Living with Environmental Change
Pilot Review Scheme
Objective B Scoping Study

Environmental Limits, Ecosystem Resilience

and Supporting Services

(Contract No: R8/H12/106)

Pilot Review Report

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Executive Summary

A bibliographic analysis has been undertaken to find out whether it is possible on the basis of current knowledge, to estimate either in physical or monetary terms the cost of maintaining the ecosystem functions that underpin to people's well-being. The investigation also considered whether the full costs of maintaining ecosystem services can be represented within an environmental accounting framework. These are clearly complex and wide-ranging issues, and so to make progress the work adopted the evidence-approach to systematic review widely in the area of conservation and management. Using two widely available internet search engines, the volume and content of the relevant peer-reviewed literature was investigated. The analysis sought to identify published materials that considered the impact of loss of ecological functioning (supporting services) on ecosystem resilience or maintenance.

The scope of the analysis and search strategy was tested using expert opinion. This process confirmed that the questions posed by the study both important and topical, and that the results could contribute to the current discussions that surround the issues of ecosystem accounting, ecosystem services and resilience. However, when undertaking the bibliographic study it was found that unlike work in the area of evidence-based conservation, where tightly specified review questions can be constructed, the general the subject matter of this study meant that a wide range of papers were identified; many had limited relevance to the core ideas that needed to be considered.

Since the initial bibliographic analysis identified a large and diffuse body of literature, subsequent effort turned to finding ways of narrowing the search to select only the most relevant materials. Thus the analysis was focused around three more specific issues:

- Can resilience be measured in terms of levels of ecological functioning (output of supporting services)?
- Can minimum levels of ecological functioning be used to define ecological thresholds and limits for service?
- Is it possible to calculate the costs (in physical or monetary terms) of maintaining the minimum levels of ecological functioning required to sustain ecosystem resilience?

Separate search protocols were developed to investigate each of them in turn. The results were consolidated into a single EndNote library; duplicates, non-English publications and materials other than journal articles were eliminated. The resulting resource contained 659 records. Using the resource created a pilot qualitative review was undertaken and the outcomes presented using the three focal questions to structure the discussion.

A feature of the literature assembled is that notion of ecological resilience is now central to the questions about whether changes in ecological functioning (or supporting services) can alter the capacity of systems to withstand or absorb disturbance, or to respond to external drivers in an adaptive way. In relation to the focal questions it was found that:

Measuring resilience and service output

While a large number of theoretical and review papers discuss the problems of measuring the resilience of ecosystems, fewer provide any empirical data that test core concepts. It is apparent, however, that methods exist for constructing indicators or surrogates to measure the *resistance* a system to disturbance, and its subsequent *speed of recovery*, at least for specific ecosystem variables rather than for systems as a whole. The results of this study suggest that by focusing on such studies that there is probably a sufficiently large body of material available for a full systematic review in this topic area. Although the empirical studies identified in searches do not always use formal experimental controls, the use of contrasts between sites or within sites over time, offers the prospect of constructing 'comparators' in any future meta-analysis.

- The age of the literature identified by searching on 'measurement of resilience' means that that the link to ecosystem service issues is often not made, and so some interpretation of material would be necessary if a further, more detailed study is undertaken. It is clear, that from the more limited contemporary literature that such a link can be traced, and so a further and more detailed bibliographic analysis may be one way of showing the relevance of this older material to current debates, and of framing new empirical research questions

Identifying thresholds and minimum levels of ecological functioning

Although a number of theoretical and empirical studies have been published describing threshold effects in ecosystems, the volume of material dealing specifically with the question of ecosystem services, and the minimum level of ecosystem functioning required to deliver them, is still limited. There is, for example, little systematic information available across the range of ecosystem types that are important, for example, in the UK (other than for aquatic systems). From the available case study material it is clear that as thresholds are crossed, the level of ecological functioning and the output of services is *likely* to change, but studies providing complete cause-effect analyses are rare.

- Nevertheless, it is apparent that from a theoretical point of view, the existence of thresholds is a way of defining the minimum levels of ecological functioning that need to be sustained to maintain service output in the face of disturbance. The time available for screening of papers during this study was insufficient to determine whether there is an even wider body of information available on critical limits for other ecosystem types, since it is apparent even from the restricted number of publications found that such limits can be discussed without reference to the existence of thresholds or regime shifts. A further more extensive literature review in this area would be valuable.

Ecosystem accounting and the costs of ecosystem maintenance

Despite recent attempts to value ecosystem services, the scale and relative importance of to society remains uncertain at both local and global scales. This review suggests that estimates tend to made on a case by case basis, and there a general lack of integrated measurement or accounting tools that would the contribution that ecosystem services make to national incomes to be identified. The analysis of supporting services (underpinning ecological functions or intermediate services) is particularly problematic.

Although the approach to emerging in the literature, of separating intermediate and final products, avoids the risk of 'double counting' in valuation studies, it is inadequate for the development of a full set of ecosystem accounts. The latter must systematically describe both the ***costs*** and ***benefits*** associated with ecosystems. In physical terms the costs of supporting services, which include biogeochemical cycling and the flux of energy through the different tropic levels of an ecosystem, represent the level of 'reinvestment in natural capital' needed to maintain ecological integrity or resilience, and thus sustain the output of ecosystem services.

To see the way the issue of reinvestment is currently being discussed, the papers identified by the literature search were examined to from the accounting perspective. Accounting systems are being actively developed at present, given the need to revive the UN System of Integrated Economic and Environmental Accounts (SEEA 2003) and efforts to green GDP.

- Only a limited number of studies are currently available that look at the problem of environmental accounting for ecosystem services in general and the costs of ecosystem maintenance in particular. Methodologies are, however, developing rapidly and while there is probably not sufficient literature in this area to conduct any kind of meta-analysis, the development of further targeted case-study work would be valuable.

Conclusion

The experience gained in this pilot suggests that while there is probably sufficient literature to undertake a full systematic review in relation to the problem of measuring resilience and of estimating the minimum levels of ecosystem function required to sustain ecosystem services, the accounting literature is more limited. We recommend, therefore, that to address this evidence gap further empirical work should be encouraged in relation to the accounting problem. If such studies are undertaken, they could usefully be informed by more detailed reviews in the other two thematic areas.

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Part I: Bibliographic Analysis

1. Background

The financial analogy implied by the notion of ecosystem services has lead to a considerable and rapidly growing body of work which aims to value the benefits that ecosystems provide. Although many have adopted the broad service categories proposed by the Millennium Ecosystem Assessment (MA, 2005) as an analytical framework, the role of supporting services has proved particularly problematic. Many have argued that since they are not 'final' but 'intermediate products' of nature, they should not be valued as such (Banhzaf and Boyd 2006; Boyd and Banhzaf, 2006, 2007; Fisher and Turner, 2009). Their worth, it is suggested, is captured by the values ascribed to the benefits directly enjoyed by people, and to which these supporting service contribute.

While this treatment of supporting services clearly avoids the risk of 'double counting' in valuation studies, it is clearly an inadequate basis for the development of a full set of ecosystem accounts. The latter must systematically describe both the ***costs*** and ***benefits*** associated with ecosystems. In physical terms the costs of supporting services, which include biogeochemical cycling and the flux of energy through the different tropic levels of an ecosystem, represent the level of 'reinvestment in natural capital' needed to maintain ecological integrity or resilience, and thus sustain the output of ecosystem services. It has been argued that the gap between the level of physical reinvestment in ecological infrastructure necessary to maintain the flow of ecosystem services, and the level actually achieved as a result of human impact or use can measure the 'sustainability gap' and the true costs of providing ecosystem goods and services to society. Moreover if robust estimates of the marginal changes in future value of ecosystem services are to be made, it is essential to have a good understanding of whether, under changing environmental conditions, different levels of reinvestment in natural capital might be required.

An understanding of the minimum levels of ecological functioning represented by supporting services potentially provides a way in which the notion of ecological limits can be articulated and linked into the ecosystem services debate. By considering this issue in the context of environmental accounting, it will be possible to link this important area of concern with current efforts to understand the value of ecosystem services and how they change.

In undertaking this review it is recognised that there has been much recent debate surrounding the notion of ecological resilience, and that the literature on this topic is both large and diffuse. Although some progress has been made in both clarifying the scope and content of the literature on this topic (e.g. Janssen and Ostrom (2006), Janssen (2007), Brandt and Jax (2007)), many issues remain. In the context of recent policy interest in better understanding the economics of ecosystems and biodiversity, and current initiatives to develop better ecosystem accounting frameworks, it is essential that the theoretical and empirical frameworks are better understood so that robust indicators of ecosystem function can used be for assessment and accounting purposes. If, for example, Defra's goal of maintaining healthy functioning ecosystems is to be achieved (Defra, 2007), then we need to better understand what 'ecosystem health' really means and how it might be measured. A comprehensive review of the concepts of ecosystem health is provided by Rapport (2007a & b). Ecological resilience and the level of reinvestment in natural capital needed to maintain the integrity of supporting services might be one way in which this can be achieved.

2. Objectives

The primary objectives of this study are to make an initial, review of the current published literature to determine:

- Whether it is possible to estimate either in physical or monetary terms the cost of maintaining the supporting services (ecosystem functioning) that underpins the ecosystem services that directly contribute to people's well-being.
- Whether on the basis of current knowledge, the full costs of maintaining ecosystem services can be represented within an environmental accounting framework.

It should be noted that although the approach used for this study is that proposed for a full systematic review in the area of conservation and management (see CEBC, 2009), this work represent only a pilot rather than a complete study of the issues described above. Not only was the time available for this study limited, but also the topic selected is also more open-ended than is normally considered appropriate for such a systematic review. The principle outcomes of this study will therefore mainly be:

- A set of recommendations on how the objectives can be examined through a coherent set of specific search protocols; and,
- An initial assessment of the coverage and completeness of the current, published evidence base and the scope that exists for undertaking a full systematic review of the topic.

3. Methods

3.1 Question Formulation and Search Strategy

The CEBC guidelines (CEBC, 2009) suggest that to be most effective, review questions should have a particular format that links an outcome to a specific intervention within a given subject area. Although it is recognised that the objectives of this study are somewhat more open-ended than those that generally form the basis of a systematic review, the themes that form the focus of this work can crudely be expressed in this form as follows:

- ***Subject:*** Any ecosystem
- ***Intervention:*** Loss of supporting services (ecological functioning) by crossing some threshold or limit
- ***Outcome:*** *Reduction in resilience or estimates of maintenance costs*

The exploratory nature of this study is emphasised by the fact that at this preliminary stage we are prepared to consider evidence arising from *any* ecosystem. The 'non-standard' aspect of the work arises from the way the notion of 'intervention' is framed, because rather than look for the positive effects of potential management activities, we are attempting to examine the impacts of wider sets of direct and indirect drivers of change. Finally, the complexity of what is being attempted here is illustrated by the hybrid nature of the 'outcome' which both a change resilience (however, measured) and knowledge about what kind of maintenance cost might need to be met to sustain the integrity of the system. The linkage of these two topics has been made in order to try to draw out some clear policy messages.

In order to design a search strategy, the work began in relation to the first study objective by identifying combinations of terms that would capture studies that included reference to "ecosystem services" in general, and "supporting services" in particular, and which also made some link to some notion of a "maintenance cost" for a given ecosystem. For the second objective, the focus was on the literature dealing with environmental or ecosystem accounting in general and the focus here was to look at how the general topic of ecosystem services and supporting services in particular had been treated.

Since the broad intention of the pilot review was to examine the evidence base in relation to questions about ecosystem resilience and thresholds, the initial search terms dealing with maintenance costs, supporting services and environmental accounting were combined with these ideas to investigate how closely the topics had been linked.

Table 1: Preliminary Search Terms

Run	Search Terms
1	cost* AND ecosystem*
2	maintenance cost* AND ecosystem*
3	maintenance cost* AND ecosystem* (see Table 3 note 1)
4	maintenance cost* AND ecosystem service*
5	maintenance cost* AND ecosystem* AND threshold*
6	maintenance cost* AND ecosystem* AND resilien*
7	environmental account* OR ecosystem account*
8	ecosystem account*
9	environmental account* AND ecosystem service*
10	environmental account* AND supporting service*
11	ecosystem account* AND ecosystem service*
12	ecosystem account* AND supporting service*
13	environmental account* OR ecosystem account* AND ecosystem service*
14	environmental account* OR ecosystem account* AND supporting service*
15	environmental account* OR ecosystem account* AND maintenance cost*
16	environmental account* OR ecosystem account* AND threshold*
17	environmental account* OR ecosystem account* AND threshold* AND maintenance cost*
18	environmental account* OR ecosystem account* AND threshold* AND ecosystem service*
19	environmental account* OR ecosystem account* AND threshold* AND supporting service*
20	environmental account* OR ecosystem account* AND resilien*
21	environmental account* OR ecosystem account* AND resilien* AND maintenance cost*
22	environmental account* OR ecosystem account* AND resilien* AND ecosystem service*
23	environmental account* OR ecosystem account* AND resilien* AND supporting service*
24	environmental account* OR ecosystem account* AND resilien* AND threshold*
25	ecosystem* service* AND supporting AND threshold* OR resilien*
26	ecosystem* service* AND supporting AND threshold* OR resilien* AND maintenance cost*

Table 1 lists the search term combinations that were tried in relation to each of the objectives and how there were refined to identify connections to notions of ecosystem resilience and thresholds. The search terms were set up to take account of plurals and alternative endings to key terms, and while it was recognised that they would be some redundancy in the combinations used, the search protocols were arranged in sets that potentially become more specific, so that sub-sets of references could be identified.

