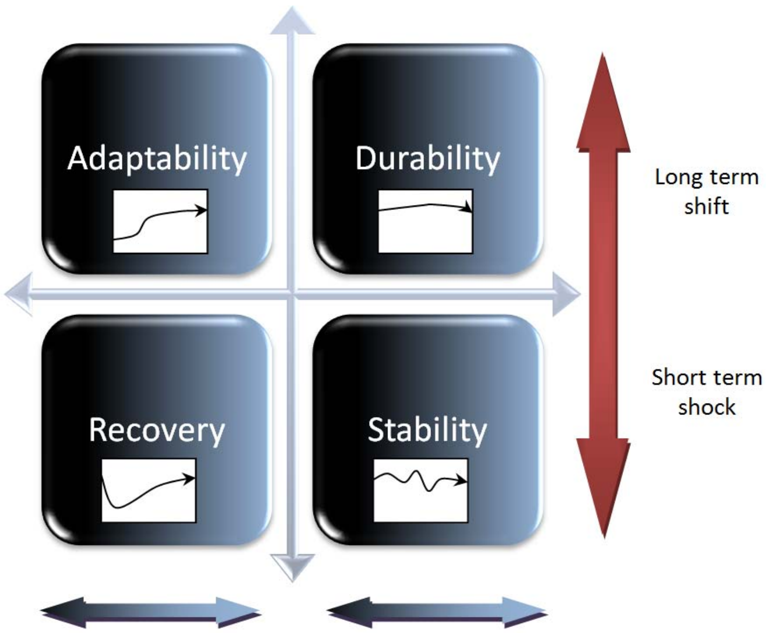
7.4 Knowledge Mapping for Resilience

Although this study did not, perhaps, focus sufficient resources on building a knowledge map for resilience as might have been desirable, the work did identify a range of material that can, nevertheless, be used retrospectively to construct a 'first draft'.

While commentators vary in the terminology that they use when discussing resilience, there is a large degree of agreement that it covers both the resistance of systems to disturbance *and* their ability to recover following some kind of perturbation. This was particularly evident in the material extracted on soils, and also apparent in the air quality analysis. Figure 7.1 shows one way in which the different dimensions of resilience might therefore be represented. It is based on a reworking of the model proposed by Dawson et al. (2010) (see also Figure 1.1), who usefully distinguish between the dynamics of systems subject to short-term, transient shocks or disruptions, with those subject to more longer lasting (chronic) changes or shifts in key drivers or pressures. Thus stability is a measure of the systems tolerance or sensitivity to short-lived perturbations, while durability is the capacity of the system to tolerate or buffer longer term stress. Where framework shown in Figure 7.1 differs substantially from the Dawson model is that it includes the concepts of 'adaptability' and 'recovery'.

Dawson et al. (2010) refer to the ability of systems to rebound and return to equilibrium as 'resilience'; we prefer instead to use the term 'recovery' to describe this concept and follow convention by using resilience as label for all the concepts shown in Figure 7.1. More significantly we have replaced 'robustness' with adaptability to more clearly capture the idea that systems may be resilient because they can sustain their functioning because the can adjust, adapt and reorganise as a result of changing external pressures, and move to some new equilibrium state. The lack of any reference to the ability of systems to adjust seemed to us, to be a deficiency of the Dawson model.

Figure 7.1: A framework for representing ecosystem resilience
(adapted from Dawson et al., 2010)



The reorganisation proposed here has a major consequence in that the distinction that the original model proposed by Dawson et al. (2010) made between internal (endogenous) short-term disturbances and external (exogenous) long-term stresses or drivers no longer applied so elegantly. Instead, we have suggested that they apply across the board. According to the model proposed in Figure 7.1 the left-right contrast between adaptability/recovery and durability/stability concerns the dynamics of systems in relation to some equilibrium state. The durability/stability paring attempts to capture the extent to which systems can maintain that equilibrium in the long and short term. By contrast, the adaptability/recovery paring focuses on the dynamics of the system if equilibrium conditions change either temporarily or over longer periods.

Figure 7.1 is clearly more complex than the original model proposed by Dawson et al. (2010). However, we suggest that it is more helpful in summarising the different research concerns identified by this study, and can be used to construct an initial knowledge map for resilience across the topic areas that have been investigated. As part of the process of developing and applying the framework shown in Figure 7.1, we have grouped in a more detailed way the different concepts that are used in discussion of resilience (Figure 7.2). This arrangement of concepts could be used as a diagnostic tool to help decide how to group the various sources of evidence in relation to the overarching question about how the resilience of systems change in the face of climate change.

Figure 7.2: Relationship between resilience concepts

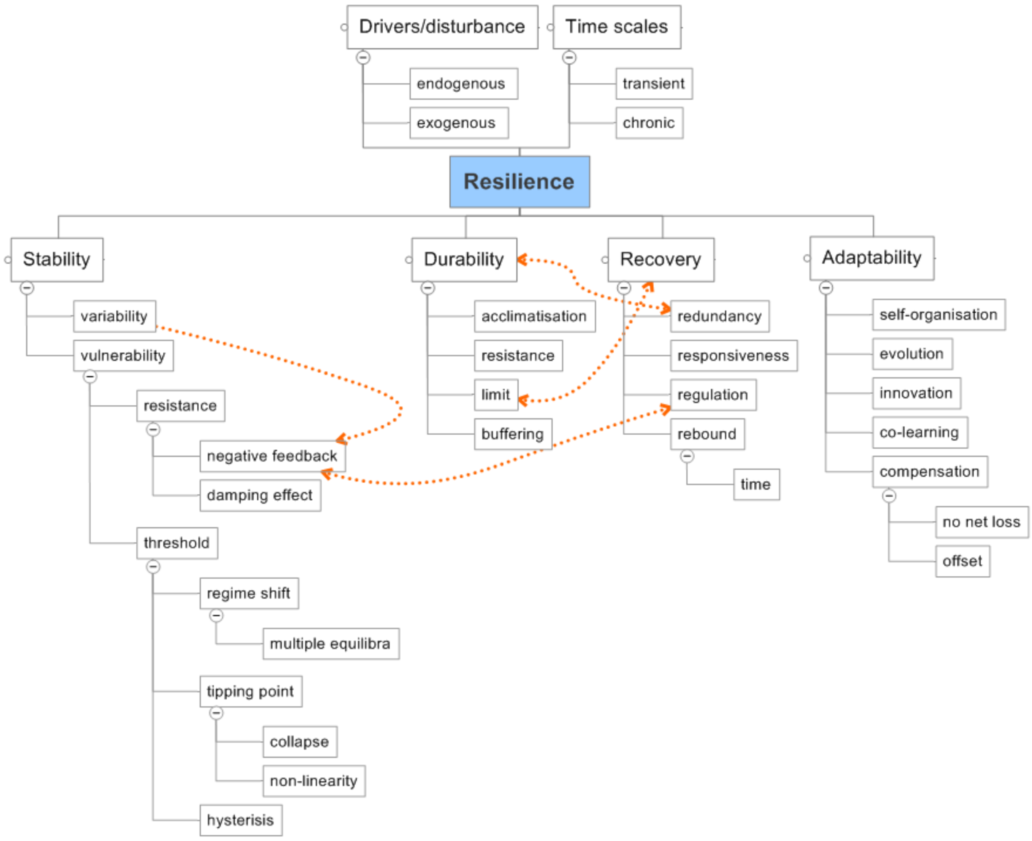


Table 7.1 is the result of applying the conceptual framework described above to the issue of how the resilience of ecosystems might change under future climates. It attempts to set out a unified constellation of questions across the four thematic areas considered in this study using the ideas of stability, recovery, durability and adaptability as a template. The table could, perhaps, be described more of an '**issues map**' or 'issue matrix' than a 'knowledge map', because it does not present results. Nevertheless, starting with questions such as these it is easy to see how it could be developed into a more comprehensive review, once the content of the individual questions had been agreed and an assessment made of the extent to which individual systematic reviews were possible within each area, given the available evidence.

