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FORUM

A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead

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Summary

1. Ecosystem services are defined as the benefits that humans obtain from ecosystems. Employing the ecosystem service concept is intended to support the development of policies and instruments that integrate social, economic and ecological perspectives. In recent years, this concept has become the paradigm of ecosystem management.

2. The prolific use of the term 'ecosystem services' in scientific studies has given rise to concerns about its arbitrary application. A quantitative review of recent literature shows the diversity of approaches and uncovers a lack of consistent methodology.

3. From this analysis, we have derived four facets that characterise the holistic ideal of ecosystem services research: (i) biophysical realism of ecosystem data and models; (ii) consideration of local trade-offs; (iii) recognition of off-site effects; and (iv) comprehensive but critical involvement of stakeholders within assessment studies.

4. These four facets should be taken as a methodological blueprint for further development and discussion. They should critically reveal and elucidate what may often appear to be ad-hoc approaches to ecosystem service assessments.

5. *Synthesis and applications*: Based on this quantitative review, we provide guidelines for further development and discussions supporting consistency in applications of the ecosystem service concept as well as the credibility of results, which in turn can make it easier to generalise from the numerous individual studies.

Key-words: conservation policy, ecosystem functioning, ecosystem management, ecosystem service assessment, environmental values, natural capital, natural resource management

Introduction

Increasing human population size, economic growth and global consumption patterns place pressure on environmental systems (Vitousek 1997); thus, the provisioning of ecosystem goods and services is affected. Ecosystem services are defined as the benefits that humans obtain from ecosystems; although the relationship between these services, human welfare and the monetisation of ecosystem services is not a new concept (Westman 1977), it has attracted more attention in recent years (Fisher, Turner & Morling 2009). The Millennium Ecosystem Assessment (MA 2005a) contributed substantially in bringing forward the ecosystem services concept as a policy tool to achieve the sustainable use of natural resources. The MA made the case for a holistic research approach, which means that ecological, economic and institutional perspectives are integrated to produce insights into mid- to long-term human impacts on ecosystems and the welfare effects of management policies. The MA did not, however, deliver a fully operational method to implement the concept, which would assist policy makers and provide policy oriented researchers with sufficient tools for taking provisioning of natural goods and services into account (Armsworth *et al.* 2007). As a result, the ecosystem service label is currently used in a range of studies with widely differing aims. This variation presents a problem for policy makers as well as researchers because it makes it difficult to assess the credibility of assessment results and reduces the comparability of studies. To strengthen the political relevance of the concept, we need to improve the scientific basis for its practical implementation (Ash *et al.* 2010).

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The topic of how to implement the ecosystem service assessments has been taken up by several previous publications. Boyd & Banzhaf (2007) and Fisher, Turner & Morling (2009) focus on the quantification of ecosystem services and their value to stakeholders and suggest various classification schemes. Cowling *et al.* (2008) recommend mainstreaming the concept in the assessment, planning and management phases of policy-making. Turner & Daily (2008) propose that ecosystem service research should address the various stages in decision-making, from problem identification to policy evaluation and capacity building. They also make a plausible argument that the major hurdles preventing the concept from being operational are a lack of information at scales relevant to decision-making, a limited practical knowledge of institutional decision and implementation structures and a scarcity of models that align economic incentives with conservation.

These contributions are valuable steps supporting the ecosystem service research community with conceptual input. Our interest here is to provide a concise summary and to analyse recent achievements in ecosystem service research based on a quantitative review. Based on this, we have tentatively identified core facets of ecosystem service studies, which should help to structure further discussion, improve assessments and help to make results comparable.

Quantitative review of ecosystem services studies

Our review is based on publications found through an ISI Web of Knowledge search of articles up to 2010 with the terms 'ecosystem service', 'ecosystem services' or 'ecosystem valuation' in the title, which resulted in 460 studies in the past 20 years. In doing so, we omitted studies published outside the focus of the Web of Knowledge, e.g. the sub-global assessments (MA 2005b) or projects led by NGOs, such as Conservation International (http://www.consvalmap.org). Nevertheless, our sample allows us to draw representative conclusions on the scientific environment. By focussing only on regional case studies, we reduced this sample to 153 publications and analysed this final set of papers using different indicators (see Appendices S1 and S2, Supporting information).