3.2 Bibliographic Sources

In keeping with the exploratory nature of this study, which aimed to scope and test an appropriate search strategy that could be used in a full systematic review, only two bibliographic courses were in the initial stage of the work, namely: ISI's *Web of Knowledge*, and Elsevier's *ScienceDirect*. The assumption here was that since these are two of the more comprehensive bibliographic sources, they would be sufficient to identify a significant part of the core literature that related to the topic under investigation. In each case the search terms were applied to selecting the 'all years' and 'all sources' options.

In an attempt to check the coverage of the searches and identify any further key references linking the study of supporting service to the literature on resilience, the on-line resources available as supplementary material to the papers by Janssen et al. (2006) and Janssen (2007), were also downloaded and examined. These two studies have provided an analysis of the resilience, vulnerability, and adaptation knowledge domains arising from research on human dimensions of global environmental change. The later paper updated the information contained in the first, and made available a dataset that contained information on 3379 unique journal papers and 20 books and other non-journal publications published between 1967 and 2007. The material was assembled using the ISI Web of Science Resource and drew upon expert feedback to help identify core texts and sources. For the purposes of this study, the bibliographic resource was downloaded and used to create an EndNote Library, what was searched using the protocols listed in Table 1.

3.3 Study Inclusion Criteria

After refining the specificity of the search protocols, studies from the database searches were initially filtered by title and any obviously irrelevant articles were removed. Subsequently, the abstracts of the remaining studies were examined with regard to their relevance to the constellation of themes identified in the study objectives.

In reviewing the material generated by the searches, two principle exploration strategies were adopted to identify the core references from the different bibliographic sources:

- A ***forward looking*** approach designed to determine whether there was a core set of widely cited papers dealing with the issues from which a wider body of literature could be determined. This approach was facilitated by looking at which references within each group were most widely cited.
- A ***backward looking*** approach designed to identify the most recent relevant publications from which an historical perspective could be constructed. This approach made use of the bibliographic tools provided with the search engines to identify the most recent and/or most relevant papers.

Where appropriate, in the report that follows these core references have been identified alongside the search terms that generated the groups in which they were found; this approach enables the relevance of the materials identified to be tested.

3.4 Data Extraction and Synthesis

In order to accomplish the objectives of this study, the long-term goal must be to examine and classify the references selected so that more specific hypotheses about the links between supporting services, thresholds and resilience, and their relevance to ecosystem accounting frameworks could be tested. In all studies of this kind, the process of data extraction and synthesis is iterative and has to be refined most usually through a process of consultation and testing. As a first step, the attributes shown in Table 2 were used as an initial template against which the references could be considered, and the aim was to use the experience gained to identify how it could be modified and if a full systematic review were to be undertaken.

Table 2: Attributes identified for preliminary data extraction

Attribute	Rationale
Ecosystem considered	*To identify what kinds of system are being examined*
Ecosystem service	*Identify service using MA terminology, and alternative terms for supporting services (ecological functioning)*
Empirical, conceptual or review	*To identify studies that could potentially form the basis of a meta-analysis*
Threshold(s) identified	*To identify if and how thresholds defined*
Resilience components investigated	*To identify how resilience concepts are framed (cf. definitions provided by Brand and Jax, 2007)*
Resilience measure	*To identify how resilience was measured*
Accounting aspects considered	*To identify if any links to ecosystem or accounting methodologies were identified*
Maintenance costs considered	*To identify if and how physical or monetary measures of maintenance costs for supporting services were estimated*
Spatial scale and geographical relevance	*To identify spatial scale of the study and location details*

In the proposal for this work it was suggested that the topic area was an important one, because it potentially addressed a number of interesting and policy relevant questions. An initial set of questions were circulated to a small expert group (see acknowledgements) who were requested to modify them in any way they saw fit so that they could be used to testing the robustness the available evidence and its relevance to the policy concerns that underpinned this study. The questions initially proposed were:

- **Question 1:** Can resilience be measured in terms of levels of ecological functioning (output of supporting services)?
- **Question 2:** Can minimum levels of ecological functioning be used to define ecological thresholds and limits?
- **Question 3:** Is it possible to calculate the costs (in physical or monetary terms) of maintaining the minimum levels of ecological functioning required to sustain ecosystem resilience?

4. Results

4.1 Search efficacy and search statistics

The search protocols listed in Table 1 were used to search the Science Direct (SD) and Web of Knowledge (WOK) databases. The results, in terms of numbers of references extracted by these protocols and variations upon them are shown in Table 3. The two databases showed significant differences in the number of hits for each protocol, a situation that reflects both their coverage of topics and the way each of them search the available sources.

Table 3: Search statistics

Run	Search Terms	Science Direct	Web of Knowl'ge
1	cost* AND ecosystem*	53,352	3,234
2	"maintenance cost*" AND ecosystem*	1314	163
3	"maintenance cost*" AND ecosystem* (see note 1)		106
4	"maintenance cost*" AND "ecosystem service*"	98	19
5	"maintenance cost*" AND ecosystem* AND threshold*	333	5
5a	"maintenance cost*" AND "ecosystem service*" AND threshold*	*36*	1
6	"maintenance cost*" AND ecosystem* AND resilien*	115	3
6a	"maintenance cost*" AND "ecosystem service*" AND resilien*	*17*	0
7	"environmental account*" OR "ecosystem account*"	1427	22351
8	"ecosystem account*"	81	3490
9	"environmental account*" AND "ecosystem service*"	171	54
10	"environmental account*" AND "supporting service*"	12	9
11	"ecosystem account*" AND "ecosystem service*"	13	233
12	"ecosystem account*" AND "supporting service*"	1	7
13	("environmental account*" OR "ecosystem account*") AND "ecosystem service*"	175	233
14	("environmental account*" OR "ecosystem account*") AND "supporting service*"	12	25
15	("environmental account*" OR "ecosystem account*") AND "maintenance cost*"	78	97
16	("environmental account*" OR "ecosystem account*") AND threshold*	221	431
17	("environmental account*" OR "ecosystem account*") AND threshold* AND maintenance cost*	17	5
18	("environmental account*" OR "ecosystem account*") AND threshold* AND "ecosystem service*"	44	5
19	("environmental account*" OR "ecosystem account*") AND threshold* AND "supporting service*"	3	1
20	("environmental account*" OR "ecosystem account*") AND resilien*	126	122
21	("environmental account*" OR "ecosystem account*") AND resilien* AND "maintenance cost*"	7	1
22	("environmental account*" OR "ecosystem account*") AND resilien* AND "ecosystem service*"	43	13
23	("environmental account*" OR "ecosystem account*") AND resilien* AND "supporting service*"	4	1
24	("environmental account*" OR "ecosystem account*") AND resilien* AND threshold*	49	12
25	("ecosystem* service*" AND supporting AND threshold*) OR resilien*	40	7
26	("ecosystem* service*" AND supporting AND threshold*) OR resilien* AND maintenance cost*	16	0

Note1: Run 3 is a refinement of Run 2 using WOK, by performing a refining search that focussed on ecological and environmental science journals. This search tool was not available in SD

It is clear from a preliminary inspection of the results shown in Table 3 that some combinations of search terms produced large numbers of hits, which probably contained many references that were not relevant to the study. The search protocols shown in the table are arranged to show the effect of progressively being more specific in the selection of terms for the different thematic elements covered by the study. This arrangement was used to help identify the level of search generality that might be appropriate.

In relation to the thematic area that primarily focuses on the concept of "maintenance costs", it is clear that set 4, which represents the combination (maintenance cost* AND ecosystem service*) yields a reasonable number of references that could be used for initial screening for this topic. To check the degree of overlap between the two sources the number of common references were investigated using EndNote and no duplicates were identified.

Although search runs 5 and 6 introduce additional terms to identify material that potentially links "maintenance costs" and "ecosystems" to "thresholds" or "resilience", by eliminating the word "service" similar numbers of references were identified to that found by run 4. Thus variations on these two searches were tried to investigate the outcomes in more detail. It was found that:

- By introducing the term "service" into the protocols (runs 5a and 6a) the subsets of run 4 are identified that specifically mention either threshold or resilience; thus it appears that from run 4, 45 references (38%) specifically refer to threshold and resilience concepts in the context of ecosystem services and maintenance costs.
- By excluding the term "service" (run 5 and 6) a broader set of references were identified compared to the set identified by run 4; by aggregating runs 4, 5 and 6 and eliminating duplicates an expanded library of 476 references was produced.

If we turn to the second thematic area, dealing with the environmental or ecosystem accounting concepts, it is apparent that while a large number of references refer to these topics, the number that link them to the concepts "ecosystem services", "maintenance costs", "thresholds" or resilience" are more limited. In order to build a consolidated reference base that could potentially be used to investigate these associations further, runs 13, 15, 16 and 20 were combined and duplicates eliminated; using the two sources a set of 1067 references were identified.

To complete the preparation of the reference set for the initial review, the two subsets described above (i.e. Combined runs 4, 5, 6 (476 records) and Combined runs 13, 15, 16, 20) were consolidated, and the small number of additional references identified by run 25 added. After the elimination of duplicate records, and those which referred to abstracts or book chapters, a reference-base of 1563 unique publications was generated; for convenience we will refer to this record set as the 'Draft Bibliographic Database 1' (DB1).

4.2 Relevance Assessment

4.2.1 Review of DB1

In order to test the relevance of the materials generated by the searches and the resulting database (DB1), an approximate 20% random sample was generated, and the documents assessed as to their potential value for this study according to the information contained in their title and abstract. The criteria for inclusion were:

- That they should be peer reviewed articles;
- That they should be in English; and
- In the concepts and topics covered they should be seen by an 'expert' as relevant in some way to the search question constructed in section 3.1, above.

Clearly the final criteria for inclusion are subjective, but perhaps this is inevitable at this preliminary stage. Of the 1563 records in the database, 306 were reviewed by the person who constructed the database, and 204 (~66%) were initially found to be broadly relevant to the topics under investigation, 97 (31%) were rejected and 5 (~2%) could not be assessed on the basis of the information available (e.g. no abstract or ambiguous title or abstract).

A test of the judgements about the relevance of the sample records was made by asking a second independent expert to also screen the material (Table 4). Agreement on inclusion between the reviewers was initially deemed to be 'slight' (Cohen's Kappa test: K = 0.19). Inspection of the results shown in Table 4 suggests that the second reviewer was more restrictive in what was seen to be relevant compared to the initial expert, rejecting many that the first thought to be useful. The second expert also assessed a higher proportion as marginal.

Table 4: Test of the agreement on relevance between independent experts on 20% sample.

		Second expert			
		Y	N	?	Total
First expert	Y	34	121	49	204
	N	1	85	11	97
	?	0	5	0	5
	Total	35	211	60	306

The low level of agreement is, perhaps, to be expected given the general nature of the concepts being considered here. Nevertheless the implication is that there are probably a number of references in the initial reference base that are of limited relevance and that further refinement of protocols is probably required to identify a core set that could form the basis of a systematic review.

Given the limited time available for this work it was not possible to refine the selection criteria used screen the initial reference base and re-test them with the independent expert. Instead, given the pilot nature of this work, it was decided to work with this initial record set and seek to identify the likely most relevant papers using the tools available with each of the search engines. Both WOK and SD allow search sets to be ranked according to some criteria of relevance (usually the number of times the search terms are mentioned in the sections of the document that are inspected); in each case the 'top-10' records were identified.

Table 5 and Table 6 shows those sources found using protocols that looked at aspects of ecosystem or environmental, and ecosystem services; they are listed in order to decreasing relevance. Table 7 and Table 8 illustrate the searches that dealt with maintenance costs or a more general association between the key concepts. In the case of Table 8 it should be noted that the two sets of results come from the same source – but use different protocols.

Table 5: Most relevant records identified for protocols dealing with accounting and ecosystem services

Science Direct	Web of Knowledge
1. Zhang, Y., Z. Yang, and X. Yu, *Evaluation of urban metabolism based on emergy synthesis: A case study for Beijing (China).* Ecological Modelling. **In Press, Corrected Proof**.	1. Hooper, D.U., et al., *Effects of biodiversity on ecosystem functioning: A consensus of current knowledge.* Ecological Monographs, 2005. **75**(1): p. 3-35.
~~2. Zhang, X., et al., *Emergy evaluation of the sustainability of Chinese steel production during 1998-2004.* Journal of Cleaner Production, 2009. **17**(11): p. 1030-1038.~~	2. Yu, G., et al. *Grassland ecosystem services and their economic evaluation in Qinghai-Tibetan Plateau based on RS and GIS.* in *25th IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2005).* 2005. Seoul, SOUTH KOREA.
3. Ruggeri, J., *Government investment in natural capital.* Ecological Economics, 2009. **68**(6): p. 1723-1739.	3. Egoh, B., et al., *Integrating ecosystem services into conservation assessments: A review.* Ecological Economics, 2007. **63**(4): p. 714-721.
4. Franzese, P.P., et al., *Sustainable biomass production: A comparison between Gross Energy Requirement and Emergy Synthesis methods.* Ecological Indicators, 2009. **9**(5): p. 959-970.	4. Li, J., Z.Y. Ren, and Z.X. Zhou, *Ecosystem services and their values: a case study in the Qinba mountains of China.* Ecological Research, 2006. **21**(4): p. 597-604.
5. Tilley, D.R. and M.T. Brown, *Dynamic emergy accounting for assessing the environmental benefits of subtropical wetland stormwater management systems.* Ecological Modelling, 2006. **192**(3-4): p. 327-361.	5. Boyd, J. and S. Banzhaf, *What are ecosystem services? The need for standardized environmental accounting units.* Ecological Economics, 2007. **63**(2-3): p. 616-626.
6. Bastianoni, S., et al., *Correlations and complementarities in data and methods through Principal Components Analysis (PCA) applied to the results of the SPIn-Eco Project.* Journal of Environmental Management, 2008. **86**(2): p. 419-426.	6. Ghazoul, J., *Recognising the complexities of ecosystem management and the ecosystem service concept.* Gaia-Ecological Perspectives for Science and Society, 2007. **16**(3): p. 215-221.
7. Tonon, S., et al., *An integrated assessment of energy conversion processes by means of thermodynamic, economic and environmental parameters.* Energy, 2006. **31**(1): p. 149-163.	7. Zheng, B.F., et al., *Assessment of ecosystem services of Lugu Lake watershed.* International Journal of Sustainable Development and World Ecology, 2008. **15**(1): p. 62-70.
8. Kangas, P., *Ecological economics began on the Texas bays during the 1950s.* Ecological Modelling, 2004. **178**(1-2): p. 179-181.	8. Swinton, S.M., et al., *Ecosystem services and agriculture: Cultivating agricultural ecosystems for diverse benefits.* Ecological Economics, 2007. **64**(2): p. 245-252.
9. Matete, M. and R. Hassan, *Integrated ecological economics accounting approach to evaluation of inter-basin water transfers: An application to the Lesotho Highlands Water Project.* Ecological Economics, 2006. **60**(1): p. 246-259.	9. Matero, J. and O. Saastamoinen, *In search of marginal environmental valuations - ecosystem services in Finnish forest accounting.* Ecological Economics, 2007. **61**(1): p. 101-114.
10. Herendeen, R.A. and T. Wildermuth, *Resource-based sustainability indicators: Chase County, Kansas, as example.* Ecological Economics, 2002. **42**(1-2): p. 243-257.	10. Rodriguez, J.P., et al., *Trade-offs across space, time, and ecosystem services.* Ecology and Society, 2006. **11**(1).
Search protocol 13: (environmental account* OR "ecosystem account*") AND ecosystem service*	