Table 7.1: 'Issue matrix' based on the framework for representing ecosystem resilience (Fig. 7.1) and climate change impacts

	Soils	Biodiversity	Water	Air quality
Stability & Sensitivity	• How sensitive is soil respiration to changes in temperature and CO_2 concentrations? • Overall how sensitive are soil carbon stores to changes in temperature and CO_2 concentrations given the wider feedback effects on productivity levels?	• How sensitive are different habitats to changes in changing climate regimes in terms of composition and above and below ground productivity? • How sensitive is community productivity to changes in biodiversity characteristics?	• What is the impact of changing moisture regimes on ecosystem productivity and soil function? • How do changing moisture regimes impact on community composition?	• To what extent will changing levels of O_3, nitrogen, sulphur and acidification changes growth patterns and reproductive performance that can potentially shift the competitive balance within communities?
Recovery	• How effective are management interventions as a means of increasing soil carbon?	• To what extent is the speed of recovery of community processes dependent on biodiversity?	• How do changes in biodiversity affect the drought resistance of communities?	• To what extent can ecosystem processes recover if critical loads are no longer exceeded?
Durability	• How vulnerable are carbon stores represented by organic soils to changing climate? Where are the tipping points? • Are there acclimatisation effects in relation to impact of warming and CO_2 on soil respiration? • What are the ancillary benefits of increasing soil carbon levels on other aspects of soil quality?	• To what extent can the effects of climate change on community characteristics be mitigated by management interventions?	• How will extreme moisture events impact on the structure and function of ecosystems (including soils)? • How does moisture stress affect the sensitivity of species and habitats to changes in air quality?	• How sensitive are community processes to chronic impacts at sub-lethal critical loads? • How will critical loads exceedances change under conditions of future climate change?
Adaptability	• How do soil microorganisms react to changes in temperature, moisture and CO_2 levels? • Is there an upper limit to the amount of carbon that can be sequestered in soils as a result of warming and CO_2 changes?	• To what extent can shifts in community composition buffer changes in biogeochemical cycles within ecosystems? • What opportunities does management offer in terms of increasing the climate mitigation potential of different habitats?	• What kinds of shift in community composition can we expect under future moisture regimes and where are these effects likely to occur?	• How will changing species and habitat patterns affect the assessment of critical loads?
Uncertainties	• *Significant interaction between community processes an climate variables makes outcomes in terms of carbon balance difficult to determine.*	• *Sensitivity of community processes such as productivity and nutrient cycling to changes in biodiversity are unclear.*	• *Impacts of changes in moisture regime in community composition and soil function are uncertain.*	• *There may be significant interaction effects between air quality parameters at higher temperatures and* CO_2 *levels.*

The issues identified in Table 7.1 have partly been drawn from the materials identified in the separate reviews. This is particularly so in the case of soils and air quality. As noted above, the water review looked more at the impacts of changes biodiversity on the water regulating characteristics of ecosystems, and so less easily linked into the this general framework. However, the merits of using this approach in terms of identifying a more coherent set of issues to investigate are clear. Inevitably, given the wide ranging nature of questions about resilience, evidence likely to be spread across a number of discipline areas. The four topic areas are not the only ones that could have been considered in a review of resilience. Nevertheless they are useful to illustrate how we could use the idea of an issues map to look at the kinds of evidence that would be needed to make an overall judgement about ecosystem resilience and climate change.

Thus in developing the issues set out in Table 7.1, we have not confined ourselves to the materials identified in the separate reviews, but also drew more widely on the questions and linkages between the topic areas.

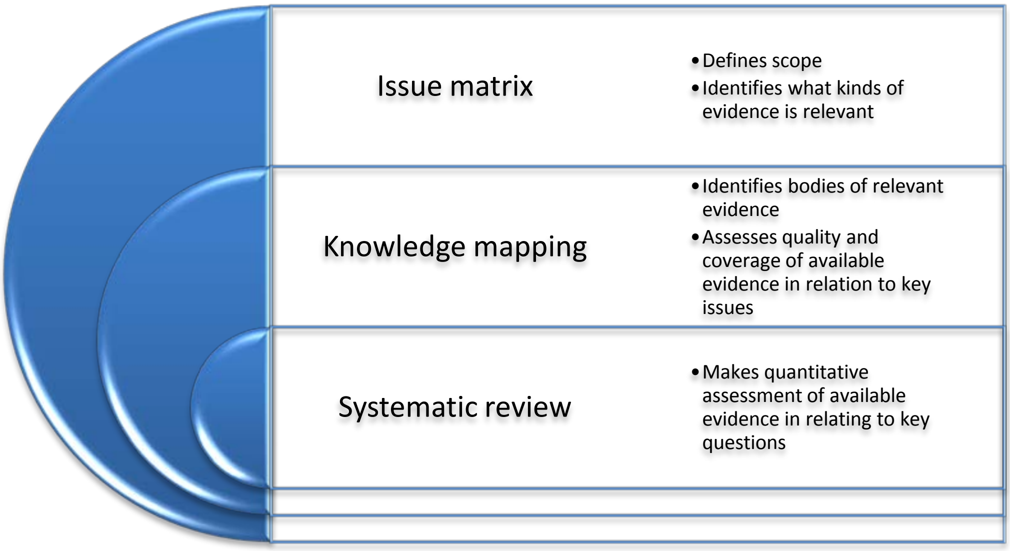
An illustration of the benefits of using this 'issues mapping approach' is provided by the identified in the soils review. This analysis showed that key questions in the field, for example, concerned the sensitivity of soil respiration warming and changes in CO_2 concentrations, how these factors interacted with each other and how the overall balance between storage and loss of soil carbon might shift as ecosystem productivity was modified. There we also note the potential interaction effects with other components such as changing moisture regimes and changing nutrient input. The construction of Table 7.1 attempts to indicate where these cross-linkages exist, and where therefore a more integrated consideration of the available evidence might have been attempted. The table highlights these cross-cutting issues in the last row of the matrix.

At this stage it must be acknowledged that the issues map shown in Table 7.1 is a preliminary one, and ideally should be refined not only by bibliographic analysis but also by the involvement of policy and subject experts seeking to apply the key resilience concepts (Figure 7.2). With the benefit of hindsight, this study should perhaps might have devoted more time to the construction of this framework, and paid more attention to its refinement and testing via a review of the available evidence. **Starting with a more formal 'issues matrix'** would have helped to more clearly define the scope and focus of the review activities. The value of the matrix approach is that it also defines the context in which individual reviews might be set and evaluated. Thus unlike those presented here, experts would not assess adequacy in terms of stand-alone reviews of each topic, but rather as ***contributions*** to an evidence base constructed to address a specific science or policy question.

7.5 Implications and Next Steps

There is little doubt that systematic review is a vital part of developing evidence-based policy. However, it must be recognised that policy questions are often more complex and open ended than the methods of systematic review seem to allow. This certainly seems to be the case for resilience. Systematic review has its place in taking discussions of resilience forward in a policy context, but they should not be embarked upon lightly. The experience of this study is that when terms are so malleable and open to different readings and interpretations, an important preliminary stage in any review process must be something equivalent to issues mapping.

Figure 7.3: Relationships between issues and knowledge mapping and systematic review



As part of our critical reflection on the outcomes of this study we have described how this issues mapping process might work. Figure 7.3 describes its relationship to the knowledge mapping and systematic review process as described by the 'Guidelines for Systematic Review in Environmental Management' (Centre for Evidence-Based Conservation, 2010). We suggest that it is perhaps distinct from the knowledge mapping process they outline and can usefully precede any mapping and systematic review exercise. We also suggest that it is distinct from the idea of a 'pilot review', which mainly focuses on the potential availability of evidence given a defined review question.

We suggest that review activities driven by policy needs would often use concepts like resilience in ways that have multiple meanings and that imply normative perspectives. To some extent this is the very essence of policy debates, which depend on these kinds of 'boundary objects' or open-framed concepts to enable discussion between different interest groups and knowledge domains. However, if we are to bring evidence to bear in these debates, then we must find ways of operationalising the process of making evidence open to scrutiny. While decisions are ultimately always based on judgement, we have to find ways of agreeing about what kinds of evidence that we consider relevant it a particular policy context. A rigorous 'issues mapping' exercise is may provide part of what is required.

Thus if the objectives set for the present project are to be fully realised, then we suggest that unfortunately further work is required. Specifically we suggest the following next steps:

1. that there should be a round of further discussion to refine the issues matrix proposed above, with the specific aim of agreeing just how the answers to these questions would inform the use of 'resilience thinking' in a policy context;
2. that the existing preliminary but partial reviews be used to refine and extend the initial search strategies so that the outcomes are potentially more relevant to the overarching question about resilience and climate change;
3. that a detailed knowledge map is then prepare, based on an agreed set of keywords and codes that can be used to classify and to characterise the different studies so that information can be extracted from them in a systematic and transparent way;

4. that once the availability of evidence in the specific areas identified in the 'issue matrix' is established through the knowledge mapping process, targeted quantitative systematic reviews are constructed if no published material exists;
5. that where quantitative, systematic reviews cannot be undertaken, peer reviewed descriptive reviews should be made; and,
6. that the conclusions from the separate systematic and descriptive reviews be assembled and discussed using the framework of the issues matrix, to form a judgement about the nature of ecosystem resilience in the face of climate change.

The Action Plan for embedding an Ecosystems Approach in decision making (Defra 2007, 2010b) emphasises that adaptive management involves consultation and the co-construction of knowledge, as well as making the use of the best evidence available. The recommendations we have made about the construction of an 'issue matrix' via a dialogue between policy customers and topic experts is clearly consistent with and compatible with this proposition. Brand (2009) has argued that 'resilience thinking' is probably best viewed as part of the process of adaptive ecosystem management. The experience gained in this study has provided some pointers as to how this can be taken forward by combining the focused methods of systematic review, with more open deliberative approaches designed to better understand how broad, normative policy concerns can be translated into manageable review questions.

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Appendix A: Invitation to Tender for this study

Research Study

TITLE: - A SYSTEMATIC REVIEW INTO THE RESILIENCE OF ECOSYSTEMS AND THE SERVICES THEY PROVIDE TO SOCIETY IN THE FACE OF CHANGING EXTERNAL PRESSURES.