Figure 1 depicts the spatial distribution of ecosystem service study regions of the final set of papers. Apparently this research field is mostly driven by studies in the US (more than 35), followed by China (more than 20). In total, 50% of the studies represent only six countries. The ecosystem service value assigned to these six countries by Sutton & Costanza (2002) is merely 23·5% of the global sum of ecosystem services.

A variety of methods are commonly employed in these studies. A common approach to ecosystem service assessment

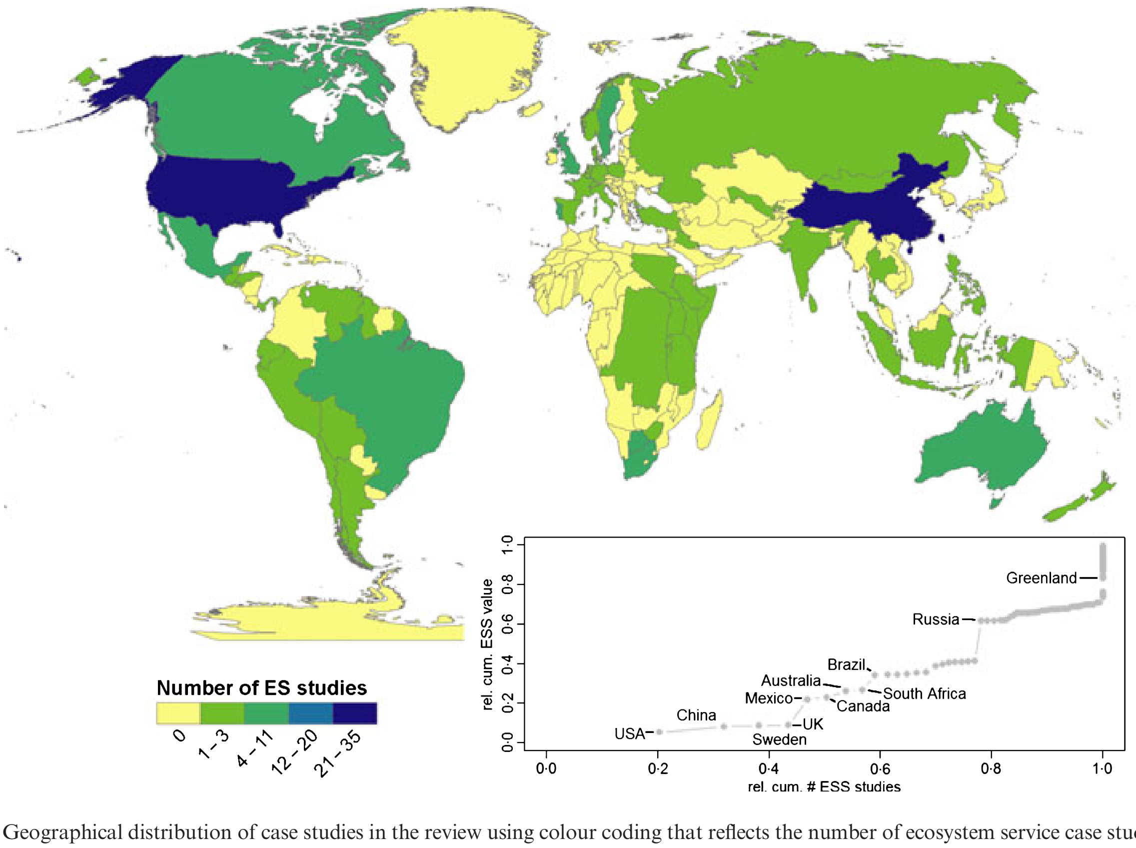

Fig. 1. Geographical distribution of case studies in the review using colour coding that reflects the number of ecosystem service case studies per country. The size of the countries reflects the total sum of the value of the ecosystem service (Sutton & Costanza 2002). The value of the ecosystem services includes terrestrial as well as marine ecosystem services, which is the reason for the huge size of 'countries' such as Antarctica or Greenland. To provide a consistent data base, we included nine studies focusing on marine ecosystem services. The inset shows a scatter-plot of the countries regarding their relative contribution to the cumulative number of case studies and the cumulative value of the ecosystem services.