Table 6: Most relevant records identified for protocols dealing with accounting, ecosystem services and resilience

Science Direct	Web of Knowledge
1. Bastianoni, S., et al., *Correlations and complementarities in data and methods through Principal Components Analysis (PCA) applied to the results of the SPIn-Eco Project.* Journal of Environmental Management, 2008. **86**(2): p. 419-426.	1. Maler, K.G., S. Aniyar, and A. Jansson, *Accounting for Ecosystems.* Environmental & Resource Economics, 2009. **42**(1): p. 39-51.
2. Midmore, P. and J. Whittaker, *Economics for sustainable rural systems.* Ecological Economics, 2000. **35**(2): p. 173-189.	2. Jansson, A., et al., *Linking freshwater flows and ecosystem services appropriated by people: The case of the Baltic Sea drainage basin.* Ecosystems, 1999. **2**(4): p. 351-366.
3. Turner, R.K., et al., *Valuing nature: lessons learned and future research directions.* Ecological Economics, 2003. **46**(3): p. 493-510.	3. Bohensky, E.L., *Discovering Resilient Pathways for South African Water Management: Two Frameworks for a Vision.* Ecology and Society, 2008. **13**(1).
4. Fisher, B., R.K. Turner, and P. Morling, *Defining and classifying ecosystem services for decision making.* Ecological Economics, 2009. **68**(3): p. 643-653.	4. Carpenter, S.R. and C. Folke, *Ecology for transformation.* Trends in Ecology & Evolution, 2006. **21**(6): p. 309-315.
5. Patterson, M.G., *Development of ecological economics in Australia and New Zealand.* Ecological Economics, 2006. **56**(3): p. 312-331.	5. Tscharntke, T., et al., *Landscape perspectives on agricultural intensification and biodiversity - ecosystem service management.* Ecology Letters, 2005. **8**(8): p. 857-874.
6. Ruth, M., *A quest for the economics of sustainability and the sustainability of economics.* Ecological Economics, 2006. **56**(3): p. 332-342.	6. Lebel, L., et al. *Governance and the capacity to manage resilience in regional social-ecological systems*. in *Workshop of Resilience Alliance.* 2004. Nagambie, AUSTRALIA.
7. Ekins, P., et al., *A framework for the practical application of the concepts of critical natural capital and strong sustainability.* Ecological Economics, 2003. **44**(2-3): p. 165-185.	7. Barthel, S., et al., *History and local management of a biodiversity-rich, urban cultural landscape.* Ecology and Society, 2005. **10**(2): p. 10.
8. Dasgupta, P. and A.L. Simon, *Economic Value of Biodiversity, Overview*, in *Encyclopedia of Biodiversity*. 2001, Elsevier: New York. p. 291-304.	8. Lacitignola, D., et al., *Modelling socio-ecological tourism-based systems for sustainability.* Ecological Modelling, 2007. **206**(1-2): p. 191-204.
9. Weber, J.-L., *Implementation of land and ecosystem accounts at the European Environment Agency.* Ecological Economics, 2007. **61**(4): p. 695-707.	9. Hougner, C., J. Colding, and T. Soderqvist, *Economic valuation of a seed dispersal service in the Stockholm National Urban Park, Sweden.* Ecological Economics, 2006. **59**(3): p. 364-374.
10. Harborne, A.R., et al., *The Functional Value of Caribbean Coral Reef, Seagrass and Mangrove Habitats to Ecosystem Processes*, in *Advances in Marine Biology*. 2006, Academic Press. p. 57-189.	10. Deutsch, L., et al., *Feeding aquaculture growth through globalization: Exploitation of marine ecosystems for fishmeal.* Global Environmental Change-Human and Policy Dimensions, 2007. **17**(2): p. 238-249.
Search protocol 22: (environmental account* OR ecosystem account*) AND resilien* AND ecosystem service*	

Table 7: Most relevant records identified for protocols dealing with accounting, ecosystem and resilience

Science Direct	Web of Knowledge
1. Kooijman, S.A.L.M., J. Grasman, and B.W. Kooi, *A new class of non-linear stochastic population models with mass conservation.* Mathematical Biosciences, 2007. **210**(2): p. 378-394.	1. Resh, V.H., *Multinational, freshwater biomonitoring programs in the developing world: Lessons learned from African and Southeast Asian river surveys.* Environmental Management, 2007. **39**(5): p. 737-748.
2. Krause-Jensen, D., et al., *Empirical relationships linking distribution and abundance of marine vegetation to eutrophication.* Ecological Indicators, 2008. **8**(5): p. 515-529.	2. Smits, A.J.M., P.H. Nienhuis, and H.L.F. Saeijs. *Changing estuaries, changing views*. in *Symposium on Living Rivers - Trends and Challenges in Science and Management held in Honour of Piet Nienhuis*. 2003. Nijmegen, NETHERLANDS.
3. ~~Diprose, P.R. and G. Robertson, *Towards a fourth skin? Sustainability and double envelope buildings.* Renewable Energy, 1996. **8**(1-4): p. 169-172.~~	3. Norberg, J. and D. DeAngelis, *Temperature effects on stocks and stability of a phytoplankton-zooplankton model and the dependence on light and nutrients.* Ecological Modelling, 1997. **95**(1): p. 75-86.
4. Ferron, A., et al., *An Appraisal of Condition Measures for Marine Fish Larvae*, in *Advances in Marine Biology*. 1994, Academic Press. p. 217-303.	
5. de la Torre-Castro, M. and P. Ronnback, *Links between humans and seagrasses - an example from tropical East Africa.* Ocean & Coastal Management, 2004. **47**(7-8): p. 361-387.	
6. Reynolds, C.S., *Planktic community assembly in flowing water and the ecosystem health of rivers.* Ecological Modelling, 2003. **160**(3): p. 191-203.	
7. Kramer, K., T.A. Groen, and S.E. van Wieren, *The interacting effects of ungulates and fire on forest dynamics: an analysis using the model FORSPACE.* Forest Ecology and Management, 2003. **181**(1-2): p. 205-222.	
8. Berg, P.G., *Sustainability resources in Swedish townscape neighbourhoods: Results from the model project Hågaby and comparisons with three common residential areas.* Landscape and Urban Planning, 2004. **68**(1): p. 29-52.	
9. Marais, C. and A.M. Wannenburgh, *Restoration of water resources (natural capital) through the clearing of invasive alien plants from riparian areas in South Africa -- Costs and water benefits.* South African Journal of Botany, 2008. **74**(3): p. 526-537.	
10. Didion, M., M.J. Fortin, and A. Fall, *Forest age structure as indicator of boreal forest sustainability under alternative management and fire regimes: A landscape level sensitivity analysis.* Ecological Modelling, 2007. **200**(1-2): p. 45-58.	
Search protocol 6: maintenance cost* AND ecosystem* AND resilien*	

Table 8: Most relevant records identified for protocols dealing with ecosystem service, thresholds, resilience and maintenance costs

Science Direct	Science Direct
1. Gordon, L.J., C.M. Finlayson, and M. Falkenmark, *Managing water in agriculture for food production and other ecosystem services.* Agricultural Water Management. **In Press, Corrected Proof**.	1. Beaumont, N.J., et al., *Economic valuation for the conservation of marine biodiversity.* Marine Pollution Bulletin, 2008. **56**(3): p. 386-396.
2. Wallace, K.J., *Classification of ecosystem services: Problems and solutions.* Biological Conservation, 2007. **139**(3-4): p. 235-246.	2. ~~Miller, B.G., *Emissions Control Strategies for Power Plants*, in *Coal Energy Systems*. 2005, Academic Press: Burlington. p. 283-392.~~
3. Fiedler, A.K., D.A. Landis, and S.D. Wratten, *Maximizing ecosystem services from conservation biological control: The role of habitat management.* Biological Control, 2008. **45**(2): p. 254-271.	3. Vassallo, P., et al., *Dynamic emergy evaluation of a fish farm rearing process.* Journal of Environmental Management. **In Press, Corrected Proof**.
4. Fisher, B., R.K. Turner, and P. Morling, *Defining and classifying ecosystem services for decision making.* Ecological Economics, 2009. **68**(3): p. 643-653.	4. Mayer, A.L. and P.M. Tikka, *Biodiversity conservation incentive programs for privately owned forests.* Environmental Science & Policy, 2006. **9**(7-8): p. 614-625.
5. Egoh, B., et al., *Integrating ecosystem services into conservation assessments: A review.* Ecological Economics, 2007. **63**(4): p. 714-721.	5. Ledoux, L. and R.K. Turner, *Valuing ocean and coastal resources: a review of practical examples and issues for further action.* Ocean & Coastal Management, 2002. **45**(9-10): p. 583-616.
6. Kumar, M. and P. Kumar, *Valuation of the ecosystem services: A psycho-cultural perspective.* Ecological Economics, 2008. **64**(4): p. 808-819.	6. Ward, F.A. and M. Pulido-Velázquez, *Efficiency, equity, and sustainability in a water quantity-quality optimization model in the Rio Grande basin.* Ecological Economics, 2008. **66**(1): p. 23-37.
7. Raymond, C.M., et al., *Mapping community values for natural capital and ecosystem services.* Ecological Economics, 2009. **68**(5): p. 1301-1315.	7. Ward, F.A. and M. Pulido-Velazquez, *Incentive pricing and cost recovery at the basin scale.* Journal of Environmental Management, 2009. **90**(1): p. 293-313.
8. Fisher, B. and R. Kerry Turner, *Ecosystem services: Classification for valuation.* Biological Conservation, 2008. **141**(5): p. 1167-1169.	8. Moberg, F. and P. Rönnbäck, *Ecosystem services of the tropical seascape: interactions, substitutions and restoration.* Ocean & Coastal Management, 2003. **46**(1-2): p. 27-46.
9. van Wilgen, B.W., et al., *A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa.* Journal of Environmental Management, 2008. **89**(4): p. 336-349.	9. Reichert, P., et al., *Concepts of decision support for river rehabilitation.* Environmental Modelling & Software, 2007. **22**(2): p. 188-201.
10. Patterson, T.M. and D.L. Coelho, *Ecosystem services: Foundations, opportunities, and challenges for the forest products sector.* Forest Ecology and Management, 2009. **257**(8): p. 1637-1646.	10. Karlen, D.L., S.S. Andrews, and J.W. Doran, *Soil quality: Current concepts and applications*, in *Advances in Agronomy*. 2001, Academic Press. p. 1-40.
Search protocol 25: (ecosystem* service* AND supporting AND threshold*) OR resilien*	**Search protocol 26: (ecosystem* service* AND supporting AND threshold*) OR resilien* AND maintenance cost***

From an inspection of Table 5, Table 6, Table 7 and Table 8 is apparent that:

- the two search engines identified different records when the same search terms were used – suggesting that the criteria they used to identify 'relevancy' are different;
- only a small number of records that are not relevant to the topic under investigation in terms of discipline area were included– these have been shown using a strike-though font in the tables;
- the term 'emergy'[1] was commonly used in the context of environmental accounting, and its wider linkages might be worth investigating; and,
- a mixture of conceptual and empirical studies are available, suggesting that it may be possible to undertake a more detailed, meta-analysis of studies drawing upon those based on the collection of measurement or observational data.

As a result of this analysis it was decided to retain the whole record set it would probably be more profitable to work initially with the subset of materials identified in Tables 5-8 for an initial assessment of the quality of the underlying database, the assumption being that if this subset of records were inadequate then those of the large dataset would be too.

4.2.2 Assessment of other sources

As noted above, a bibliographic analysis of the different meanings associated with the term resilience in the ecological literature has been prepared by Janssen et al. (2006) and Janssen (2007). The resource is available for others to download, and so has been used here alongside the database created using WOK and SD. Table 9 summarises some initial searches of the resilience database indicating the references that also make reference to the core terms used in this study.

The analysis suggests that this resource (3339 records) has only limited material that links to the notion of ecosystem or environmental accounting (1 record), although works relating to ecosystem services are well represented. Of the 111 which mention the latter, 10 do so in the context of thresholds and a further 4 in relation to thresholds and resilience. One key point to emerge is that while the term "supporting services" was not found in any of the records, the term "ecological functioning" was more common, and should probably be used as a synonym when searching through the main database created by this study.