Policy Background

1. The UK Sustainable Development Strategy[14] identified protection of natural resources and enhancement of the environment as a key priority. It recognised the progress made in dealing with threats to the environment (e.g. point sources of pollution) but recognised the more complex and cross-cutting challenges we now face such as diffuse pollution and climate change. It identified the need for a more integrated policy framework to address these challenges, with decisions made based on consideration of whole ecosystems, and the services they provide. It identified living within environmental limits as one of five key principles. And it also committed to piloting open and innovative ways to allow stakeholders to influence decisions.

2. The Natural Environment Public Service Agreement (PSA 28), states the government's vision for the Natural Environment is to secure a diverse, healthy and *resilient* natural environment, which provides the basis for everyone's well-being, health and prosperity now and in the future; and where the value of the services provided by the natural environment are reflected in decision-making.

3. In December 2007, Defra published *Securing a healthy natural environment: An action plan for embedding an ecosystems approach*[15]**.** Alongside this action plan was also published *An introductory guide to valuing ecosystem services*[16]**.** Both documents highlight the need to develop a more strategic framework for policy-making and delivery on the natural environment, based on the principles of an ecosystems approach.

4. This approach lies in integrating and managing a range of demands placed on the natural environment in such a way that it can indefinitely support essential services and provide benefits for all. The approach requires shifting the focus of policy making and delivery away from looking at the natural environment policies in separate silos e.g.- air, water, soil, biodiversity- and towards a more holistic or

[14] 'Securing the Future: Delivering UK Sustainable Development Strategy' 2005, http://www.defra.gov.uk/sustainable/government/publications/uk-strategy
[15] The action plan can be found by following the links at this address http://www.defra.gov.uk/environment/policy/natural-environ/index.htm
[16] The valuation guide can be found by following http://www.defra.gov.uk/environment/policy/natural-environ/index.htm

integrated approach on whole ecosystems. It also seeks to ensure the value of ecosystems is fully reflected in policy and decision-making at all levels. Further information relating to this work can be found on our website at **http://www.defra.gov.uk/environment/policy/natural-environ/index.htm**.

5. The Delivery Plan for PSA 28 states that: "*to ensure a healthy and resilient natural environment, it is vital to take into account the impacts of climate change.*" The Adapting to Climate Change Programme and UK Climate Projections 2009 form part of a concerted programme of action in response to climate change currently being pursued across Government and form the basis for Defra's *Natural Environment – Adapting to Climate Change* project. This project focuses on reviewing policy and practice within Defra and its network to ensure that they are well placed to respond to a changing climate. The output will be a clearly articulated framework setting out current and planned activities aimed at adapting management of the natural environment in England within the context of PSA 28 and Defra's Departmental Strategic Objectives 1 and 2 (**http://www.defra.gov.uk/corporate/about/what/objectives08.htm)**

Rationale for Research

6. Generating evidence to assist policy making around an ecosystems approach and adaptation to climate change requires knowledge from a broad range of scientific, economic, and social science disciplines to be integrated to answer policy-relevant questions. For this reason, Defra and NERC commissioned through the Living With Environmental Change (LWEC) initiative six pilot systematic reviews relevant to Objective B of LWEC (**http://www.lwec.org.uk/objectives**) which focuses on the management of ecosystems for human well-being and protecting the natural environment as the environment changes. Two of these pilot reviews suggested that the topic of ecosystem resilience in the face of environmental change would be highly suitable for a full systematic review to bring together the existing scientific evidence to answer questions relevant both to climate change adaptation policy and policy aiming to take an ecosystems approach. These reviews can be found at (**http://www.defra.gov.uk/evidence/science/publications/index.htm)**

Aims of research

- 7. Through a thorough review of the existing evidence base, the aim of the research is to examine critically a small set of policy relevant questions based around the theme of the resilience of ecosystems and the (ecosystem) services and benefits that they provide to society and the economy in the face of changing external pressures, including (but not limited to) those from a changing climate.

Objectives

8. Generic guidance on running a systematic review in the natural sciences can be found in: (Pullin & Stewart 2006. Guidelines for systematic review in

conservation and environmental management. Conservation Biology vol. 20, n^{o}6, pp. 1647-1656).

The objectives for this particular study will be to:

a. Define the question and the sub questions that the review will answer. This will need to be tested and possibly modified as the review progresses and may involve science/policy expert input.

b. Develop and deploy a search strategy and selection of search terms to ensure that publications relevant to exploring the question(s) are accessed. It is important to note that, in this cross cutting area, the selection of and access to a variety of evidence sources (i.e., not just academic journals) will be key to a thorough understanding of the issue.

c. Select relevant publications for further investigation by developing and using inclusion criteria that capture the wide range of evidence necessary to address the question, yet filter unrelated publications from the process.

d. Through the development of a set of criteria, quality assure the information generated through the search and selection processes and ensure that the evidence is both robust and truly pertinent to exploring the review question(s).

e. Synthesise and critically examine the remaining information to explore the review question(s) and provide a report on the policy-relevant conclusions that can be drawn from the existing evidence, together with an annotated reference library of the publications forming the evidence base for the review.

f. Drawing from the outputs of objectives a-e, provide an evidenced commentary on apparent evidence gaps in the current body of literature and, where appropriate, provide suggestions as to what sort of evidence activity would be most appropriate to fill these evidence gaps.

Scope

9. Although the specifics of the review question and search protocols will be refined in the early stages of the study, researchers should show in their tender application a clear understanding of how they will develop the processes and protocols required for each of the objectives, giving examples of suggested review questions, likely literature sources, and ideas for quality and selection criteria in their application.

10. The range of evidence relevant to this area is broad, and will encompass both scientific literature (social and natural), economics literature, and other sources of "grey" literature, including government reports and publications from non-governmental organisations. The researchers will therefore be expected to show how they intend to access a wide range of information sources in performing their

searches and how they will quality assure the data they collect before using it to examine the policy relevant questions.

11. Similarly, researchers should show clearly how they intend to incorporate expert advice into their review, and how they will engage with the wide range of expertise relevant to the ecosystems and environmental change agendas.

Uses and Users of the Results

12. The customer for this work will be Defra's Environmental and Rural Group but the findings and recommendations will be relevant to a wider audience interested in policy surrounding the natural environment and environmental change, including, but not exclusively, other Government Departments and the Defra Network.

-
- **Research methods**
- 13. We do not believe that a survey is necessary to complete this study, but if an external survey is to be undertaken as part of this study approval will need to be gained from the Survey Control Liaison Unit (SCLU) in Defra. The Defra Policy Division will make the application for approval, but a contract involving a survey cannot be let prior to receipt of outline approval from SCLU.

Key Deliverables

20. Interim report(s) at appropriate point(s) in the contract.
21. A final "overview report" covering the policy and scientific background to the work, the methodologies employed, results, and conclusions. This should follow the format of the Defra SID5 form (max. about 50 pages). This final report will contain an Executive Summary of no more than 2 pages. There should also be a headline messages paper of approximately three to five pages aimed at policy-makers. Any further reports (and e.g. reference libraries) can be provided as Annexes to the SID5. All reports should be written in plain English.

Timetable

22. The contract is expected to commence by the start of February 2010. The contract is envisaged to last 4-5 months from the date of contract award.

Publication

23. It is the intention of Defra to publish the results of the work on the external website. All reports should therefore be suitable for publication on the Internet and should be accessible to a wide audience.
24. If you are going to include verbatim comments in your reports, please do inform people of your intention to do so, and obtain their permission.

Appendix 1: Interviews with Experts

A1.1. Background to the RECCE Project: Briefing for Expert Interviews

About RECCE

The RECCE (The Resilience of Ecosystems to Environmental ChangeE) project is undertaking a systematic review of resilience and how it relates to key policy areas of concern to Defra and its partners. The goal is to better understand how policy action might help to sustain ecosystems in the face of environmental change or to protect the capacity of ecosystems to recover following disturbance. The work seeks to take stock of the scientific, management and policy literatures on this topic, and assess the robustness of the current evidence base that could be used to frame policy and management responses (see www.RECCE.org.uk) .

Perspectives on resilience

The analysis of ecosystem resilience is challenging because there is considerable divergence in the way the concept of resilience has been framed. Moreover, since it is often discussed conceptually as a 'whole systems' property, it is often difficult to relate more focused empirical studies of individual ecosystem properties to the dynamics of entire ecosystems. Nevertheless, given present concerns that losses in biodiversity may lower the resistance of ecosystems to disturbances or their ability to recovery from external impacts (e.g. Loreau et al., 2002; van Ruijven and Berendse, 2010), it is important to examine what is known about what kinds of factor might enhance system stability and how policy or management intervention might help secure greater resilience to external pressures.