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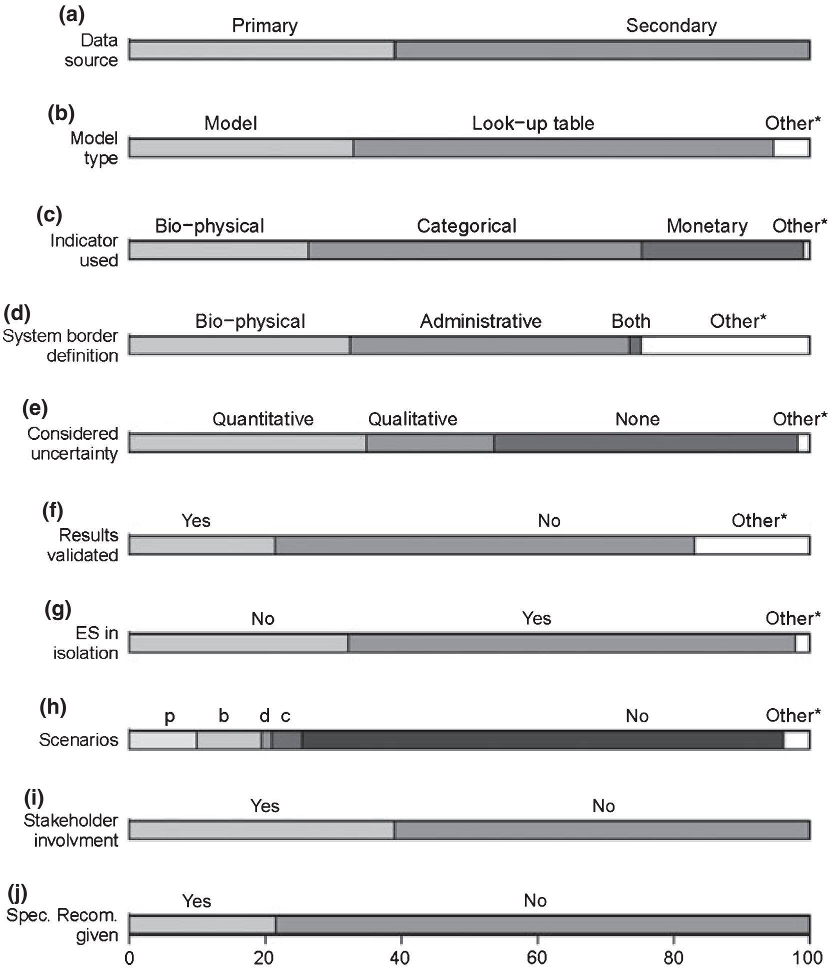

Fig. 2. Percentage of the studies (weighted by the number of ecosystem services in each article that belong to the specified factor level) that belong to the specified factor level. See Appendix S2 in Supporting information for a definition of the indicators. The factor level 'other' refers to cases in which insufficient information to assign the article to a factor was given in the article. The factor levels for scenarios are p, political; b, behavioural; d, demographic; and c, climate change.

is to use proxy variables, particularly land cover, to represent ecosystem processes and provide maps of ecosystem service. Less than 40% of the studies derived their results on primary data from observations or measurements, whereas *c.* two-thirds based their results on (mainly unvalidated) secondary data (Fig. 2a). Two-thirds of all studies made use of look-up tables, which map land use or land cover onto ecosystem service indicators. In addition to monetary and biophysical values, coarse and largely arbitrary categorical indicators or classifications were often employed (Fig. 2c). Only a minor portion of these studies used simulation models to compile assessments (Fig. 2b). Independent of the use of simulation models, only 18% of all studies addressed the issue of independent validation (Fig. 2f). Nearly half of the studies verbally acknowledged uncertainty in their assessment, but only one-third did so in even the most basic quantitative way (Fig. 2e). In summary, less than one-third of all studies provided a sound basis for their conclusions (i.e. data, measurement or biophysical, for ecosystem service mappings).