The material provided by the work of Janssen et al. (2006) and Janssen (2007) is useful in its entirety because it allows us to identify the different understandings of the concept of resilience and the associated ideas of 'adaptability' and 'vulnerability'. While all of these materials can clearly be used to inform this pilot review, the subsets identified in Table 9 offer the prospect of extending the core set identified from DB1. Thus the initial bibliographic database was merged with that provided by Janssen and Ostrom (2006) and Janssen (2007), with the subset of potentially useful records from the latter identified.

[1] Emergy can be defined as the total solar energy needed to making a product or service

Table 9: Potentially relevant records identified from the bibliographic source provided by Janssen 2007.

Search Protocol	References
ecosystem maintenance OR maintenance cost*	none
ecosystem accounting OR environmental accounting	1. Ludwig, D., W.A. Brock, and S.R. Carpenter, *Uncertainty in discount models and environmental accounting.* Ecology and Society, 2005. **10**(2): p. 13.
ecosystem service* AND accounting	1. Barthel, S., et al., *History and local management of a biodiversity-rich, urban cultural landscape.* Ecology and Society, 2005. **10**(2): p. 10. 2. Deutsch, L., C. Folke, and K. Skanberg, *The critical natural capital of ecosystem performance as insurance for human well-being.* Ecological Economics, 2003. **44**(2-3): p. 205-217. 3. Holmlund, C.M. and M. Hammer, *Effects of fish stocking on ecosystem services: An overview and case study using the Stockholm archipelago.* Environmental Management, 2004. **33**(6): p. 799-820. 4. Hutton, J.M. and N. Leader-Williams, *Sustainable use and incentive-driven conservation: realigning human and conservation interests.* Oryx, 2003. **37**(2): p. 215-226.
ecosystem service* AND threshold	1. Balmford, A. and W. Bond, *Trends in the state of nature and their implications for human well-being.* Ecology Letters, 2005. **8**(11): p. 1218-1234. 2. Batabyal, A.A., J.R. Kahn, and R.V. O'Neill, *On the scarcity value of ecosystem services.* Journal of Environmental Economics and Management, 2003. **46**(2): p. 334-352. 3. Bodin, O., et al., *The value of small size: Loss of forest patches and ecological thresholds in southern Madagascar.* Ecological Applications, 2006. **16**(2): p. 440-451. 4. Carpenter, S.R., D. Ludwig, and W.A. Brock, *Management of eutrophication for lakes subject to potentially irreversible change.* Ecological Applications, 1999. **9**(3): p. 751-771. 5. Chapin, F.S., et al., *Directional changes in ecological communities and social-ecological systems: A framework for prediction based on Alaskan examples.* American Naturalist, 2006. **168**(6): p. S36-S49. 6. Dayton, P.K., et al., *Marine reserves: Parks, baselines, and fishery enhancement.* Bulletin of Marine Science, 2000. **66**(3): p. 617-634. 7. Folke, C., *Resilience: The emergence of a perspective for social-ecological systems analyses.* Global Environmental Change-Human and Policy Dimensions, 2006. **16**(3): p. 253-267. 8. Hein, L. and E. van Ierland, *Efficient and sustainable management of complex forest ecosystems.* Ecological Modelling, 2006. **190**(3-4): p. 351-366. 9. Roe, E. and M. Van Eeten, *Threshold-based resource management: A framework for comprehensive ecosystem management.* Environmental Management, 2001. **27**(2): p. 195-214. 10. Thrush, S.F. and P.K. Dayton, *Disturbance to marine benthic habitats by trawling and dredging: Implications for marine biodiversity.* Annual Review of Ecology and Systematics, 2002. **33**: p. 449-473.
ecosystem service* AND threshold AND resilience	1 Chapin, F.S., et al., Directional changes in ecological communities and social-ecological systems: A framework for prediction based on Alaskan examples. American Naturalist, 2006. 168(6): p. S36-S49. 2. Dayton, P.K., et al., *Marine reserves: Parks, baselines, and fishery enhancement.* Bulletin of Marine Science, 2000. **66**(3): p. 617-634. 3. Folke, C., *Resilience: The emergence of a perspective for social-ecological systems analyses.* Global Environmental Change-Human and Policy Dimensions, 2006. **16**(3): p. 253-267. 4. Thrush, S.F. and P.K. Dayton, *Disturbance to marine benthic habitats by trawling and dredging: Implications for marine biodiversity.* Annual Review of Ecology and Systematics, 2002. **33**: p. 449-473.
ecosystem functioning	1. Aarts, B.G.W. and P.H. Nienhuis, *Ecological sustainability and biodiversity.* International Journal of Sustainable Development and World Ecology, 1999. **6**(2): p. 89-102. 2. Cabezas, H., et al., *Sustainable systems theory: ecological and other aspects.* Journal of Cleaner Production, 2005. **13**(5): p. 455-467. 3. Dorren, L.K.A., et al., *Integrity, stability and management of protection forests in the European Alps.* Forest Ecology and Management, 2004. **195**(1-2): p. 165-176. 4. Holmlund, C.M. and M. Hammer, *Ecosystem services generated by fish populations.* Ecological Economics, 1999. **29**(2): p. 253-268. 5. Hooper, D.U., et al., *Effects of biodiversity on ecosystem functioning: A consensus of current knowledge.* Ecological Monographs, 2005. **75**(1): p. 3-35. 6. Jefferies, R.L., R.F. Rockwell, and K.E. Abraham, *Agricultural food subsidies, migratory connectivity and large-scale disturbance in arctic coastal systems: A case study.* Integrative and Comparative Biology, 2004. **44**(2): p. 130-139. 7. Lundberg, J. and F. Moberg, *Mobile link organisms and ecosystem functioning: Implications for ecosystem resilience and management.* Ecosystems, 2003. **6**(1): p. 87-98. 8. Maass, J.M., et al., *Ecosystem services of tropical dry forests: Insights from long-term ecological and social research on the Pacific Coast of Mexico.* Ecology and Society, 2005. **10**(1): p. 17. 9. Rogers, C.E. and J.P. McCarty, *Climate change and ecosystems of the Mid-Atlantic Region.* Climate Research, 2000. **14**(3): p. 235-244. 10. Rogers, K., D.J. Roux, and H.C. Biggs, *Challenges for catchment management agencies: Lessons from bureaucracies, business and resource management.* Water Sa, 2000. **26**(4): p. 505-511. 11. Zhou, Z., et al., *Land use affects the relationship between species diversity and productivity at the local scale in a semi-arid steppe ecosystem.* Functional Ecology, 2006. **20**(5): p. 753-762.

/cont.

Table 9, cont

Search Protocol	References
ecosystem functioning AND threshold	none
ecosystem functioning AND resilience	1. Dorren, L.K.A., et al., *Integrity, stability and management of protection forests in the European Alps.* Forest Ecology and Management, 2004. **195**(1-2): p. 165-176. 2. Holmlund, C.M. and M. Hammer, *Ecosystem services generated by fish populations.* Ecological Economics, 1999. **29**(2): p. 253-268. 3. Jefferies, R.L., R.F. Rockwell, and K.E. Abraham, *Agricultural food subsidies, migratory connectivity and large-scale disturbance in arctic coastal systems: A case study.* Integrative and Comparative Biology, 2004. **44**(2): p. 130-139. 4. Lundberg, J. and F. Moberg, *Mobile link organisms and ecosystem functioning: Implications for ecosystem resilience and management.* Ecosystems, 2003. **6**(1): p. 87-98. 5. Rogers, C.E. and J.P. McCarty, *Climate change and ecosystems of the Mid-Atlantic Region.* Climate Research, 2000. **14**(3): p. 235-244. 6. Rogers, K., D.J. Roux, and H.C. Biggs, *Challenges for catchment management agencies: Lessons from bureaucracies, business and resource management.* Water Sa, 2000. **26**(4): p. 505-511.

4.2.3 Expert Consultation

As a final check on the approach used to construct the search protocols and the relevance of the materials generated by the searches, the materials were circulated to a group of six experts with experience in environmental accounting, resilience and ecosystem services. The experts were briefed on the project background and given a short questionnaire on the draft materials provided. The questionnaire has been reproduced in Table 10 and for clarity cross-referenced to the materials they were asked to comment on as they now appear in the numbered sections in this document.

Table 10: Questionnaire for Expert Input into development of search strategies

Issues for Comment
1. Your reaction to the objectives (see Section 2) and in particular how they might be modified to ensure that they have the greatest general policy relevance.
2. Your thoughts on the way we have formulated the review question that arises from these objectives, in terms of the ***subject-intervention-outcome*** structure suggested by the CEBC guidelines (see section 3.1).
3. The appropriateness or otherwise of the preliminary search terms listed in Table 1 (also section 3.1) for preliminary data extraction; are there combinations of key terms missing?
4. The appropriateness of the proposed template for data extraction that follows from the review question, which shown in Table 2 (section 3.4).
5. Any key references or other materials or sources that spring to mind in relation to achieving the objectives (or your suggested modifications). 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.
6. Your reaction to the three questions listed in section 3.4, which we propose to use as the basis for testing specific ideas using the reference sources identified by the search.
7. Any general views you have about the relevance of the materials generated by the initial search – as identified by the example references listed in Tables 4 through 8.

In terms of the relevance of the objectives of the study (Table 10, issue 1) there was general consensus that it was and adequately formulated and policy relevant. It was felt that such a review could potentially contribute to the discussions surrounding the 'TEEB process' and the revision of the SEEA. There was also general agreement that the objectives of the study were ambitious. One expert advised that the terminology used in the overall object needed to be clarified, commenting:

> *The meaning of "maintaining" may have to be narrowed down, by making explicit whether maintenance entails preservation of baseline performance ("costs of maintaining* ***non-declining levels*** *of supporting services") or not exceeding critical ecological thresholds ("costs of maintaining* ***minimum levels*** *of functioning/ supporting services").*

In terms of the issues surrounding the possibility of estimating the costs of maintenance, another expert suggested that the issue that needs to be examined is not so much whether monetary or biophysical estimates can be found in the literature, but whether consistent estimates could be found.

In relation to the formulation of the specific review question (Table 10, issue 2) a number of issues were raised, mainly in relation to its hybrid nature. It was noted that the 'intervention' (i.e. loss of supporting services) was not really a deliberate management or policy action as is normally the case in a systematic review, but more of a driver of change. Similarly in terms of the outcome element ('loss of resilience') the multiple interpretations of the term was also noted as a problem, with one expert arguing that when investigating the question it was important to be clear in each source was actually using the idea and what time scales it was being considered.

The search terms were generally thought to be adequate (Table 10, issue 3), although some experts suggested that the list could be broadened, with additional terms being used, including:

- ecosystem function*
- ecosystem health
- restoration cost*
- mitigation cost*
- valuation of resilience

It was noted that the term 'supporting service' mainly stems from the classification used in the MA, and that elsewhere 'ecosystem functions' or even 'intermediate services' are used as synonyms. However, it was noted that the terminology used in the literature is still developing:

> *For instance, Gren et al. (1994) refer to "primary values" or "infrastructure value" as necessary condition to maintain "secondary" or "output" values (which focus on end products). More recently, Balmford et al. (2008) have reflected on the same issue in terms of "core ecosystem processes" needed to maintain "beneficial processes" (intermediate products) and "benefits" (final products).*

Ideas about the integrity of basic ecological functioning are implicit in the notion of ecosystem health, and so it was suggested that the literature might be broadened by including this term in the set of protocols. The recommendation to also consider restoration and mitigation costs alongside maintenance costs also seems a useful one, although it may significantly broaden the range of material that might need to be considered. At this stage it was however, decided to not to examine the ecosystem health literature in detail, the assumption being that any material from this topic area that specifically mentioned concepts of resilience and maintenance costs would have been identified by the current searches. A search using the string "valuation of resilience" yielded record sets that included many of the records already identified, and so the protocols were not expanded further at this stage.

The draft design for template that proposed to extract information on the content of the reference sources for additional screening was generally thought to be satisfactory (Table 10, issue 4). It was suggested, however, that details on the type of valuation and the metric used might be recorded, along with the nature of the cost identified (maintenance, restoration, mitigation).

Table 11: Additional potential sources suggested though expert consultation

Item
Studies in bold were not already identified by the initial literature search **1. Gren, I.-M., Folke, C., Turner, R.K., Bateman, I.J., (1994) Primary and secondary values of wetland ecosystems. Environmental and Resources Economics 4 (4), 55-74.** **2. Fromm, O. (2000) Ecological structure and functions of biodiversity as elements of its total economic value. Environmental and Resource Economics 16:303-328.** 3. Deutsch, L., Folke, C., Skaanberg, K., (2003) The critical natural capital of ecosystem performance as insurance. Ecological Economics 44: 205-217. **4. Vergano, L., Nunes P.A.L.D. (2006) Analysis and Evaluation of Ecosystem Resilience: An Economic Perspective NOTA DI LAVORO 25.** **5. Balmford, A., Rodrigues, A., Walpole, M., ten Brink, P., Kettunen, M., Braat, L., de Groot, R., (2008) Review on the economics of biodiversity loss: scoping the science. European Commission.** **6. Rapport, D.J. (2007) Sustainability science: and ecohealth perspective. Sustainability Science, 2, 77-84.** **7. Rapport, D.J. (2007) Healthy Ecosystems: An Evolving Paradigm. In, Pretty, J. , Ball, A., Benton, T., Guivant, J., Lee, D., Orr, D., Pfeffer, M. and Ward, H. (eds) *Handbook of Environment and Society*. Sage, London.** **8. Houdet, J. (2008) Integrating Biodiversity into Business Strategies. The Biodiversity Accountability Framework. Fondation pour la recherche sur la biodiversité and Association *Orée.*** **9. Walker, B. (2005) A resilience approach to integrated assessment. The Integrated Business Journal, 5, 77-97.** database of the Resilience Alliance: http://www.resalliance.org/183.php

Experts were asked to identify any key references that might be used as alternative means of exploring the literature (Table 10, issue 5); these are shown in Table 11. Those not already identified in the intial searches have been shown in bold. Alongside these it was suggested that the materials available through the database of the *Resilience Alleince* should also be considred, as well as the non-English literature.