Following the discussion of the concept of resilience by a number of recent commentators (Brand and Jax, 2007; Janssen and Ostrom, 2006; Janssen 2007; and Dawson et al., 2010), within RECCE it has been decided that the primary focus of this study is ecological or ecosystem resilience, defined as both:

- *The magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour; and,*
- *The capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity.*

And that the following terms are either indicative of literature linked to current debates or have been used to refer to notions embedded in the resilience concept: *resilience, resilient, adaptation, adaptability, adaptive, resistant, resistance, vulnerable, vulnerability, recover, recovery, stability and variability, durability and threshold or limit.*

Key Policy Areas

Given the difficulty of exploring resilience both conceptually and empirically, the approach suggested by Carpenter et al. (2000) and Cummings et al. (2005) has been adopted, involving the being precise in terms *of what* ecosystem properties are being considered in relation *to what* kinds of disturbance?' Following a series of discussion with the project sponsors four thematic areas have been identified concerning soils, biodiversity, water and the impact of pollution on ecosystems as being of particular interest in relation to thinking about issues of environmental change, and this has led us to pose the following four broad questions as candidates for systematic review:

> Q1: *Do management interventions mitigate the impacts of environmental change on the supporting services associated with soils?*

Q2: *Can management interventions mitigate the impact of environmental change on the biodiversity characteristics of UK Broad Habitats?*

Q3: *Can management interventions mitigate the impacts of environmental change on the water regulating characteristics of ecosystems?*

Q4: *Can management interventions mitigate the (sub-lethal) impacts of pollution loads on ecosystems under conditions of environmental change?*

In addition to these questions a fifth (Q5) has been added, concerning whether there is any evidence that the impacts or effects in each of the four areas covered in Q1-Q4 lead to changes in service output that result in changes in economic value or human well-being.

Questions 1-4 contain reference to a driver, namely environmental change. Although this can be interpreted quite broadly, it has been decided that climate change should be the primary focus, and if the volumes of literature identified permits, the systematic review in each area should look at the impact of change drivers only in this topic area. Moreover, it should be noted that each question contains reference to a management intervention. Again this can be interpreted very broadly, and for the purposes of the present study is taken to be any intervention that could be brought about (or modified) by policy action. It has been recognised, however, that the numbers of studies that exist that deal with both environmental change ***and*** the mitigating effect of management interventions may be limited. Thus as a minimum the review should look at the effect of the driver on the various ecosystem outputs (i.e. ecosystem services).

Purposes of this Consultation

In order to support the systematic review process this round of consultation with selected experts has been organised to:

- *Elicit their views on the way notions of resilience have been framed in the review questions.*
- *Determine whether they think the questions in each of the topic areas have scientific relevance and are tractable, given the volumes of literature likely to be available.*
- *To identify key or relevant studies, either in the published or grey literatures, that might help refine the way the systematic review will be made, or might assist in identifying more precisely empirical outcomes or measures that can be used to test ideas about resilience.*

Interview questions

A. Resilience experts

1. Framing the resilience concept

If resilience is defined as:

- *The magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour; and,*
- *The capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity.*

Do these two aspects cover the key issues that need to be investigated when looking at resilience from an ecological or ecosystem perspective?

Are the suggested synonyms or linked terms sufficient? Namely: *resilience, resilient, adaptation, adaptability, adaptive, resistant, resistance, vulnerable, vulnerability, recover, recovery, stability and variability, durability and threshold or limit.*

2. Measuring resilience properties empirically

While resilience is a whole system property, is it appropriate to break the study down into individual system elements or components? What outputs should be used to characterise the resilience properties of ecosystems?

3. Resilience and Environmental Change

Can you suggest any key empirical studies in relation to changing ecosystem resilience in the context of environmental change in general or climate change in particular?

4. Search Protocols for the review

Are the preliminary search terms listed appropriate for resilience and management interventions for preliminary data extraction; are there combinations of key terms missing? What key terms do you suggest to add for the full review?

5. Systematic review question

What are your thoughts on the way we have formulated the systematic review questions, in terms of the ***subject-intervention-outcome (driver and comparator)*** structure suggested by the CEBC guidelines?

6. Policy relevance

Your thoughts on whether the review questions are sufficiently policy relevant? Are there additional areas that ought to be covered given the empirical evidence that you think could be reviewed?

B. Thematic experts

1. Framing the resilience concept

If resilience is defined as:

- *The magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour; and,*
- *The capacity of a system to experience shocks while retaining essentially the same function, structure, feedbacks, and therefore identity.*

Do these two aspects cover the key issues that need to be investigated in relation to your thematic area?

Are the suggested synonyms or linked terms sufficient in terms of your thematic area? Namely: *resilience, resilient, adaptation, adaptability, adaptive, resistant, resistance, vulnerable, vulnerability, recover, recovery, stability and variability, durability and threshold or limit.*

2. Measuring resilience properties empirically

While resilience is a whole system property, is it appropriate to break the study down into individual system elements or components? What outputs should be used to characterise the resilience properties in your thematic area?

3. Resilience and Environmental Change

Can you suggest any key empirical studies in relation to changing ecosystem resilience in your thematic area in the context of environmental change in general or climate change in particular?

4. Search Protocols for the review

Are the preliminary search terms listed appropriate for your thematic area; are there combinations of key terms missing? What key terms do you suggest to add for the full review?

5. Systematic review question

What are your thoughts on the way we have formulated the systematic review questions, in terms of the ***subject-intervention-outcome (driver and comparator)*** structure suggested for your thematic area? Do you think the question is scientifically interesting and tractable?

6. Policy relevance

Your thoughts on whether the review questions are sufficiently policy relevant? Are there additional areas that ought to be covered given the empirical evidence that you think could be reviewed?

7. Other materials

Any key references or other materials or sources that spring to mind in relation to achieving the objectives (or your suggested modifications), that we could use as 'starting points' for further bibliographic searches. This issue is particular important, and so if you could identify say 5 key references from you area of expertise, this would be really helpful.

A.1.2: Interview with Professor Kurt Jax, Department of Conservation Biology, Helmholtz-Centre for Environmental Research - UFZ, Wednesday 7.7.2010, for RECCE. Resilience Expert Consultation.
Interview Notes (approved by expert)

General comments and conclusions

The approach to resilience through empirical studies is accepted and deemed worthwhile by the expert. It is a timely and interesting study although it is very difficult to pin down the essence of resilience.

It will be important to be explicit and make the link from the systematic review questions that focus on the capacity of ecosystems to deliver ecosystem services under circumstances of environmental change, and how it relates to the concept of resilience through the ecosystem properties.

<u>Measuring resilience properties empirically</u>

While resilience is a whole system property, is it appropriate to break the study down into individual system elements or components? What outputs, in your view, can be used to characterise the resilience properties of ecosystems?

It is a worthwhile approach to test how far the resilience concept can be applied empirically. Proxies that are used to indicate resilience should either be composed of many different independent variables properties that represent multiple variables, such as some predator species. The challenge is to extrapolate from a number of proxy variables to the whole system property and there no agreed upon methods to go from measures of single variables to understand the function and structure of a whole system

What is the whole system?

Resilience does not have to be a whole ecosystem trait, just as the concept ecological resilience was first applied on studies of insect populations (Holling, 1973) it just as well focus on a subsystem of an ecosystem. By limiting the systematic review to specific ecosystem services the project has found a way of defining the system boundaries and this should be described explicitly with the final results.

In order to assess resilience or any whole system property one has to identify the system and the properties that constitute the system. The first question is: what is the whole system? In the case of this review it seems like the system is the part of a habitat that delivers a function such as water quality or quantity regulation and the performance of that function or ecosystem service. It seems like resilience is normative with the aim of maintaining ecosystem services. Then the threshold at which service delivery is impaired represents a sudden shift in ecosystem functioning.

In a recent dissertation Brand (Resilience and Sustainable Development, 2009) suggests three possibilities to operationalising resilience:

1. To assess how far a system is from a known threshold, distance to threshold
2. To analyse the identity of the system, similar to Cummings (2005)
3. To assess the resilience conducive properties of a system.

The last possibility may be the most promising and is based on the idea that a system that has many properties that induce resilience is likely to be resilient. Elements that can conduce resilience is heterogeneity, redundancy of functional traits of for example plant species, and overlapping niches. Species will have different tolerance to different types of disturbances and the system as a whole has better chances to persist perturbations.

Point number two is explored by Cummings et al (2005) and suggests that four aspects of identity (components, relationships, innovation and continuity) are required for a resilient system. They argue that this can be applied to both social-ecological systems as well as ecological systems, it is however unclear how innovation can be measured in an ecological system, and there is lack of evidence that all four are requirements for resilience.

The strength of the idea of resilience is that if it can be operationalised, it is not only a measure of a dynamic or state but says something about the capacity of the system to evolve and maintain its integrity over time.

What do you think of applying resilience to a system with mainly physical properties such as soil or water?

Resilience can definitely be applied to non biological systems, especially to deterministic systems, including machines. As long as the variables have known physical relations and you understand the interdependencies. It is important that the properties are statistically linked and respond to the same driver and experience the same threshold, thus are interdependent and can be regarded to belong to the same system. Saying that it is of course rare with systems where all components respond with the same strength to the same drivers or disturbances. In the case of soil the physical properties of soil aggregates, carbon content, and nutrient content can be the variables of resilience and the ecosystem output could be the amount of microbiota that it sustains or the plant biomass that can grow in the soil.