The application of the integrative ecosystem service concept implies the investigation of several relevant indicators in concert. Figure 2g shows that more than 50% of the studies analysed ecosystems services in isolation (i.e. without considering any feedback or interrelations). A more detailed analysis shows that approximately 50% of all studies considered only five or fewer ecosystem services simultaneously (Fig. 3).

The services that were studied followed a non-uniform distribution; of the provisioning services, 81 studies looked at food provisioning, but only 13 studies considered biochemical products and medical resources. Similarly, the group of cultural services strongly focussed on opportunities for tourism and recreational activities. This could be explained either by the higher relevance of these services in general or by a bias originating from non-uniform geographical spread (USA, China, see above) of studies with country-specific priorities regarding certain ecosystem services.

Figure 3 shows a peak of 12 studies covering 19 ecosystem services. These studies were all unmodified (and unvalidated) applications of global benefit-transfer data (Costanza *et al.* 1997). A minority (29%) of studies considered scenarios or policy instruments (Fig. 2i). Scenarios focussed on policy options (10%) or behavioural scenarios (10%), whereas demographic development (1·5%) and climate scenarios (4%) contributed only a minor portion. There was no consistent methodology for the definition of the system boundary, which could be biophysical, political or both (Fig. 2d). None of the studies (0%) investigated any flow or exchange of ecosystem services (either through external effects or through trading) across the defined system boundary.

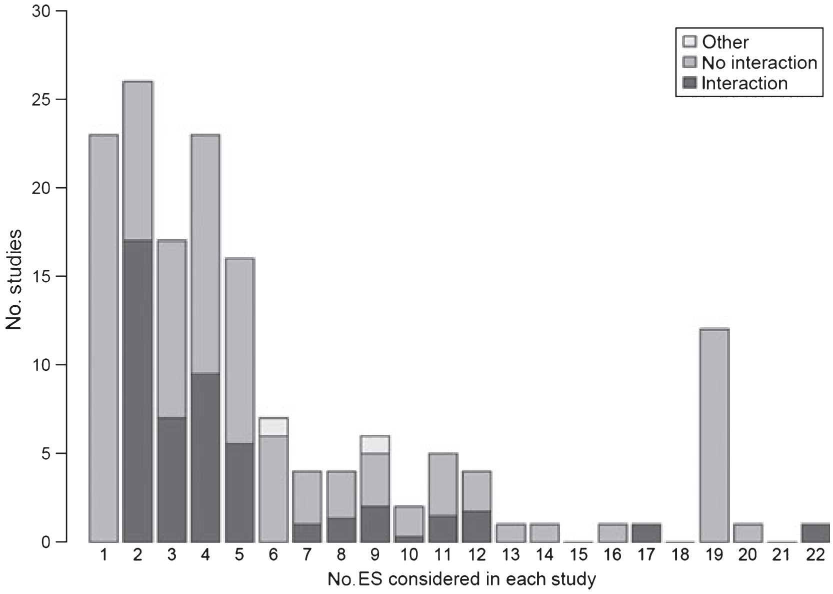

Fig. 3. Frequency of the number of ecosystem services studied in the articles analysed. In addition, the portion of the articles that considered interactions between the ecosystem services studied is displayed. 'Other' refers to articles that did not contain sufficient information to judge whether a study considered interactions. The peak of 12 studies covering 19 ecosystem services represents unmodified applications of global benefit-transfer (Costanza *et al.* 1997) on a regional scale.

Finally, many studies involved stakeholders primarily to evaluate parameters and outcomes of simulations. Of the reviewed studies, 39% reported some degree of stakeholder involvement (Fig. 2i). This may indicate that a curiosity-driven selection of assessment studies was more frequent than the response to specific local issues. This interpretation is supported by the observation that only 21% of all studies concluded with specific recommendations.

The methodological diversity detected by this quantitative review illustrates that ecosystem service research is currently a fragmented field. To rally ecosystem service research behind the common aim of sustainable use of natural resources, we regard it as useful to identify some key research topics specific to ecosystem services. We present four potential research facets, summarised by core questions listed in Table 1.