The final two questions concerned the formulation of the questions that were proposed as the focus of the preliminary review and other issues the experts identified, given the material they considered (Table 10, issues 6 and 7). The comments received concerned the specificity of the questions and the possible problematic nature of the 'emergy' concept that emerged as the result of the preliminary searches. Once again it was suggested that the way the resilience concept is framed is critical – the questions assume that it is, in fact, measurable. This difficulty was noted, and this issue of how the concept was operaitonalised in particular studies was identified as an important aspect that needed to be explored in the review.

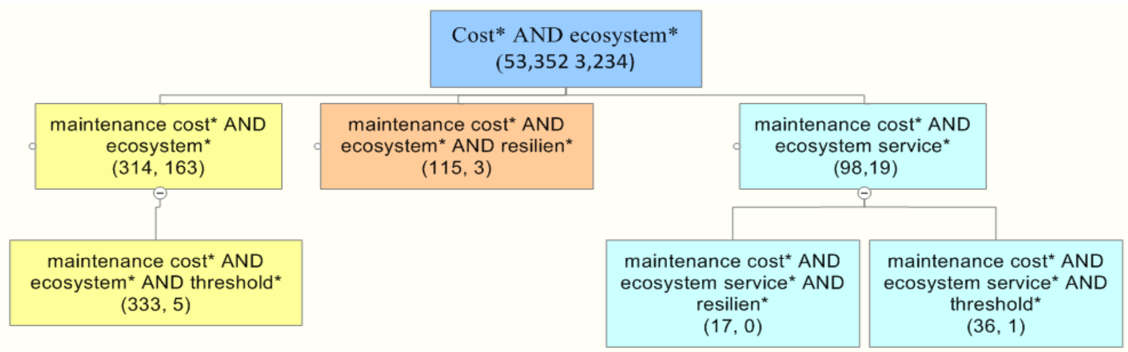
The link to emergy it was noted as problematic by two experts who both argued that it has more to do with the "production costs [in terms of solar energy equivalent] rather that maintenance costs". It was pointed out that the review by Brown and Ugliaty (2004), which lists nine issues to which emergy is relevant (p. 209), makes no reference to measures of 'maintenance'.

5. Review Outcomes and Draft Protocols

A bibliographic analysis has been undertaken to find out whether it is possible, on the basis of current knowledge, to estimate either in physical or monetary terms the cost of maintaining the ecosystem functions that underpin to people's well-being. The investigation also considered whether the full costs of maintaining ecosystem services can be represented within an environmental accounting framework. Since this was a pilot study, at this preliminary stage evidence from any ecosystem was considered to be relevant.

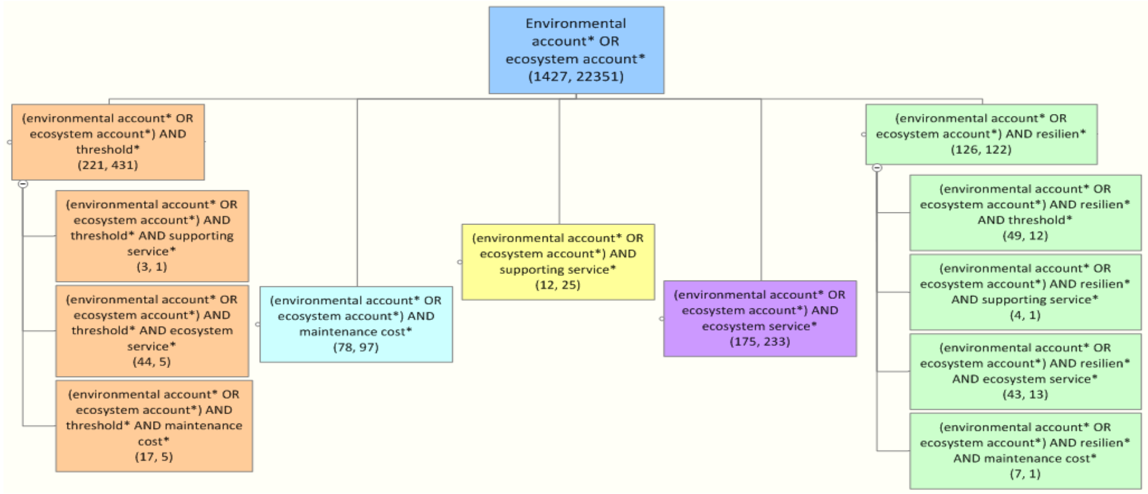
The objectives of the study were tested by consulting a range of experts, who confirmed that it was both important and topical, and that the results could potentially contribute to the current discussions that surround the issues of ecosystem accounting, ecosystem services and resilience. However, when undertaking the bibliographic study it was found that unlike work in the area of evidence-based conservation where tightly specified review questions can be constructed, the general nature of the subject matter meant that a wide range of papers were identified, many of which had only limited relevance to the core ideas that needed to be considered.

For example, while a large number of papers dealt with the topics of environmental or ecosystem accounting (Figure 1), much smaller numbers deal specifically with the maintenance costs associated with ecosystems or their resilience. A similar pattern existed in relation to the literature dealing with concepts of 'costs' and 'ecosystems' (Figure 2).



Numbers of hits per search engine shown in parentheses: (SD, WOK)

Figure 1: Number of articles found by two search engines (Science Direct (SD) and Web of Knowledge (WOK)) dealing with the concepts of 'environmental' or 'ecosystem accounting' in combination with other search criteria.



Numbers of hits per search engine shown in parentheses: (SD, WOK)

Figure 2: Number of articles found by two search engines (Science Direct (SD) and Web of Knowledge (WOK)) dealing with the concepts of 'costs' and 'ecosystems' in combination with other search criteria.

Since the initial bibliographic analysis identified a large and fragmented body of literature subsequent effort turned to finding ways of narrowing the search to identify only the most relevant materials. This was achieved by looking at the smaller number of papers flagged up by more detailed combinations of search criteria; these are at the intermediate and terminal nodes of the search trees shown in Figure 1 and Figure 2.

The resulting draft protocols are presented in Table 12. They have been set out in relation to the three issues devised to explore the broad topic area, and have been constructed to be as specific as possible without being so restrictive as to identify only a limited number of papers. As an indicator of their efficiency, the number of references identified using the combined results from the two search engines are noted. The inclusion criteria applied were that they should be in English, should be a journal article and not be published in an IT, energy or recycling-related publication.

Table 12: Finalised Draft Protocols

	Question	Draft Protocol	References
1	Can resilience be measured in terms of levels of ecological functioning (output of supporting services)?	(("measurement of resilience") OR ("measure* of resilience") OR ("resilience measur*") OR ("index of resilience") OR ("indicator of resilience") OR ("resilience indicator") OR ("resilience indicator")) AND ecosystem*	149
2	Can minimum levels of ecological functioning be used to define ecological thresholds and limits?	("ecosystem* service*" AND "supporting" AND ("threshold*" OR "resilien*"))	468
3	Is it possible to calculate the costs (in physical or monetary terms) of maintaining the minimum levels of ecological functioning required to sustain ecosystem resilience?	("environmental account*" OR "ecosystem account*") AND ("ecosystem service*") AND ("cost*" OR "maintenance")	138

The searches generated by each protocol were consolidated into a single EndNote library and the duplicates eliminated. The resulting resource contains 659 records. It is likely that this dataset still contains references that are marginal to the issues that are the focus of this study, but given the exploratory nature of the this work a precautionary approach has been adopted. To explore the character of the literature identified, a preliminary review has been prepared using these materials. This is presented in Part II of this document.

Part II: Pilot Review

6. Investigating Environmental Limits, Ecosystem Resilience and Supporting Services

6.1 Introduction

The results of the bibliographic analysis are best presented by structuring the review around three specific issues, namely:

- Can resilience be measured in terms of levels of ecological functioning (output of supporting services)?
- Can minimum levels of ecological functioning be used to define ecological thresholds and limits for service?
- Is it possible to calculate the costs (in physical or monetary terms) of maintaining the minimum levels of ecological functioning required to sustain ecosystem resilience?

The construction of these questions were discussed and refined with the expert panel to ensure that they captured the major issues that needed to be considered, given the objectives of the study. Although the answers to these questions are of interest in their own right, given that this is a pilot study the following discussion seeks mainly to identify whether a full systematic review across some or all of these subject areas is feasible.

6.2 Measuring Ecosystem Resilience and Minimum Ecological Functioning

Despite recent attempts to value ecosystem services, the scale and relative importance of their contribution to society remains uncertain at both local and global scales. Estimates tend to be made on a case by case basis, and there is a general lack of integrated measurement or accounting tools that would the contribution that ecosystem services make to national incomes to be identified (TEEB, 2008). As recent discussion surrounding the proposed revision of the UN *Handbook for Integrated Economic and Environmental Accounting* (SEEA2003) has emphasised, the difficulty we face is that estimates of wealth must include both market and non-market value of ecosystem services ***and*** the reinvestment that society needs to make to maintain, protect and restore ecosystem services. Information on the cost inputs to service production as well as the benefits they generate is essential if society is to understand the implications of different policy or management options on ecosystems.

The nature of the 'accounting problem' is illustrated in Figure 3. This diagram has been designed to summarise current views about the relationships between capital stocks and flows that make up coupled 'socio-ecological' system identified by this study in current literature. Thus Fisher et al. (2009) and Boyd and Banzhaf (2007), for example have argued that in accounting terms we should attempt to distinguish between 'intermediate' and 'final' products or services to avoid the problem of 'double counting'. This proposal is designed to negotiate the problem posed by the category of 'supporting services' used in the Millennium Assessment which were used to identify those more fundamental ecological processes and functions that underpin the provisioning, regulating and cultural services that contribute more directly to human well-being.

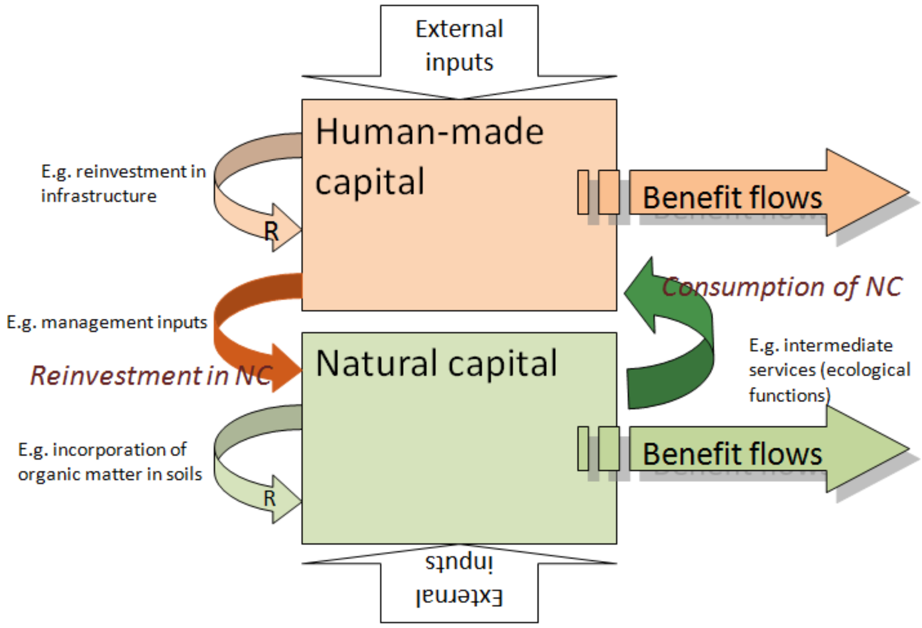


Figure 3: The relationships between natural and human-made capital, and the flows of final and intermediate ecosystem services represented as an accounting model

While much of the current literature dealing with the problem of valuing the benefits from natural capital has focused on these final products or services, the importance of the intermediate or supporting services, even in accounting terms, should not be underestimated. Figure 3 highlights two important features that must be considered. First, that many benefits that society derives from ecosystems are, in fact, produced by a combination of natural- and human-made capitals. 'Food production', for example, depends on elements of built and manufactured capital as well features of nature. Thus the scale and/or value of the intermediate services consumed in this production chain must be identified (Bartelmus (2009). Second, in just the same way that society has to reinvest in human-made capital to take account of depreciation and damage to capital stocks, then we must also consider the level of reinvestment in our natural capital needed to sustain the output of ecosystem services (Bartelmus (2009); Mäler et al. (2009)).

This 'reinvestment' in natural capital may take many forms including, most obviously, maintenance or management, protection and restoration costs; that is the steps society has to take to make good the 'ware and tear' on natural capital brought about by human activities. However, it could also include less tangible things like 'use forgone'; which can be thought of as the stock of natural capital that must not be appropriated to ensure that ecosystems retain their capacity renew and sustain themselves. In the literature identified, resilience, interpreted as a kind of insurance against the risk of ecosystem disruption and the interruption of the supply of services to people has been a recurring theme in much of the literature identified by this study (e.g. Vergano and Numes (2007); Deutsch et al. (2003)). Resilience, like other benefits provided by ecosystems, is not priced by current markets, but as Vergano and Numes (2007) point out, this does not mean that it is of no value to people. The challenge for those interested in assessing its importance lies in making the concept 'operational' or measurable, so that changes in resilience can be monitored and ultimately valued.