Framing the resilience concept
Do these two aspects of resilience that are presented cover the key issues that need to be investigated when looking at resilience from an ecological or ecosystem perspective?

It is good to focus on ecosystem resilience and include the social influence through management intervention as the social component rather than defining a social ecological system, because there is some scepticism of how to apply an overarching concept to a naturalistic super system that includes very diverse components. The notion of resilience has expanded to include almost everything but it is not feasible to operationalise or empirically measure the resilience of such a system. In previous discussions with Carl Folke from the Resilience Alliance it was confirmed that resilience is more metaphorical for a social-ecological system and difficult to operationalise or measure empirically. It may still be worth to try to operationalise it because of the possibility to obtain a measure of a systems future or inherent capacities.

How do you see the links between adaptive management and resilience?

Management of resilience is difficult because it is mostly an unknown capacity that may change in the evolution of a system if you see in the context of the adaptive cycle. The fluctuations of the adaptive cycle would be an additional theoretical burden to this project. The adaptive cycle also poses the questions of in which state an ecosystem is within the cycle, and how the resilience space changes depending on these states. It has been applied *a posteriori* as a conceptual framework to explain past events, but is difficult to use in prediction of future events which is the main interest in policy making. Questions that may rise from a management perspective is can we maintain a high level of resilience throughout the cycle? Can we accept the states of collapse and reorganisation of the adaptive cycle? Resilience is a part of the adaptive cycle, but it is possible that not all systems have an adaptive cycle.

Search Protocols for the review
EXAMPLE OF POLICY QUESTIONS: AIR QUALITY

Q1 Can management interventions mitigate the (sub-lethal) impacts of pollution on ecosystem under conditions of environmental change?

Q2 How does environmental change affect the (sub-lethal) impacts of pollution loads on ecosystems?

Subject – Driver – Outcome – Intervention
Comparators – degrees of environmental change (with and without intervention)

The search protocols seem very elaborate and complicated, and this may be necessary in order to achieve what you aim for. Below are suggestions of additional search terms policy areas and sources of information.

Additional search terms

- Regime shift, examples of this is in lakes and also of estuaries and tidal flats.
- Alternative stable states
- Vulnerability is most often operationalised in social system terminology and less in ecological systems, in natural system the term is basically used as a metaphor of weakness rather than a measurable entity.

Additional policy areas
Marine ecosystems and the recreational and regulating services such as storm protection or tidal flat ecosystems.

Additional sources
The REBECCA project, which aims to bring new information of the relationships between chemical and ecological status of surface waters in order to support the implementation of the Water Framework Directive. http://www.rbm-toolbox.net/rebecca/index.php

Ontologies for systematic search and classification of words for compatibility studies that may be useful in a discussion of how effective the search terms are in a systematic review in a field with heterogeneous usage of terminology.
Madin et al. 2008 S
Thresholds in lakes
Solheim et al. 2008

A1.3: Interview with Professor Jim Harris, Natural Resources Department, University of Cranfield, Friday 9.7.2010, for RECCE: Theme Expert Soil supporting services. Interview Notes (approved by expert)

SOIL QUESTIONS

Q1 Do management interventions mitigate impacts of environmental change on the supporting services associated with soils?

Q2 Does environmental change impact on the output of supporting services associated with soils?

Subject – Driver – Outcome – Intervention
Comparators – degrees of environmental change (with and without intervention)

Interview Notes
Recommendations from the expert:
The systematic review should focus on the biological entities and functions of soil as ecosystem properties because the microbiota is both useful as an indicator of physicochemical properties and a driver and essential component of nutrient cycling, soil formation and physical properties such as porosity, aggregate stability or soil organic carbon. Physicochemical properties of soil are measured more routinely , but there are more methods being developed for biological analysis with direct ecological relevance.

Current work
Cranfield has an on-going project with Defra on land use and soil biology called "Development of biological indicators of soil quality: Parts 1 and 2" known as "SQID" and another funded by Defra to devise a method for assessing climate change impact on soil biology

There are UK specific studies on microbiological studies on belowground communities (for example multiple papers by Griffiths, Ritz et al, 2000, 2001, 2004, 2005). Previous response from Defra to the notion of the importance of biology of soils has been positive and Cranfield is working on techniques to inform policy on what the impacts of management can be on soil and microbiota.

<u>1. Framing the resilience concept</u>
What resilience means in soil arena:
The expert defines resilience of soil systems as the degree and time it takes for a system to return to earlier state. This idea fits in the definition of recovery. Such a system may appear vulnerable, but is stable in the long term due to the capacity to reorganise and return to an earlier state. The other understanding of resilience (the first point in the definition in RECCE), of resistance to change can be a system that seems stable but is brittle and fragile because as soon as it leaves its basin of attraction it may never be able return to that state.

In order to understand the properties and processes of soil, you need a wide spectrum of variables but it is difficult to pin down how many or the specific requirements. The soil biological community is the most sensitive marker of the dynamics in the soil ecosystem type and both depends on and drive other variables. There is on-going work in the area of soil biology and soil stability although it is still somewhat limited. There is solid data that underpins that microbiota is essential for the physical and chemical properties of soil such as the nutrient cycling.

What is the whole system?

Resilience is a whole systems concept, although the system is always defined by the researcher in relation to the study area. For soils the whole system is quite ample, so a suggestion is that the structural and biological components of soil can be looked at as a subcomponent of the transient and inherent properties of soil.

There may be debate on what which components that are part of soil. For example the leaf litter layer is especially important in forest ecosystems and reforestation projects. High temperatures and high precipitation due to climate change can increase the litter layer. Some consider the litter layer as a part of the soil, especially in high pH soil as earthworms and microbiota are pulling down litter material into the soil and integrate the two layers of top soil and litter layer. In the case of low pH the litter layer is more intact and separate from the top soil and rots down slowly.

2. Measuring resilience properties empirically

The soil is alive, and it is hugely important to measure the biology of soil in order to understand the dynamics and resilience of soil (Harris, 2009). Physicochemical measures are more straightforward to measure and there are usually multiple measures in the same study to indicate soil functionality, although they only represent a part of the whole system. Inherent properties of soils supporting services can be measured through these components which are commonly included in experimental soil studies:

- Porosity
- Bulk density
- Nutrient retention

Other indicators of soil functioning and transient properties are just as important to assess, especially as they are more dynamic and vulnerable to management changes. SOM is a good indicator of soil functioning, however it is a slow variable and thresholds may be passed before the impacts are noticed by management. Soil biological community is the most sensitive variable and may also drive other variables such as organic matter formation. There are some standard methods used to measure soil microbiology. The ratio of fungi to bacteria (fungal: bacterial ratio) is one common measure. Biomass is a common data point, but it is only relevant in relation to the phenotype, genotype and functional capacity. In order to assess the biological activity catabolic profiling (Degens and Harris, 1997) is a method that measures the rate at which a substrate (for example organic carbon) is broken down. Plate counts of viable colonies is a poor measure of diversity of soil biology, but can be useful if the purpose is to identify presence of a certain known species.

The biology and microbiology should be assessed using three approaches; phenotype, genotype and functional capacity. Phenotype are the observable properties of species, genotype is assessed with molecular techniques for example trFLP (Terminal Restriction Fragment Length Polymorphism) to evaluate genetic diversity and population dynamics, and phenotype by phospholipid fatty acid profiling (PLFA). Functional capacity is analysed using physiological catabolic profiling (CLPP), also known as multiple substrate induced respiration profiling (MSIR). These are some key methods, however they may not all be routinely used in papers to be identified through literature keywords.

Aggregate stability is directly dependent on biological components in microbiologic processes and is only reflected to a limited extent and poorly represented in literature. All the properties need to be measured over time in order to assess slow variables, long term changes and impact of climate change and land use change.

5. Systematic review question

The review questions follow the systematic review guidelines with the inclusion of the additional driver term of environmental change. The expert agrees that the supporting service approach is a good framework for evaluating the resilience of soil to climate change. The driver of climate change is particularly interesting although it is difficult to disentangle the impact of climate change and land use change on soil biota.

6. Relevance and Policy relevance

The impact of climate change is a relevant and urgent area to study. Increased temperatures will lead to areas being flooded more routinely, and this has a huge impact on soil biology, respiration and organic matter formation. Effects of climate change can be studied through heating studies by using heated cables in soil patches or fields, and altered precipitation rates on covered soil systems that can modulate precipitation rates. Translocation experiments of moving a patch of soil from one climate to another can provide useful data but the soil will not be intact due to vibrations, altered hydrology, subsoil and atmospheric exchange with. The soil can be reconstituted along the way, either consciously or unintentionally, and will be exposed to different properties compared to the original site circumstances.
Soil modifications due to climate change is more recently commonly included in climate change models, taking into account the green house related gas exchange with the soil in different temperatures and climatic zones, before the early 1990's soil was not included as a dynamic factor in the global climate models.