Components of ecosystem service research

BIOPHYSICAL BASIS

The measurement, modelling and monitoring of ecosystem functions are the foundation for ecosystem service assessments and are thus the basis for the sustainable use of biodiversity, ecosystems and natural resources in general (Carpenter *et al.* 2009). This requires relating ecosystem functioning to ecosystem service indicators. A variety of methodological approaches are available to describe these non-monotonous, non-linear and time-variant relationships that all require data, maps, monitoring (Lautenbach *et al.* 2010), fieldwork or experiments (e.g. Greenleaf & Kremen 2006; Sandhu *et al.* 2008) and/or models (Boumans *et al.* 2002; Schröter *et al.* 2005); see also Fig. 2a–c).

Eigenbrod *et al.* (2010) showed how unreliable proxy data based on land use and land cover can be for deriving ecosystem service indicators by comparing these to monitoring and field data for selected ecosystem services in the UK. The integrated approach of the ecosystem services concept requires the consideration of interacting ecosystem functions in any study assessing ecosystem goods and services. This necessitates a comprehensive understanding of the system and, thus, a representation of the relevant biophysical processes in a realistic way (Clark *et al.* 2001). There is a need for careful selection of the appropriate complexity of the model, which could be a set of complex but separate models (Schröter *et al.* 2005) or aggregated but fully integrated approaches (Boumans *et al.* 2002).

While some simplification is needed to effectively communicate with policy makers, oversimplification is unsatisfactory for a comprehensive system description and can mislead decision-making (Barbier *et al.* 2008). Approaching an intermediate complexity seems to be the appropriate way to offer the capability of different levels of complexity in the model (see InVeST, Nelson *et al.* 2009). However, even in its recent development, InVeST does not capture feedback between ecosystem services. We regard these elements as crucial for providing a reliable biophysical basis for ecosystem service studies: environmental data, model-based relationships for ecosystem function and feedback and test of assessment for robustness and uncertainties (Oreskes, Shrader-Frechette & Belitz 1994; Jakeman, Letcher & Norton 2006). With efforts to systematically tailor models to the degree supported by field data, ecosystem services research can take a significant step towards supplying policy makers with dependable and useable results while simultaneously achieving a better understanding of the system itself.

TRADE-OFFS

Trade-offs emerge when ecosystem services respond differently to change. According to Rodríguez *et al.* (2006), trade-offs occur due to feedback in ecological processes resulting in temporal and spatial patterns (Steffan-Dewenter *et al.* 2007) when gains and losses do not occur in the same region (Egoh *et al.* 2009). Temporal trade-offs such as a recent decision on land use have future impacts (erosion, deforestation) and can be captured and analysed by the use of simulation models,

Table 1. Critical questions for reviewing ecosystem service assessments studies at the regional scale

Critical questions for ecosystem service assessments with respect to …
… **biophysical realism**
1. How did ecosystem functions translate into ecosystem services?
2. How was the model tested or validated in this system for these indicators?
3. How robust were the results in the face of uncertainty?
… **trade-offs**
4. Which correlations between ecosystem services were shown to be causal (by literature and/or measurements/field work)?
5. How did trade-offs depend on assumptions regarding different scenarios, management options or changing environments?
6. Which secondary effects of changes in the supply of ecosystem services on the economic system or markets were considered?
… **off-site effects**
7. Which environmental processes on larger temporal and spatial scales were considered?
8. How did trade-mediated effects on larger spatial scale determine the results?
9. Which differences in the valuation of ecosystem services were studied when beneficiaries were distributed over different locations?
… **stakeholder work**
10. How were stakeholder groups set up and how were their roles described (transparency)?
11. How can the results and statements derived from stakeholder work be tested, e.g. did they match or contradict observed behaviour and why?

whereas the spatial congruence of ecosystem services is frequently due to correlations dictated by biophysical and socio-economic conditions, which may not be enough to guide policy. To support policy development, ecosystem service assessments should uncover how likely ecosystems are to respond to change in human activities and economic production. To do so, the optimisation of conservation efforts to strengthen ecosystem services is becoming more common (Chan *et al.* 2006; Holzkämper & Seppelt 2007) and might inform decision making on the trade-offs of policies such as weighing the improvements in one ecosystem service against the decreased performance of another service.