As noted in the introduction to this study, there has been much recent debate surrounding the notion of ecological resilience. This review confirms that the literature on this topic is both large and varied, but some progress has been made in clarifying the main theoretical and conceptual issues related to the link between ecological functioning and resilience. Given the focus of this study, we consider specifically the extent to which resilience can be assessed by some measurable quality of ecosystems. The goal is to determine whether such criteria have been identified in recent work, and whether they can be used to specify some minimum level (or threshold) of ecological functioning for our natural capital assets.

The literature review confirms that the measurement of resilience has emerged as an important topic for discussion. Brand et al. (2007) provide a useful review of the different meanings ascribed to the term 'resilience'. 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 by Gunderson and Holling (2002), Walker (2002, 2006), Folke et al. (2004) and 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.

Thus in the recent ecological literature, resilient ecosystems are seen as those which are best able to absorb disturbances, exhibit self-organization and show the capacity for learning and adaptation. This expansion and congruence of several themes around the notion of 'resilience' is also confirmed by the recent work of Janssen et al. (2006) and Janssen (2007). These two studies 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. As a consequence one many find many different meanings in the literature dealing with ecosystem resilience.

Brand and Jax (2007) note that the 'vagueness and malleability' of the resilience concept is both an advantage and a problem. On the plus its openness has meant that it has fostered greater trans-disciplinary debate and enlarged the understanding of 'socio-ecological systems' between different research communities. Thus increasingly these authors note that the criteria thought to promote resilience in ecosystems include ecological, social and economic characteristics that tend to enhance the capacity of systems to cope with, adapt to, and shape change, and adapt to uncertainty and unforeseen events. The disadvantage of such a broadening of meaning of resilience is that it is difficult to apply and measure.

For greater clarity 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 its meaning must, they argue, be tighter. Those using the term should be specific about what the idea of resilience is being applied to, and how changes in resilience are to be measured. Following Carpenter et al. (2001) they advise that to apply the concept one must clearly specify 'resilience of what to what'; when used in this way, Brand and Jax (2007) suggest that the terms 'ecological resilience' or "ecosystem resilience" might be used.

Brand and Jax (2007) highlight that a number of 'hybrid' definitions of resilience have begun to emerge in recent debates. Such a development is of particular interest in the context of the present study, because they not only make some progress towards operationalising the concept, but also specifically connect the concept to the output of ecosystem services and the conditions under which the output of such benefits can be sustained. Thus reliance has also been defined as:

- 'The underlying capacity of an ecosystem to maintain desired ecosystem services in the face of a fluctuating environment and human use' (Folke et al., 2002); and,
- 'The capacity of social-ecological systems to absorb recurrent disturbances…. so as to retain essential structures, processes and feedbacks' (Adger et al., 2005).

A feature of the recent literature is, the that the concept of ecological resilience is now central to the questions about whether changes in ecological functioning (or supporting services) can alter the capacity of systems to withstand or absorb disturbance, or to respond to external drivers in an adaptive way. Thus the reference base created during this work was investigated to determine how many of the papers dealt with the problem of ***measuring resilience*** and what links this had to the supporting services.

One hundred and fifty references that referred some aspect of the measurement or assessment of resilience could be identified in the bibliographic database created by this study. The papers were classified according to the criteria set out in Table 2, which assessed such characteristics as whether they were intended as a review, a theoretical exploration of the concept, a modelling study or included empirical data. In addition, the studies were also classified in terms of the type of ecosystem being considered, whether the publication mainly considered resilience from an ecological perspective or a socio-ecological one. Clearly, for each criterion papers could be placed in more than one category. Most looked at either ecological resilience specifically or ecological resilience together with the socio-ecological dimensions of the theme; a limited number were partly or wholly empirical, some combining theoretical discussions with model-based analysis.

One of the most widely cited papers was that of Cumming et al. (2005) who argued that if we are to operationalise the notion of resilience, then we must find ways of measuring whether system identity is maintained. 'Identify', they suggest, is dependent on: the components that make up the system and the relationships between them over space and time, as well as their capacity for 'innovation' and 'self-organization'. Although the focus of their work was socio-ecological rather than strictly ecological, their discussion about how to measure resilience provides some important insights that carry over to other areas. They propose *"… if system identity is maintained over the time horizon of interest, under specified conditions and perturbations, we can term the system resilient"* (Cumming et al. 2005, p987).

If system 'identity' is therefore seen as the profile of ecosystem service output, then the definition of resilience suggested by Folke et al. (2002), as the capacity of ecosystems to maintain desired levels of ecosystem services, becomes more obviously measurable. However, though service output may partly depend upon underlying biophysical structure and processes, the development of the surrogate measures of resilience sought by Cumming et al. (2005) can only be fully achieved by understanding human decisions and values. Human values are the things that determine the 'what' component in the formulation of resilience suggested by Carpenter et al. (2001). Answering the 'to what' question is then a matter of understanding the structure and dynamics of the systems that provide them, and the direct and indirect drivers of change that may impact upon them.

For the restricted purposes of this study we set aside the question of how to determine the 'identity aspect' of the resilience problem, and focus mainly on the studies of underlying ecosystem structure and functioning, and how change may enhance or undermine the capacity of systems to sustain the output of one or more ecosystem services.

The review has identified that there is a growing body of empirical literature which suggests that high species diversity can potentially enhance the level of ecosystem service output and system stability. Thus Balvanera et al. (2006) have recently undertaken an extensive meta-analysis of experimental studies involving the manipulation of different components of biodiversity and the assessment of the consequences for ecosystem processes. Their analysis showed that in general, evidence supports the contention that for various measures of biodiversity there is a positive association with a number of different measures of ecosystem functioning, including primary and secondary productivity and nutrient cycling (Figure 4). The small number of negative relationships reported in the literature, tended to be associated with studies which measured properties at the population (individual species density, cover or biomass), rather than the community level

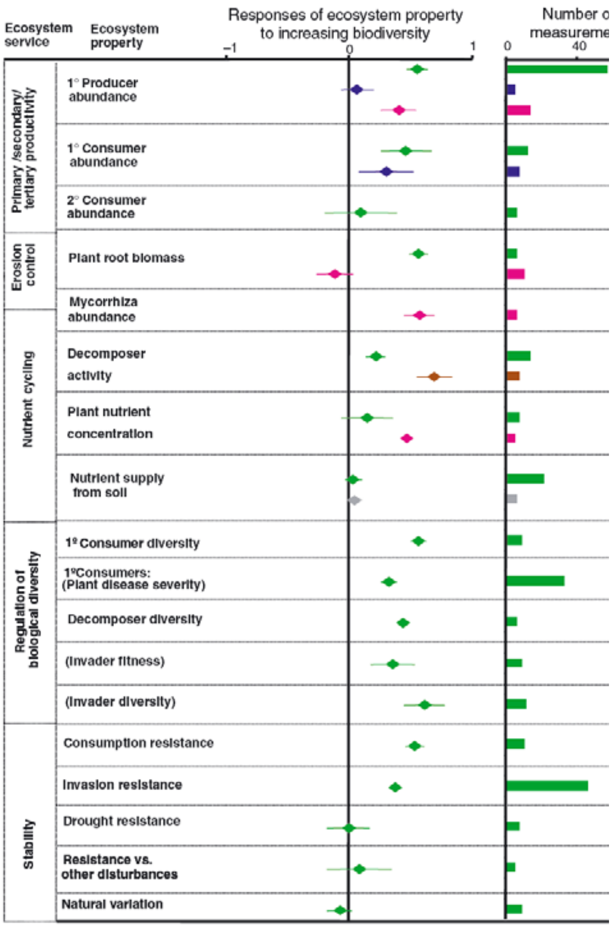


Figure 4: Magnitude and direction of biodiversity effects (shown are mean values and SE of normalized effect sizes Zr, weighted by the reciprocal of the variance of the individual Zr-values) and number of measurements available for ecosystem properties organized into ecosystem services. Coloured bars show differential effects of trophic level manipulated: green, primary producers; blue, primary consumers; pink, mycorrhiza; brown, decomposer; grey, multi-trophic (multiple levels simultaneously manipulated). Ecosystem properties shown in parentheses were considered of negative value for human well being, and thus opposite of effect sizes are shown (after Balvanera et al., 2006)

characteristics (e.g. density, biomass, consumption). The strength of the relationship between biodiversity and the measure of ecosystem function tended to be strongest at the community rather than the whole ecosystem level.

The analysis of (Balvanera, 2006) suggests that more diverse systems have greater temporal stability, as well as greater resistance to external forces such as nutrient perturbations and invading species. Most of the studies that considered stability aspects, dealt with resistance of the ecosystem to invasion of invasive species. The effects of increasing biodiversity on 'consumption stability' appeared to be the strongest of the criteria considered; consumption stability is the effect of variations in biodiversity at one tropic level on the next. The positive effects of changing species diversity on drought resistance and other kinds of disturbance was, however, less marked, and those studies which looked at 'natural variations' in ecosystem properties, as opposed to those arising from experimental manipulations, showed a negative relationship to species diversity.

A feature of the papers that focused on the problem of measuring resilience was that the range of ecosystem characteristics considered as potential indicators was diverse, but that it is useful to recognise two basic groupings of measures, namely those that record the ability of systems to resist disturbance and those which look at the speed at which systems recover. This distinction can be illustrated by one of the most widely cited publications dealing with the measurement problem, namely that by Hughes and Stachowicz (2004). These workers looked at the impact of *genetic* diversity on the resilience of manipulated eel grass communities (*Zostera marina*) grazed by geese; *Zostera* is an important habitat forming species of shallow temperate estuaries, worldwide. These authors noted the work on species diversity and ecosystem processes, and the emerging view that inter-group functional diversity between mainly affected the level of ecosystem processes, whereas intra-group diversity was more important in relation to system constancy. To test this idea they looked at the extent to which the genetic diversity within mono-specific stands of eel grass affected two components of resilience, namely the resistance of the system disturbance and its rate of subsequent recovery. The manipulative experiments showed that genetic diversity of the *Zostera* stands mainly affected it resistance to disturbance rather than its speed of recovery.

Table 13 summarises a further 29 studies that consider some aspect of the measurement of resilience and the factors that might affect it; on close inspection 17 were found to be relevant and available. A feature of these studies is that while a number consider both resistance to disturbance and rate of recovery as separate components of resilience, the surrogates used differ considerably. The studies also vary in extent to which measures are looked at changes of ecosystem properties over time.

For example, Fischer et al. (2007) devised indices of within group and between group redundancy in their study of bird communities in southeast Australia to measure resistance and recovery. They found that these indices were lower at species poor sites, but the study did not compare the temporal variability in the face of disturbance. By contrast, Orwin and Wardle (2004), looked used the temporal changes exhibited by soils to construct measures of the susceptibility of experimental systems to disturbance and the rate at which they recovered, but did not relate the outcomes empirically to any underlying ecosystem property; these workers simply noted that the soils studied showed differences in their behaviour.

Table 13: Overview of material identified by the literature review that considered some aspect of the measurement of resilience

Author	Title	Ecosystem or component	Implications for ecosystem services	Resistance	Recovery	Outcome
Bergkamp (1998)	Hydrological influences on the resilience of Quercus spp. dominated geoecosystems in central Spain	Mediterranean Oak Forest	None specified	Not explicitly measured	Resilience (recovery) assessed by comparison to control site	Shows that resilience (recovery) may be a function of landscape context (access to water following disturbance)
Bigelow et al. (2004)	Enhancing nutrient retention in tropical tree plantations: No short cuts	Disturbed Tropical Forest	None specified	Not explicitly measured, but magnitude of change in NO_3^- concentration gives insights into magnitude of disturbance	Return to low levels of NO_3^- typical of undisturbed forest used as indicator	Most frequently disturbed sites showed slower return to conditions typical of undisturbed sites.
~~Calvo et al. (2002)~~	~~Secondary succession after perturbations in a shrubland community~~					
~~Clark et al. (1979)~~	~~Lessons for ecological policy design: A case study of ecosystem management~~					
Cordonnier et al. (2008)	Permanence of resilience and protection efficiency in mountain Norway spruce forest stands: A simulation study	Simulated Norway spruce forest stands	Protection against rock-fall or snow avalanche	Not assessed	Index of regeneration and recruitment dynamics	Greater recovery and protection in uneven aged stands with high diversity of diameter classes.
DeClerck et al. (2006)	Species richness and stand stability in conifer forests of the Sierra Nevada	Conifer forests of the Siera Nevada	Provision of ecosystem services associated with forest systems	Assessed by stand variability of productivity	Speed of return to pre-disturbance productivity following drought	Moderate relationship between speed of recovery and species diversity, but not for resistance.
~~Ellingson et al. (2000)~~	~~Soil N dynamics associated with deforestation, biomass burning, and pasture conversion in a Mexican tropical dry forest~~					
Fischer et al. (2007)	Functional richness and relative resilience of bird communities in regions with different land use intensities	Diversity of bird communities from agricultural landscapes in SE Australia	Functioning of bird communities may link to pollination and pest control as well as cultural services.	Measured through an index of within-scale redundancy	Measured by cross-scale redundancy	Relative resilience reduced at species-poor sites
Flum et al. (1987)	The effects of three related amides on microecosystem stability	aquatic microcosm communities	None explicitly examined	Magnitude of disturbance following a toxicological event	Speed of recovery following a toxicological event	Resistance and recovery are positively associated
Fox et al. (2007)	Quantifying herbivory across a coral reef depth gradient	***Not available***				

Table 12, cont.: Overview of material identified by the literature review that considered some aspect of the measurement of resilience