Search words
Using soil* as a search word should be enough to capture relevant literature related to soil.
Additional search words:
*flood**
microbiology
biology
pH
litter layer
nutrient cycling
reforestation (afforestation)
deforestation
irrigation
sealing (urbanisation)

The geographical filter excludes the geographical areas that have a lot of similar temperate zone soils that are similar to UK soils and a large part of the literature on soil is from Australia, New Zealand, North America that can be used to inform UK policy.

References
The expert had collected 56 references, both empirical and conceptual on the resilience of soil. The empirical references in this list can be used to test the systematic review in order to test the specificity of the search protocol.

A1.4: Interview with Dr Allan Watt, CEH, Wednesday 14/07/2010 for RECCE: Theme Expert Biodiversity
Interview Notes (approved by expert)

BIODIVERSITY QUESTIONS

Q1 Can management interventions mitigate the impact of environmental change on biodiversity characteristics of UK Broad Habitats?

Q2 How resilient are the biodiversity characteristics of the UK Broad Habitats to environmental change?

Subject – Driver – Outcome – Intervention

Comparators – degrees of environmental change (with and without intervention)

Context of Q1 into RECCE aims

We initially discussed how the question (Q1 above) fits into the RECCE programme and how AW would interpret the question within that context. The remainder of the discussion is built around this understanding and it can be summarised as:

RECCE is interested in the resilience of ecosystems of which biodiversity is a component;

It was recognised that there was a difference between this and understanding the resilience of biodiversity to environmental change.

Measuring resilience properties empirically

The characteristics that have been suggested in the notes (see attached) are good. Species richness and similar measures (concerning the number of species within an area) are covered sufficiently. AW noted that different indices of biodiversity could be problematic in the analysis and so advised us to focus on species richness and simple measures. RM mentioned that although we initially trialled other indices in the search terms (e.g. Simpson’s Index) that these were removed due to low search results.

AW stressed two areas as being particularly important:

1. Species Composition

Composition is a critical measure, especially when some broad habitats might be characterised by particular species. For example, we could lose one species from a species-rich habitat and the measure of species richness wouldn’t change much. But if the species lost was a key species (either from an ecological or cultural value standpoint) then there would be a large change to the resilience of that habitat / ecosystem to provide certain services. The term *homogenisation* was seen as covering some of the issues associated with species composition. If you have the same species appearing in more and more habitats then you are essentially losing the special species – those ones that are unique to those habitats and provide a cultural service.

2. Functional Traits

Functional traits can be viewed in two ways:

An ecosystem that has lost one species to be replaced with another species with a similar function then this can be taken as an indication of a resilient ecosystem. However, functional trait is probably less important from the perspective of cultural services, since people will not be interested in the replacement of a rare habitat specific species with another common one that performs the same function. This distinction could be important if we are looking at the resilience of two different aspects of an ecosystem – the cultural and the regulatory aspects.

[RM to add some functional trait *terms into the search list]*

Question from RM: the use of the term "Population" as a characteristic of biodiversity

This can be split into two arguments:

Firstly, the cultural service of biodiversity could be just the knowledge that something is there – part of the value placed on a particular ecosystem is based on whether it supports a particular species that is "enjoyed" by society. In this case population-level information is not necessarily important – but what is important is the presence or absence of the species that provides the cultural service.

However, *[and this is RM's thoughts]* from a management perspective it is important to know the population level (or distribution) of a species as this will provide some measure of the likelihood of this species persisting in a particular ecosystem and/or location. Ultimately this will play a role in the assessment of whether this ecosystem is resilient in meeting the cultural service expectations.

Secondly, there was some concern from AW and RM that the addition of the term *population* would result in lots of irrelevant papers being added to the search results.

Suggestions of any empirical studies:

General comments

- Projects dealing with the impacts of climate change are generally looking effects that are ahead of us. Most of the empirical data is either modelling or experimental – or in some cases very speculative. We will get lots of opinions on the impacts of climate change on biodiversity in the literature but we might struggle to get the data out of the studies.

- We may have asked a question that the current research is probably not able to answer

The following were suggested as either being useful directly for the RECCE project, or being a good starting point for further exploration of the topic:

This a review paper looking at the impact or potential impacts of climate change on European biodiversity.

1. Brooker, R.; Young, J.; Watt, A. (2007) Climate change and biodiversity: Impacts and policy development challenges - a European case study. *International Journal of Biodiversity Science and Management*, 3 (1). 12-30[17]

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Other sources of information would be publications from the Convention on Biological Diversity Technical Series:

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2. Campbell,A., Kapos, V., Scharlemann, J. P.W., Bubb, P., Chenery, A., Coad, L., Dickson, B., Doswald, N., Khan, M. S. I., Kershaw, F. and Rashid, M. (2009). Review of the Literature on the Links between Biodiversity and Climate Change: impacts, Adaptation and Mitigation. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series No. 42, 124 pages.

The CBD reports tend to be more theoretical with less grounding in actual data. However, there will be information within the reports that are useful and will be sections which aim to separate out the subtle differences between resilience terms.

There are also studies from CEH that could also be relevant that AW has worked on and/or knows about. There are papers looking at the asynchronisation of phenology (from the early 1990s) and studies looking into trophic interactions. Recent work on the CEH "SPACE" project (?) might also contain some relevant information.

3. Morecroft, M.D.; Bealey, C.E; Beaumont, D.A; Benham, S.; Brooks, D.R.; Burt, T.P; Critchley, C.N.R; Dick, J.; Littlewood, N.A.; Monteith, D.T.; Scott, W.A.; Smith, R.I.; Walmsley, C.; Watson, H.. 2009 The UK Environmental Change Network: Emerging trends in the composition of plant and animal communities and the physical environment. *Biological Conservation*, 142 (12). 2814-2832

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For more empirical-based evidence AW suggested that it would be better to look at different types of environmental change (e.g. land use change). Although AW did note that land-use changes are in effect changing the underlying habitats / ecosystems so this might not necessarily be relevant.

Search Protocols for the review questions

RM explained the process of the search strings to AW.

Issues surrounding the description of the UK Broad Habitats were noted - that not all researchers use in the terms in describing their study habitats. There was no easy solution to getting around this.

An example mentioned was:

[17] Climate change is already impacting upon global biodiversity, and projections of climate change impacts indicate that very significant future changes will occur, although such projections are associated with key areas of uncertainty. In order to develop adaptation and mitigation strategies for the conservation of biodiversity during climate change it is necessary to 1) understand the impacts of climate change on biodiversity, 2) understand the problems associated with the implementation of policies promoting the conservation of biodiversity during climate change, and 3) highlight key areas for action, both to address gaps in our understanding of the potential impacts of climate change and to develop the necessary levels of communication between scientists and policy-makers. This paper provides a European case study of these issues. We review current knowledge of the impacts of climate change on biodiversity in Europe, examine the existing European policy framework with respect to the ways in which it can both promote and hamper biodiversity conservation during climate change, and highlight priority targets both for new research and in terms of improving the flow of information between stakeholder groups with an interest in biodiversity conservation in a world undergoing climate change.

- Ruth Mitchell has done work on Atlantic Oakwoods in Scotland and could have termed these as upland oaklands.
    -

AW noted that the results from the search indicates the way we do research – where we are not doing it at a specific habitat level. Climate Change studies are national or international in their scope and might not be looking at particular habitats. These are then not so specific for management and policy questions to draw on. It was noted that this is maybe how research starts – starting out broadly and once a pattern is identified then focussing down on specific habitats and/or ecosystems. Also climate change studies might not be looking specifically at particular habitats – they may be using much broader habitat terms (e.g. the Uplands). Therefore there is the risk that the number of papers returned for the project might be a reflection on the scale of the studies conducted. If the scale of the study is more extensive then it is less likely that they will use habitat specific terms to describe the study area.

AW did mentioned that we are probably not missing as much as I fear we are missing.

AW asked if I would be able when going through papers that have very broad habitat terms (e.g. grassland) to assess the habitats and assign them to the UK Broad Habitats (or some other level)? For example, could we do it for woodland where we classify the papers found on a general *woodland* search to say whether they were relevant to "*mixed*", "*broadleaved*" or "*don't know*" categories?

Would this change the systematic nature of the RECCE search?

Additional search terms:

If we are going to use the *resilience* terms then AW suggested adding the following:

sustainable – e.g. sustainable forest management that could pull out relevant studies from forestry research
tipping points – a synonym for limits

Are the questions policy relevant?

AW thought that the questions had policy relevance.

Another question that could be asked (and it was noted later that this could just be an alternative phrasing of the second question) is:

"Are management interventions needed to mitigate the impact of environmental change on biodiversity characteristics of UK Habitats?"

However, it was noted that hiding behind this question is an understanding of the resilience of the habitats that we already have at the moment. This may not necessarily be the case.

Other sources of information

There is a list of European projects that CEH maintains. This gives a good overview of what is being worked on:

http://www.edinburgh.ceh.ac.uk/biota/

A1.5: Interview with Dr Harriet Orr, Environment Agency, Tuesday 13/07/2010 for RECCE: Theme Expert Water
Interview Notes (approved by expert)

QUESTIONS

Q3 Can management interventions mitigate the impacts of environmental change on the water regulating characteristics of ecosystems?