OFF-SITE EFFECTS

Local decisions can affect the delivery of distant ecosystem services, a phenomenon referred to as 'off-site effects'. This is either due to causal links on the global scale or human-induced effects, such as international trade in goods, which can also involve a trade in ecological damage (Scharlemann & Laurance 2008). In general, beneficiaries of two ecosystem services are distributed over differing spatial extents or two different locations. Despite calls by governments, none of the studies that we examined considered the consequences of local decisions on distant ecosystems. Thus, ecosystem service research seems to be currently driven to seek available approaches akin to the ecological footprint (Wackernagel *et al.* 2002) or the water footprint (Hoekstra & Chapagain 2006). As these concepts are still being discussed (van den Bergh & Verbruggen 1999), ecosystem service research would greatly benefit from developing methods to study off-site effects.

STAKEHOLDER INVOLVEMENT

Stakeholder involvement is understood as an appropriate tool to relate ecosystem function to human well-being. It covers three aspects, the first of which is that stakeholders help to identify relevant ecosystem services. Suitable indicators for ecosystem services assessments change as markets evolve, requiring local stakeholders to continuously re-evaluate the appropriate indicators. Secondly, stakeholders provide ground truthing for the development of management options. Thirdly, stakeholders evaluate possible management options, either by ranking them or by assigning weights of importance to different services (Ananda & Herath 2009). However, the evaluation of the three steps in environmental research is in its infancy. The sociological literature on group processes is vast, and stakeholder involvement can be misused just as an environmental model can (Malone, Dooley & Bradbury 2010). The selection of the stakeholders, the type of questions asked, the presentations given, the behaviour of expert witnesses present, the setting, the personalities present and the scope set all affect the group consensus formed (Mullen 1991). Finally, it is a common misconception that participation leads to empowerment, the ownership of decisions and higher compliance with environmentally friendly strategies (Fraser *et al.* 2006). Although there are relatively few assessments of this type, they indicate that money is a key driver of compliance: even minor fluctuations in income can lead to a withdrawal from 'consensus decisions' (Layzer 2008), and group decisions may not be upheld by group members (Postmes, Spears & Cihangir 2001). Stakeholder involvement should thus be seen as a method to gain a wider picture, to ground-truth academic possibilities and to provide a first estimate of which measures of ecosystem management would be looked upon favourably by members of the public.

Conclusions

Different research fields have different research traditions. To quantify ecosystem services, some may primarily rely on mapping, field measurements, expert opinion or modelling. These different approaches should not be given the same weight because not every method yields equally reliable data and results. In evidence-based medicine, evidence is qualified by freedom from bias (Sackett 2000), but evidence-based environmental management has not yet reached the same standard (Layzer 2008). Although they are scientifically challenging, assessments that are tailored to ecosystem services, field-validated and based on process models have the potential to tackle issues such as thresholds, irreversibility and non-linearity (Fisher *et al.* 2008).

Our review highlights facets with which the majority of ecosystem service studies do not comply. We found that information on the specific methods employed was often presented unreliably or was missing altogether; thus, it was occasionally difficult to judge the scientific quality of a study. This problem can be approached by implementing standardised reporting of ecosystem service assessment studies (de Groot, Wilson & Boumans 2002). However, before doing so, structured discussion and further development of ecosystem services studies along the above-mentioned issues are valuable steps for tailoring the concept to the challenges of environmental management. These four research facets guide critical self-assessments of the validity of studies and can serve as a first proposal for an ecosystem service research agenda, which must focus on scientific quality to have a lasting impact. At the same time, real-world problems will necessitate compromises and shortcuts, which should be clearly stated and not suppressed by the urge to influence policy.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. 'Literature Used in Quantitative Analysis' with a specification of selection criteria (S1.1), the distribution of paper in journals (S1.2, Table S1.1) and a full reference list (S1.3).

Appendix S2. 'List of Indicators' provides a detailed description of indicators used for the meta-analysis, including a histogram of ecosystem services studied throughout the papers (Fig. S2.1), and the list of ecosystem services and abbreviations in Table S2.1.

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