Author	Title	Ecosystem or component	Implications for ecosystem services	Resistance	Recovery	Outcome
Gallet et al. (2002)	Long-term effects of trampling on Atlantic Heathland in Brittany (France): resilience and tolerance in relation to season and meteorological conditions	Heathland	Tourist use of heathland sits	Magnitude of impact of trampling pressure	Speed of recovery following trampling impact	No significant differences in either resistance or resilience between heathland communities – communities more susceptible to time of disturbance events
Griffiths et al. (2005)	Biological and physical resilience of soil amended with heavy metal-contaminated sewage sludge	Soil	Bio-remediation,	Change in short-term decomposition under transient and persistent stresses	Recovery of short-term decomposition under transient and persistent stresses	Different sludge types varied in impact, but link of response to microbiological communities not made.
Hughes et al. (2004)	Genetic diversity enhances the resistance of a seagrass ecosystem to disturbance	Genetic diversity of Zostera stands in temperate estuarine environments	Habitat for fishes and invertebrates; plays a role in nutrient cycling and sediment stabilization	Magnitude of disturbance (biomass loss)	Speed of recovery	Resistance to disturbance found to be function of genetic diversity, not recovery speed.
~~Leggett (2006)~~	~~Does land use matter in an arid Environment? A case study from the Hoanib River catchment, north-western Namibia~~					
McLaren et al. (2003)	Coppice regrowth in a disturbed tropical dry limestone forest in Jamaica	Tropical dry forest, Jamaca	None examined explicitly, but has implications for regeneration strategies – coppice compared to germination	Not examined	Per cent diameter recovery	High rates of re-growth and differences between species– but no implications explored at community level
~~Nystrom et al. (2008)~~	~~Capturing the cornerstones of coral reef resilience: linking theory to practice~~					
Orwin et al. (2004)	New indices for quantifying the resistance and resilience of soil biota to exogenous disturbances	Soil systems	Soil processes related to abundance and composition of soil biota	Magnitude of change brought about by disturbing factor	Recovery time for a standardised by amount of initial disturbance	Differences between soils detected; no prediction made in relation to other system properties
~~Pérez España (2003)~~	~~Ecological importance of snappers in the stability of modeled coastal ecosystems~~					
~~Perrings et al. (2004)~~	~~Conservation in the optimal use of rangelands~~					

Table 12, cont.: Overview of material identified by the literature review that considered some aspect of the measurement of resilience

Author	Title	Ecosystem or component	Implications for ecosystem services	Resistance	Recovery	Outcome
Potts et al. (2006)	Resilience and resistance of ecosystem functional response to a precipitation pulse in a semi-arid grassland	Semi-arid grasslands	None explored	Magnitude of disturbance measured in terms of plant physiological and ecosystem gas-exchange measurements as state variables	Speed of recovery following disturbance measured in terms of plant physiological and ecosystem gas-exchange measurements as state variables	Reduction in ecosystem functional resistance in plots planted with the non-native species.
Rice et al. (1998)	Exotic weed control treatments for conservation of fescue grassland in Montana	Grasslands, Montana	None considered	Not considered	Change in community similarity following disturbance compared to pre-treatment phase	No explicit link made to factors promoting resilience
~~Roth et al. (2009)~~	~~Small mammal herbivory: Feedbacks that help maintain desertified ecosystems~~					
~~Selmants et al. (2003)~~	~~Understory plant species composition 30-50 years after clearcutting in southeastern Wyoming coniferous forests~~					
Slocum et al. (2008)	Use of experimental disturbances to assess resilience along a known stress gradient	Saltmarsh communities	Response of communities along a stress gradient (sedimentation)	Measure of impact of lethal and non-lethal disturbance in terms of magnitude of resulting change to stand structure	Speed of recovery following disturbance	Resistance and recovery were strongly and positively affected by sediment deposition
~~Vitale et al. (2007)~~	~~Resilience assessment on Phillyrea angustifolia L. maquis undergone to experimental fire through a big-leaf modelling approach~~					
~~Wardwell et al. (2008)~~	~~A test of the cross-scale resilience model: Functional richness in Mediterranean-climate ecosystems~~					
Whitford et al. (1999)	Using resistance and resilience measurements for “fitness” tests in ecosystem health	Dry grasslands	None examined explicitly	Magnitude of change following disturbance along a stress gradient (grazing intensity)	Magnitude of change following disturbance along a stress gradient (grazing intensity)	
Zacheis et al. (2009)	Resistance and resilience of floating mat fens in interior Alaska following airboat disturbance	***Not available***				

It is also apparent from a reading of these materials identified in this study that many of them looked at resilience as an issue by itself or in the context of the dynamics of a particular ecosystem, and not from the perspective of ecosystem services. Although the relevance of change in resistance to disturbance or speed of recovery to potential service output could be inferred, only in the more recent studies was the link made explicitly. This characteristic has implications for any future systematic review, in that some interpretation by the analyst would be required to ensure that the insights from this older body of literature are drawn out. Nevertheless, given that papers identified is a sample using the material generated by only two search engines, it does seems that a basis for a more detailed meta-analysis, particularly if model-based studies were included.

Inspection of the materials summarised in Table 12 also suggest that in any future meta-analysis some consideration of spatial and temporal context would also be valuable. The results of several studies suggested that for a single ecosystem type, both resistance to disturbance and speed of recovery may vary along a stress gradient, or change seasonally. Thus Slocum et al., (2008) found that for saltmarsh communities both aspects of resilience appeared to be enhanced in where sedimentation rates were highest. Elsewhere, (Bergkamp, 1998) found that for oak-dominated woodlands in central Spain, speed of recovery following fire or clear-cut was a function of the position of the stand in the landscape, which appeared to control access to ground water. Finally, Gallet and Rozé (2002) discovered that while there were no significant differences in either resistance or recovery speed between heathland communities in Brittany, communities appeared to be susceptible tourist disturbance at certain times of the year.

Thus the following conclusions emerge from the review of the subset of literature dealing developing measures of resilience, and the question of whether these measures link to what are currently described as ecological functions or supporting services:

- Although the way the resilience concept has been used varies widely, in the ecological context, two distinct themes emerge around the ideas of resistance to disturbance and speed of recovery. In any future meta-analysis it would be essential to distinguish these two aspects clearly. While ‘resilience’ might be a term used to locate review material, subsequent analysis should identify which of these themes are being discussed, and classify the paper accordingly. If the term ‘resilience’ is used at all, it should be made clear what aspect of aspects of ecosystem dynamics is being referred to.
- The majority of the material identified either provided a review of the concept or attempted to develop the underlying theory. However, there is a body of empirical work that can potentially be used a meta-analysis designed to test relationships between the structural or functional properties of ecosystems and the resistance of systems to disturbance or speed of recovery.
- The range of ecosystem attributes used to construct resilience surrogates in these empirical studies is broad, and no universally accepted measure exists. This makes comparisons difficult. The review of the empirical studies provided here does, nevertheless, suggest that a cross-tabulation of studies using the two dimensions of resilience (resistance and recovery speed) and the biotic and aboitic factors that were hypothesised to control these aspects of ecosystem behaviour would be a next step.
- Measures of resilience (resistance to disturbance and speed of recovery) are generally used in a comparative fashion. Studies mostly looked at the ecosystem dynamics

exhibited by different ecosystem configurations across sets of sites or stands, or that result from different natural or experimental events or interventions. Although, in the experimental studies examined formal 'experimental controls' were not always used, the contrasts between sites or within sites over time does offer the prospect of using constructing some kind of 'comparator' in any future meta-analysis.

- The age of the literature identified by searching on 'measurement of resilience' means that the link to ecosystem service issues is often not made, and so some interpretation of results would be required in any future study. It is clear from the more limited contemporary literature that the link *can* be traced, however, and so a further and more detailed analysis may be one way of showing the relevance of this older material to current debates.

The major methodological point that emerges from this pilot review is that resilience is not a general ecosystem characteristic, *but a set of dynamic behaviours exhibited by particular variables under specific sets of conditions*. We need to specify what those variables are, and the conditions under which they are being considered or compared (cf. Carpenter et al., 2001). Characterisation of an ecosystem in terms of service outputs is clearly one way in which the essential features or 'identify' of an ecosystem might be represented or agreed upon. The research challenge that confronts us is to understand how stable the delivery of these 'final' products is, and how sensitive these outputs are to variations in underlying ecosystem functioning. The current literature appears to contain only limited evidence on which to base any conclusions that might guide policy in this area.

6.3 Ecological functioning, thresholds and limits for ecosystem service output.

If we acknowledge that there are intermediate or supporting services (functions) that underpin the delivery of provisioning, regulating or cultural services, then it is important to examine whether there are limits or thresholds associated these basic ecological processes that may constrain what ecosystems can potentially deliver to people.

Our review of the measurement problem suggests that there is evidence, albeit limited, to suggest that there is a strong link between basic ecosystem properties such as species richness and functional diversity and a range of ecosystem attributes that we now recognise as 'supporting services'. In addition to the review by (Balvanera, 2006) noted above, the recent report by EASAC provides a further material to support this contention (EASAC, 2009). The issue that emerges from our review is not so much that there is doubt that such relationships exist, but that we lack an understanding about how sensitive service output is to changes in these underlying functions. The situation may be illustrated by reference to Figure 5, which illustrates three hypotheses describing the potential relationship between biodiversity and ecosystem function. Curves A and B are those suggested by Schwartz et al. (2000); a third has been added to extend the discussion.

From their review of empirical studies and modelling exercises, Schwartz et al. (2000) concluded that few studies supported the hypothesis that there was a simple, direct linear relationship between species richness and some measure of ecosystem functioning like productivity, biomass, nutrient cycling, carbon flux or nitrogen use (Curve A). Instead the evidence available to them suggested that these functions did not increase proportionally above some ceiling that represented a fairly low proportion of the local species pool (Curve B). This conclusion is not really at variance with the more recent work of (Balvanera, 2006), who argue that on the basis of current evidence there is a direct

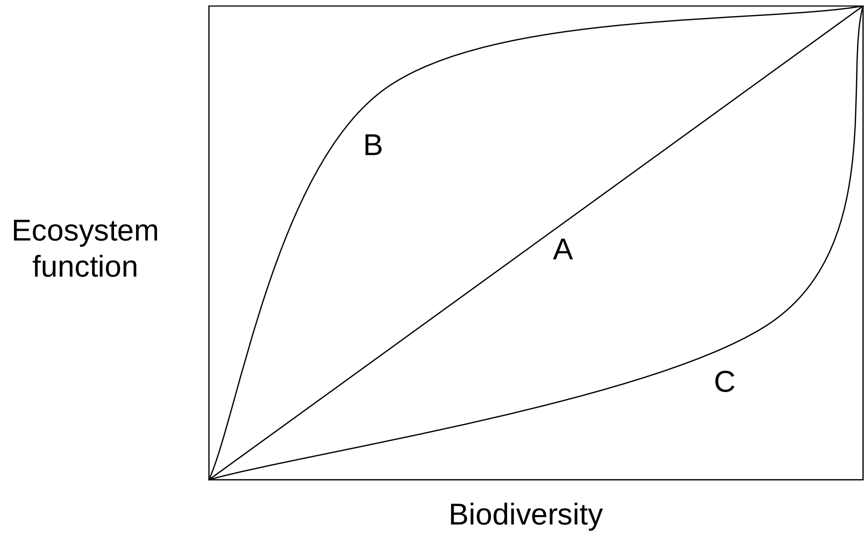


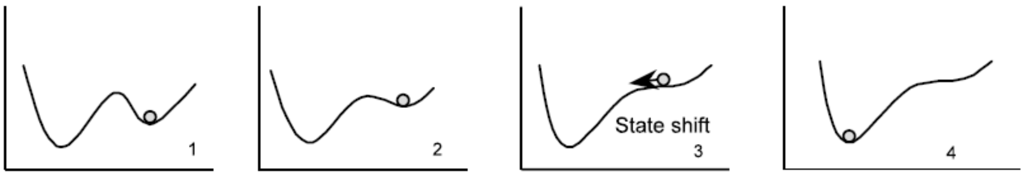
Figure 5: Potential relationships between biodiversity and ecosystem functioning (after Schwartz et al. 2000, and Kremen, 2005)

relationship, but merely that we are generally unclear about the what form it takes. The key research challenge that emerges from recent discussions is to determine the extent to which non-linearities exist and what might cause them (cf Curve C).

A number of explanations might underlie the 'saturation effect', including the notion that there are redundancies wired into the system, such that loss of one component of biodiversity can compensate for another – up to a point. This review confirms that a number of workers have commented on the 'insurance value' of biodiversity, most notably Deutsch et al. (2003). These authors suggested that functional diversity in ecosystems could be viewed as providing as 'natural insurance capital' since it effectively spreads risks in the face of uncertainty and secures the important source and sink functions that ecosystems provide to people. Similar arguments about there being a critical level of natural capital necessary to sustain human well-being have also been made by Ekins, (2003). The difference between critical levels of natural capital needed to perform these essential functions for people and the biosphere, and the current situation defines, they suggest, the 'sustainability gap'. Unfortunately the material uncovered by the present literature review provides only a limited understanding of what in, general terms, these 'sustainability standards' might be.

One feature that does, however, emerge from the review of current debates about critical levels of ecosystem functioning is concern with the identification of potential 'regime shifts' or thresholds, which arise when ecosystem exhibit alternative stable states; these issues are once again bound up with discussions about the nature of resilience.