Q3.1 How resilient are the water regulating characteristics of ecosystems to environmental change?

Subject – UK Broad Habitats; Driver - environmental change; Outcome – regulation of water quantity and quality [regulatory services]; Intervention – management, habitat restoration, etc.;Comparators – degrees of environmental change (with and without intervention)

General thoughts

Another way of looking at (or phrasing) the resilience question would be to identify those parts of the ecosystem that are more susceptible to change or disturbance. This raises the questions:

- How can we identify those parts of the ecosystem that are more susceptible to change / disturbance?
- What makes environments / ecosystems more vulnerable?

Finding empirical evidence related to different management interventions might be hard. Benefits of management interventions might not be realised for a long time. Therefore there is a timing issue surrounding results from these sorts of empirical studies, where:

- Empirical data might not yet have been collected on particular management interventions (if the time lag between implementation and realisation is less than the time since implementation); or
- There is doubt (whether justified or not) regarding the possible impacts that a management intervention will have (due to the time lag).

An example of this could be the linking of ecosystem degradation to an increase in diffuse pollution.

A recent study on Coho Salmon showed how the exploitation of the fishery in different places along the catchment resulted in changes of how the fish utilised the different ecosystems. The paper will need to be sourced (if it is relevant) but it does seem to demonstrate the importance of variation within a catchment and the need for conserving that variation.

Policy relevance

HO agrees that the question posed is relevant to policy with the two main hydrological concerns at the moment being (1) changes in run-off speed and volume and (2) diffuse pollution. The other characteristics can be divided into two main sections:

- those dealing with water quantity; and
- those dealing with water quality

Thoughts on empirical evidence to support the question

Follow on from the discussion above with reference to some studies that will be worth pursuing.

Water Quantity

The water regulating component of the RECCE question (Q3) can be summarised as *"what can we do on land to reduce flood run-off, both in terms of increasing the time to peak and also decreasing the volume of the runoff"*.

HO directed me to a project that brought together a number of experts to look at the evidence that land management activities could reduce runoff. This is a Defra project FD2114, and there is an updated version of the project *FD2120 Analysis of historical data sets to look for impacts of land use and management change on flood generation*[18]*. This paper could be either a useful source of information for the RECCE project or it could be the lead to other research that deals directly with the RECCE question.*

HO says that the findings from the review suggest that there is a lot of evidence for the local impact of land use and management change on flooding, but there is little evidence for a reduction when looking at larger scales. This is possibly a consequence of the modelling approaches used, where the types of models employed are not necessarily suitable for larger scale detection.

Water Quality

One of the main ways of improving water quality is to reduce the connectivity between pollution sources and waterways. "Buffer zones" were much in the literature about 20 years as a measure ofor reducing diffuse pollution entering into rivers and streams. The majority of the literature is mostly concerned with riparian buffer zones. Although there has been two decades of implementation and work on riparian buffer zones, there is very little direct evidence to link diffuse pollution and ecosystem degradation.

In general, even if we could improve the ecology of habitats, the ecological improvement might be difficult to measure.

Climate change

There are a limited number of studies that have focused on the impact of climate change on water courses. These generally focus on the effects of an increase or decrease in water flow and associated knock-on effects. For example, a decrease in flow rate will concentrate pollution).

[18] http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=13972&FromSearch=Y&Publisher=1&SearchText=fd2120&SortString=ProjectCode&SortOrder=Asc&Paging=10#Description

It is generally accepted that less modified habitats are more resilient to change. There is a recent study of macro invertebrates within rivers (Mike Dunbar, CEH) that showed that their response to changes was better in less disturbed damaged ecosystems.

Additional terms

Additional terms for the search strings that were suggested:

Water Parameters
Low-flow
Environmental flow
Land drainage
Flow regulation
Soft Engineering *a lot of physical river management is done from an engineering background and HO though it would be good to include some terms that might capture the very different approach the engineers.*

Management
Abstraction
Discharge
Programme of Measure – a recent term that “just means doing something”

Environmental Change
Temperature

Additional terms?
Farming related activities: fertilizers, slurry application, ploughing, timing of application
Diffuse pollution terms – particularly form the agricultural sector
Urban related developments – sustainable urban drainage systems

Related studies

1. Tim Pagella (Bangor University) is running a project in Pont Bren (Wales) that is examining the how trees planted for animal shelter are helping to reduce run-off (afse0c@bangor.ac.uk). Papers on the work here have been published by Howard Weater (Imperial College)

2. Rob Macall and Clive Walmsley (Countryside Council for Wales) running a project integrating existing climate vulnerability assessments of priority habitats and species, along with other components of vulnerability, into a site-level assessment for a large proportion for the protected sites network in Wales. This may have considerable relevance to the RECCE programme. The project is aimed at biodiversity preservation. Draft report might have been submitted June 2010. (c.walmsley@ccw.gov.uk)

Additional sources of useful information

A1.6: Interview with Dr Linda Davies, Centre for Environmental Sciences, Faculty of Natural Sciences, Imperial College, Wednesday 7.7.2010, for RECCE: Theme Expert Air Quality
Interview Notes (approved by expert)

AIR QUALITY QUESTIONS

Q1 Can management interventions mitigate the (sub-lethal) impacts of pollution on ecosystem under conditions of environmental change?

Q2 How does environmental change affect the (sub-lethal) impacts of pollution loads on ecosystems?

Subject – Driver – Outcome – Intervention
Comparators – degrees of environmental change (with and without intervention)

The interviewee suggested at the beginning of the discussion that there are other experts in the network of air quality specialists that may be able to give more specific advice on critical loads and pollution impact on ecosystem services, and names and contact information for these references were given. She stated that her expertise was in lichenology, ambient air pollution, and general policy measures for air quality not critical loads although she was familiar with them.

Discussion on current policy areas for air quality and pollutants
The expert described the current priorities in air quality policy and the data that underpins decision making.

Pollution impact varies with duration (peak pollution or background pollution) concentration, species and ecosystem sensitivity , and the substrate on which those species live or feed. The current status is that there is published evidence of which habitats are sensitive and at what loads for acidification, eutrophication and total N these habitats and a limited number of sensitive species would show signs of stress. Critical Loads have been agreed by UNECE and the UK uses various models to calculate where exceedances are likely across the UK. Defra works with a range of organisations to review those habitats most at risk and to consider mitigation options. Modelling is used to identify the extent of the area and exceedance for each of habitat at the national level. More recently improved modelling has been refined to identify protected areas most at risk. There is usually a range with an upper and lower limit for each critical load. This range could be reviewed with a view to focusing on the lower/upper band only if the purpose of intervention is target management intervention more effectively or to reduce intervention measures.

Ambient concentrations are included within the European Air Quality Directives but they are not incorporated into regulation and do not have timelines associated at the present time. There are two Limit Values for sensitive vegetation and ecosystems for oxides of nitrogen and sulphur dioxide plus particulate matter. In the UK most areas do not exceed the latter but there is widespread exceedance of the former. Options to reduce the former would need to target the emission source, as with critical loads, and these are primarily for NO_x from vehicles and regulated industry.

The attention for pollution policy is currently focused on mitigation in these areas;
1. Nitrogen (NO_x, ammonia, aerosols) and eutrophication – deteriorating – sources: agriculture, vehicles, power stations (regulated industry)
2. Acidification (SO_2) and resulting aerosols (sulphates) - improving

3. Increased background levels of ground level ozone – increasing and most likely to continue to do so due to reductions in NO_x (affects chemistry), increasing temperatures and increasing global emissions. Sources of precursors such as VOCs from industry (some natural sources).
4. Heavy metals pollutants

Policy decisions are underpinned by scientific studies of air pollution impacts on species and communities both in field experiments and fumigation studies. Impact on plants is recorded through parameters of i.e. growth rate, photosynthesis, flowering, seed production, dry weight etc. Base level is recorded against controls as well as before/after experimentally increased pollution concentrations (NH_4 and NO_x is added as wet deposition, and ozone and SO_2 through fumigation) and various climatic variables.
Open top fumigation chambers with exposures of various species and communities to different concentrations of ambient pollutants such as ozone are used to explore impact of ambient pollutant level.

Pollutants
The systematic review aims to collect evidence for the impact of pollutants on ecosystems in terms of the UK Broad Habitats. Different types of pollution were discussed and the expert explained how different pollutants impact on vegetation and habitats and the measures used currently to measure pollution levels in order to be able to limit the impact.

Critical Load/ Deposition
Critical loads are set based on studies of pollutant impact on vegetation and ecosystems, and provide a threshold of when a population or community or sensitive elements in a system begin to show signs of harmful effects (definition from OECD Statistics). Critical loads are tested and assessed for a selection of species in a habitat and may not cover all species present in an area, also some species are more resistant or resilient to pollutants than others and can survive the critical load set for a habitat. Critical loads are likely to be agreed as a range (10-20) rather than a discrete number.