Thus far we have considered resilience to incorporate two distinct ideas: how resistant a system is to disturbance and how fast a system can recover following some disturbance event. A number of papers identified in our review also argue that resilience is the magnitude of disturbance that can be tolerated *before an ecosystem moves into a different state with a different set of controls* (e.g.; Carpenter, 2006; Muradian, 2001; Scheffer et al., 2001).



coral dominance	overfishing, coastal eutrophication	disease, hurricane	algal dominance
clear water	phosphorous accumulation in soil and mud	flooding, warming, overexploitation of predators	turbid water
grassland	fire prevention	high rainfall and intense grazing	shrub-bushland

Figure 6: Systems exhibiting multiple stable states and threshold responses. The sets of graphs show the effects on changing conditions on each of the ecosystems (1 through 4). The individual graphs show the shape of the stability landscape for a given state variable (coral abundance, water quality and grassland condition); these landscape show how the system would change if displaced from an equilibrium point (a 'valley bottom') and how large a displacement from an equilibrium point would be needed move the system to an alternative stable state (diagram after Deutsch et al. 2003)

The idea of a regime shift is often illustrated by reference to a diagram such as that shown in Figure 6, taken from Deutsch et al. (2003). The three ecosystems described have all been discussed widely in the literature as theoretical examples, although there is some empirical data to back up the interpretations made. Thus in the case of the reef system the pristine state characterised by the dominance of living, healthy coral is relatively stable, able to return to the original equilibrium state rapidly following disturbance. Moving from left to right across the diagram (1 through 4), the effects of overfishing or eutrophication gradually changes the domain of stability, making it more shallow, so that disturbances against which once the reef system was resistance can flip the system in to an alternative stable state, namely one in which algal species are dominant (state 4). Nyström et al. (2000) provide a succinct review of these kinds of change, and has subsequently identified the particular characteristics of coral ecosystems that provide the 'cornerstones' of their resilience in their pristine state (Nystrom et al., 2008). It is proposed that these cornerstones be used as operational indicators to predict or recognize vulnerability before disturbance occurs that may lead to abrupt phase shifts. The recent review of Harborne et al. (2006) provide extensive review of empirical studies that provide insights into the susceptibility of coral and other coastal habitats in the Caribbean to different kinds of disturbance go on to trace susceptibility both to locational characteristics and functional properties. This work illustrates that a number of limiting values can be identified that can be used to identify the susceptibility of different ecosystems to disruption.

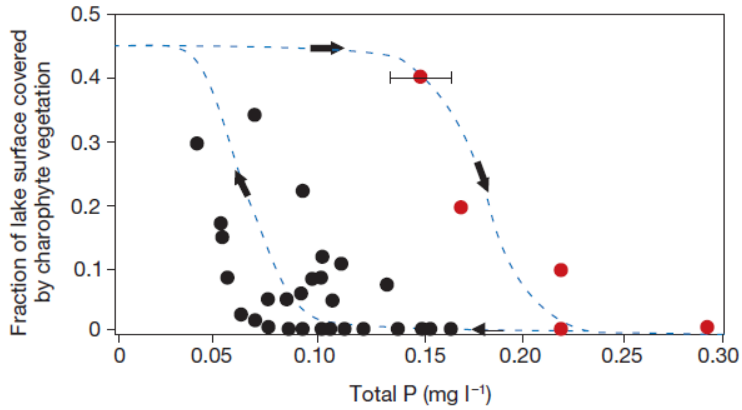


Figure 7: Hysteresis in the response of charophyte vegetation in the shallow Lake Veluwe to increase and subsequent decrease of the phosphorus concentration. Red dots represent years of increasing nutrient loads in the late 1960s and early 1970s. Black dots show the effect of gradual reduction of the nutrient loading leading eventually to the restoration of the initial state in the 1990s. From {Scheffer, 2001 #1868}

In the case of the lake system described in Figure 6, eutophication may transform the stable clear-water condition to a turbid state, from which is more difficult to recover. The shift to turbid conditions clearly transforms the range of ecosystem services that such systems can potentially deliver. There have been a number of published empirical studies documenting these kinds of threshold effect, including the data cited by Scheffer, (2001) for Lake Veluwe in the Netherlands. Figure 7 shows the effects of progressive nutrient loading on this system in terms of the fraction of the lake surface covered by charophyte vegetation. Between the late 1960s and the early 1970s the lake condition hardly changed from its natural state as nutrient loading increased, until a threshold was reached beyond which the cover of charophyte vegetation fell rapidly, and turbid conditions became established. Following efforts to reduce nutrient loading from the 1970s onwards, previous levels of cover by charophyte vegetation were not restored until phosphorous concentrations fell far beyond the threshold that triggered the regime shift in the first place.

In addition to the examples from coral and lake ecosystems, other widely reported threshold effects have been reported from rangeland systems, where grazing and fire management practices have been found to trigger the shift to scrub vegetation (Figure 6, see also Perrings and Walker, 2004). The interesting insight that all these case studies provide is that in relation to discussions about resilience, the degraded states (algal dominated corals, turbid lakes, scrub-bushland) can be as resistant to change than the natural state, or even more so. In many respects the scientific challenge is not to predict what particular kinds of ecosystem structures produce particular dynamic characteristics, but to discover the resilience characteristics (resistance, speed of recovery, domain of stability etc.) of the ecosystem states that one seeks to sustain or restore. This may be difficult, and as Carpenter et al. (2005) note, in practical terms probably the only way to identify a threshold is to cross it.

From the preliminary screening of the papers dealing with the minimum levels of ecological functioning and the identification of thresholds, the following conclusions therefore emerge:

- Although a number of theoretical and empirical studies have been published describing threshold effects in ecosystems, the volume of material dealing specifically with the question of ecosystem services, and the minimum level of ecosystem functioning required to deliver them, is still limited. From the existing case study material one may observe that as thresholds are crossed, the level of ecological functioning and the output of services is likely to change, but complete cause-effect analyses are rare. There is little systematic information available across the range of ecosystem types that are important, for example, in the UK (other than for aquatic).

- Nevertheless, it is clear that from a theoretical point of view, that the identification of thresholds is one way of defining the minimum levels of ecological functioning that must be sustained in the face of different drivers of change. Thus Erftemeijer et al. (2006), for example, have for submerged, eel grass species, identified critical levels of sedimentation and light required for their survival, and used these to make recommendations on the framing of regulations for dredging. Ralph et al. (2007) provide a more extensive review for the impact of light levels for seagrasses in general. Using such information the costs of damage by dredging or other impacts on the services associated with these ecosystems could be calculated and an estimate of the minimum levels of functioning made.
- The time available for screening of papers during this study was, however, insufficient to determine whether there is a wider body of information available on critical limits for other ecosystem types, since it is apparent even from the restricted number of publications found that limits can be discussed without reference to the existence of thresholds or regime shifts (e.g. Pearce et al., 2008). It is interesting to note that the number of publications dealing with critical loads was, however, limited and so some further refinement of the search protocols in this topic are may be beneficial.

The major methodological point that seems to emerge from this aspect of the pilot review, is that while identification of threshold responses can be useful in identifying the minimum level of ecological functioning that must be maintained to sustain the output of ecosystem services, a more refined approach probably needed that takes account of different kinds of response patterns.

The study recently published by Müller et al. (in press) illustrate the kinds of analysis that might be now be possible using a mixture of review, modelling and/or empirical investigation (Figure 8). These workers use a suite of basic ecological functions (supporting services) to define ecosystem integrity of wetland systems. They show how they change along different succession pathways, some of which are characterised by threshold responses that are difficult to reverse, and others which represent more continuous and reversible transitions. Müller et al. (in press) argue that the profile of ecosystem services delivered by these systems change along these pathways as a result of changes in these underlying ecological functions. In this study the notion of integrity is clearly equivalent to the idea of identity discussed above, and could be used to characterise a broader set of ‘limits’ for ecological functioning once the relationship they have to the output of provisioning, regulating and cultural services is better understood.

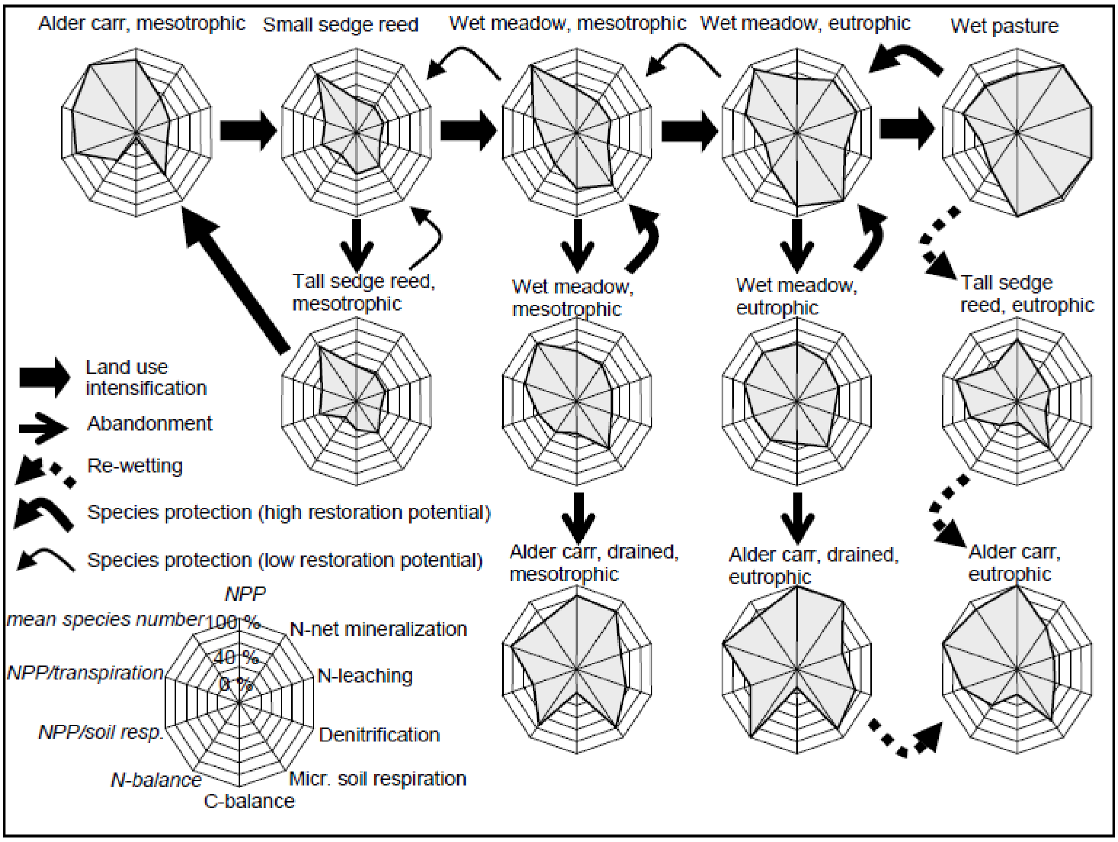


Figure 8: Sequential indicator values showing change in ecosystem integrity as a result of during land use intensification, and subsequent succession following abandonment in different wetland systems after Müller et al. (in press).

6.4 The costs of maintaining the minimum levels of ecological functioning required to sustain ecosystem resilience

The final topic area considered in this pilot review was the extent to which the costs of ecosystem maintenance can be estimated on the basis of the evidence currently available. The search strategy used here focussed particularly on the literature dealing with the issue of ecosystem accounting, because the volume of literature dealing with cost issues in the context of ecosystems was very large. The link to ecosystem accounting is, however particularly relevant, given the international revision of current approaches and the growing interest in estimating the cost of consumption of natural capital. Although the number of papers identified in relation to these issues was small, they do, nevertheless, demonstrate that progress is being made in this area.

Thus Boyd, et al. (2007) has argued for a standardised approach to environmental accounting units, and suggested how we might take account of the non-market value of nature in greening GDP. Bartelmus (2009) has also considered what methodological developments might be needed in the context of the SEEA revision, using the approach has estimated that the world total of environmental depletion and degradation costs as about 6% of world GDP or 3 trillion US$ in 2006; this analysis suggests that these costs have more than quadrupled over the period 1990–2006. However, the maintenance costs considered by this study only cover the non-sustainable, overuse of environmental sinks, such as the atmosphere, and exclude important natural resources such as soil, water, fish and genetic resources. As Bartelmus (2009) notes, the handling of ecosystem services in such accounting is particularly problematic.

Mäler et al (2008, 2009) have recently considered the general problem of accounting for sustainable development, and how ecosystem services can be included in the analysis. They argue that while many of the techniques are in place to make valuations of services and include them in accounts, such assessments are very 'case sensitive'. They base their conclusions on a range studies, dealing with issues related to fisheries, use of topical mangroves for shrimp production, and the role of pollinators in the production of cash crops, and suggest that currently it is probably not possible to build 'a standardised model for a wealth-based accounting system for ecosystems' (Mäler et al., 2008, p.9506). A more targeted approach dealing with the specifics of individual ecosystems is recommended.

Walker and Pearson (2007) has also considered the problem of constructing environmental accounts that include consideration of ecosystem services, and have argued that a 'resilience perspective' is urgently needed in such work. Noting that systems can exhibit alternative stable states, and that these different states can be characterised by their ability to deliver ecosystem services, Walker and Pearson (2007) argue that the value of resilience can therefore be estimated using insights about the change in benefits gained from this system before and after a regime shift. The idea is illustrated by reference to the problem of rising water tables in the Goulburn-Broken Catchment in Southeast Australia.

The major methodological point to emerge from the review of materials considered here is that there are few estimates of the costs of maintaining natural capital and the associated supply of ecosystem services. Thus in contrast to the other areas considered there is probably little value in considering a full systematic review in this topic area. However, methodologies are developing and may usefully be informed by developing further, targeted case study material that could be used to build on the insights developed in the other two topic areas considered.

6.5 Conclusions and the case for a full systematic review

The primary aim of this study has been to examine the case for making a full systematic review to find out whether it is possible, on the basis of current knowledge, to estimate either in physical or monetary terms the cost of maintaining the ecosystem functions that underpin to people's well-being. The study has broken this broad question into three distinct areas, concerning the problem of measuring ecosystem services and the resilience of ecosystems, the identification of thresholds and environmental limits, and the task of environmental accounting. The pilot review suggests that there is probably sufficient literature to undertake a full review in relation to the first two themes and that the results could usefully inform the development of more empirical studies that aim to explore and identify the costs of ecosystem maintenance.

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