Critical load is mapped over the UK habitats on $1km^2$ grid (by linking it to the vegetation types associated to each habitat, CEH Lancaster) and exceedence of the threshold is modelled as blanket pollution. Defra's mitigation approach is to focus on the most sensitive areas, identified as the SSSI's and add those polygons to the national mapping of critical loads in order to address those areas with priority on a local level and to identify the source of pollution. There are no critical load calculations for urban areas because the blanket approach does not apply to unvegetated zones.

Pollutant deposition is more habitat specific than ambient pollutant concentrations, and critical loads are developed for each plant type or habitat type. Resources for this can be found from Jane Hall at CEH Lancaster, who is leading policy and research work on critical loads. Deposition pollution of major concern (N) arises from gaseous NH_4 and NO_x which can be transformed into aerosols and other compounds leading to eutrophication, acidification and excessive N and SO_2 levels have decreased over the recent decades.

Ambient concentrations
Tropospheric ozone concentrations are increasing, and ozone is particularly severe because it can travel further than other pollutants and affect remote places that have been exempt from pollution in the past. Ozone is created in higher temperatures and is thus closely linked to effects of warming due to climate change. UNECE use a flux measure of ozone in plants (so called *ozone flux critical load*) and is measured as the sum of the differences between hourly concentrations greater than the threshold 40 parts per billion (+80 $\mu g/m^3$), known as AOT40. This is a measure of the amount of

ozone a plant takes up during the growing season and is dependent on the temperature because the plant stomatas open when it is warm. Ozone levels have increased as SO_2 concentration has decreased over the last decades, since SO_2 is a reducing agent of ozone. Peaks in ozone have however reduced over recent years. Another issue for consideration is the chemistry driving ozone production which is tightly linked to NOx that reduces ozone concentrations. NO_x is decreasing in concentration leading to increased ozone

Applying the concept of resilience

The systematic review is also aiming to draw conclusions on how changing air quality impacts on the resilience of the UK Broad Habitats. The expert said that she was not familiar with the term resilience in the arena of air quality but understands it to mean that some species have a natural ability to withstand pollution whereas others are sensitive but can respond to stress by mechanisms such as increased enzyme activity.

In the policy and research theme of Air Quality resilience is conceptualised as the threshold below which a system remains intact, and can be equated to the critical load. The threshold levels are set through research that measure parameters of plant communities under different levels of pollution stress. The threshold is an upper limit of the pollution load, however the studies that underpin the critical load limits can give indications of slow variables and non-lethal effects of pollutants that may decrease the resilience of the system even before a critical load limit is reached. Critical load studies could be most useful in the context of resilience of ecosystems to changing air quality, because they provide the evidence at which selected species or habitats show sensitivity. These studies are limited but nevertheless identify some of the physiological and other parameters affected by stress from pollutants.

The species composition of lichens in the London urban zone is an example of a regime shift due to ambient concentration of pollutants. In the recent study (Davies, 2007) identified 80 species on a single tree species, and only 9 of them were present when recorded in a similar study in the 1960s. study. 13 of the species were most frequent at high levels of NO_x (above the critical level for oxides of nitrogen for vegetation and ecosystems. This change in community structure which also recorded the almost complete loss of the most frequent and abundant species in the 1960srepresents a shift from the earlier state of increased concentrations of SO_2 which suited acidophilic lichens to a communities dominated by nitrophilic species. The regime shift was triggered by policy intervention for reduction and control of S emissions. The physiology of lichens in relation to the pollutant exposure still needs further study and is the topic of a current COST application.

Another example of a habitat shift is the impact of a cattle farm on the lichen diversity, where ammonia from intensive cattle and poultry farming has increased pH of the bark in trees which were previously suitable as lichen substratum but which now host a different community. Pollution can have a direct effect on sensitive species and an indirect effect on their substratum.

Suggested sources of literature

WHO has carried out systematic reviews of existing information for pollution loads and levles. http://www.who.int/topics/environmental_pollution/en/

There is extensive literature and lists of individual pollutants with WHO and the UK Environment Agency.

Nigel Bell, M. Treschow, *Air Pollution and Plant life*, 2 Edition, 2002: John Wiley & Sons

CEH Edinburgh hosts data on impact of pollution on UK habitats.

CEH in Lancaster, Jane Hall, should also be able to provide references to data for critical loads in the UK Broad Habitats.

Davies, L, Bates, J.W., Bell, J.N.B., James, P.W., Purvis, O.W. (2007). Diversity and sensitivity of epiphytes to oxides of nitrogen in London. Environmental Pollution **146** 299-310.

Additional search terms
Wet deposition
Dry deposition
Ozone (omit tropospheric for better inclusion)

Exclusion terms
River*

Appendix 2: Appendices for Chapter 4:

Appendix 2.1: The total number of publications that refer to the UK Broad Habitat and Priority Habitats[19], as part of a test of the suitability of these as search terms for UK habitats and ecosystems. Searches were conducted on Title, Abstract and Keywords in the Web of Science search engine.

UK Broad Habitats	Priority Habitats Associated	*Potential Alternatives for Broad Habitat terms*[20]
Acid grasslands (61)	Lowland dry acid grassland (0)	
Arable and Horticulture	Cereal field margins (5)	*Arable field margin (45)*
Bogs (5042)	Blanket bog (217) Lowland raised bog (11)	
Boundary and Linear Features	Ancient and/or species-rich hedgerows (3)	*Hedgerow (1221)*
Broadleaved, mixed and yew woodland	Lowland beech (0) and yew woodland (1) Lowland wood-pasture (0) and parkland (737) Upland mixed ashwoods (0) Upland oakwood (1) Wet woodland (7)	*Broadleaved woodland (129)* *Mixed woodland (101)* *Wood pasture (47)* *Woodland (3975)* *Forest (>100,000)*
Calcareous grassland (659)	Lowland calcareous grassland (2) Upland calcareous grassland (1)	
Coniferous woodland (69)	Native pine woodland (5)	
Dwarf shrub heath (95)	Lowland heathland (28) Upland heathland (10)	*Heathland (1712)*
Fen, Marsh and Swamp	Fens (882) Purple moor grass (4) and rush pasture (0) Reedbeds (160)	*Peatland (1340)* *Marsh (6449)* *Swamp (2028)* *Moorland (828)*
Improved grassland (105)	Coastal grazing marsh (23) floodplain grazing marsh (0)	*Grassland (10039)* *Coastal grassland (31)*
Inland rock	Limestone pavements (42)	
Neutral grassland (17)	Lowland meadows (16) Upland hay meadows (5)	*Meadow (3189)*
Rivers and streams	Chalk rivers (332)	
Standing open water and canals	Aquifer fed naturally fluctuating water bodies (0) Eutrophic standing waters (1) Mesotrophic lakes (517)	
Supralittoral rock	Maritime cliff and slopes (18)	
Supralittoral sediment	Coastal sand dunes (315) Coastal vegetated shingle (0) Machair (40)	*Sand dune (878)*
Broad habitats not included: Continental shelf slope, Inshore sub-littoral rock, Inshore sub-littoral sediment, Littoral rock, Littoral sediment, Offshore sediment		

[19] See http://www.ukbap.org.uk/genpagetext.aspx?id=91
[20] These terms were compiled from casual searches of suitable literature.

Appendix 2.2.

Synonyms used for each of the elements of the search string. Wildcards (*) were used to cover alternative spellings and forms of words.

UK Broad Habitats

cereal field margin
arable field margin
species-rich hedgerow
hedgerow
lowland raised bog
yew woodland
upland oakwood
wet woodland
native pine woodland
mixed woodland
broadleaved woodland
coniferous woodland
woodland
wood
forest
wood pasture
lowland calcareous grassland
upland calcareous grassland
calcareous grassland
calcicolous grassland
neutral grassland
acid grassland
coastal grassland
improved grassland
grassland
machair
lowland meadow
upland hay meadow
meadow
upland heathland
dwarf shrub heath
lowland heathland
heathland
purple moor grass
moorland
blanket bog
bog
peatland
marsh
swamp
fens
reedbed
coastal grazing marsh
saltmarsh
salt marsh

eutrophic standing water
maritime sea cliff
maritime slopes
coastal sand dune
limestone pavement
chalk river
river
river flood
floodplain
mesotrophic lake

Biodiversity Characteristics
biodiversity
species richness
geographic distribution
genetic diversity
species diversity
ecological diversity
species evenness
alpha diversity
beta diversity
gamma diversity
community composition
species composition
functional group
functional trait
homogeni*

Management Intervention	Environmental Change
manage*	climat* change*
restor*	global warming
conserv*	environment* change*
protect*	drought
remediat*	warming
interven*	

Resilience
resilien*
recover*
adapt*
stability
resistan*
variability
threshold*
tipping point
vulnerab*

sustainable

Geographic Exclusions

Asia*
Australia*
Africa*
Amazon*
Arizona
Brazil*
Cambodia
Chile
China*
India*
Japan*
Madagascar*
Mesoamerica*
Mexic*
Papua New Guinea
Patagonia*
South* America*
Taiwan
Tenerife
Tibet*
Zealand*
desert
tropic
neotropic*
subtropic*
savanna*
sea*
semiarid
semi arid
glacial
marine fisheries
sri lanka*
silvi*
plantation*
oceanic*

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