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FORUM

Priority research areas for ecosystem services in a changing world

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Summary

1. Ecosystem services are the benefits humans obtain from ecosystems. The importance of research into ecosystem services has been widely recognized, and rapid progress is being made. However, the prevailing approach to quantifying ecosystem services is still based on static analyses and single services, ignoring system dynamics, uncertainty and feedbacks. This is not only partly due to a lack of mechanistic understanding of processes and a dearth of empirical data, but also due to a failure to engage fully with the interdisciplinarity of the problem.

2. We argue that there is a tendency to ignore the feedbacks between and within both social and ecological systems, and a lack of explicit consideration of uncertainty. Metrics need to be developed that can predict thresholds, which requires strong linkages to underlying processes, while the development of policy for management of ecosystem services needs to be based on a broader understanding of value and drivers of human well-being.

3. We highlight the complexities, gaps in current knowledge and research, and the potentially promising avenues for future investigation in four priority research areas: agendas, processes, metrics and uncertainty.

4. *Synthesis and applications.* The research interest in the field of ecosystem services is rapidly expanding, and can contribute significantly to the sustainable management of natural resources. However, a narrow disciplinary approach, or an approach which does not consider feedbacks within and between ecological and social systems, has the potential to produce dangerously misleading policy recommendations. In contrast, if we explicitly acknowledge and address uncertainties and complexities in the provision of ecosystem services, progress may appear slower but our models will be substantially more robust and informative about the effects of environmental change.

Key-words: ecological thresholds, human well-being, natural resource management, social–ecological systems, uncertainty

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Introduction

Ecosystem services are the benefits we obtain from ecosystems and upon which our existence depends. Ecosystem services include provisioning services (e.g. fresh water), regulating services (e.g. climate and flood regulation), cultural services (e.g. aesthetic and spiritual benefits) and supporting services (e.g. nutrient cycling) (Millennium Ecosystem Assessment. 2005). Quantifying the value of these services and formulating the means for their management and continued provision in a changing world is a significant priority that is being addressed by research teams worldwide (e.g. Daily *et al*. 2000; Walker & Meyers 2004; Schröter *et al*. 2005; Naidoo & Ricketts 2006; Nelson *et al*. 2008). To drive this research agenda forward and facilitate the development of interventions that will be rapidly adopted, there is a need to move from a description of ecological patterns to an understanding of the underlying ecological and socio-economic processes, demanding an interdisciplinary approach and explicit consideration of sources of uncertainty. This is increasingly recognized by researchers (e.g. Walker & Meyers 2004; Díaz *et al*. 2006; Sukhdev *et al*. 2008; Carpenter *et al*. 2009) and research funding bodies, including the UK government, US National Science Foundation and the European Commission. The purpose of this study is to develop this research agenda in more precise terms and identify four priority areas where further research is urgently required.

1. *Agendas*: the ethical and economic frameworks for defining the values derived from ecosystem services and for evaluating trade-offs between different values.

2. *Processes*: the interactions between socio-economic and ecological systems, between multiple ecosystem services, and among the ecological processes that underpin ecosystem service provision.

3. *Metrics*: the quantification of the value of ecosystem services and processes for implementing ecosystem service valuation and detection of trends.

4. *Uncertainty*: identifying sources of uncertainty, reducing uncertainty, and making decisions in the face of uncertainty.

Agendas

Valuing and governing ecosystem services requires a moral framework where the standards and principles underlying value are agreed, and an ethical framework that can serve as a guide to policy implementation. Defining these frameworks raises issues such as which types of value are important (Parfit 1984; Farber, Costanza & Wilson 2002); for example, how great a role should public preferences play in defining the policy agenda for public goods such as ES? And how do we weight the very different values that are perceived by different cultures and sectors of society? Such debates can be informed through further understanding of how ecosystem services affect human well-being and how to quantify this link, but this alone will not be sufficient to determine policy responses. There are three main accounts of well-being (Parfit 1984): objective lists, desire fulfillment and mental states. The Millennium Ecosystem Assessment (2005) is primarily concerned with objective lists, including basic materials (e.g. food and shelter), health and freedom, and utilitarian ecosystem indicators (e.g. water flow). Although most economists are concerned with desire fulfillment through people's revealed and stated preferences (Daily *et al*. 2000; Atkinson & Mourato 2008), others aim to use people's mental states to value nonmarket goods (e.g. in health, Dolan & Kahneman 2008). A critical distinction exists between approaches that focus upon intended and revealed choices and those based on experienced well-being (Kahneman & Sugden 2005). Put another way, can people only place a meaningful value on change in an ecosystem services once they have experienced it? Researchers in ecosystem services need to be aware of other areas of economics and philosophy where debates about measuring well-being are taking place.

Further considerations include determining whose preferences count, spatially and temporally (Kremen *et al*. 2000). Temporally, the issues extend to intergenerational equity (Atkinson & Mourato 2008). Spatially, a major area of research interest is the trade-off between the different values of multiple ecosystem services derived from the same area. For example, tropical forests provide a range of services to local, national and international stakeholders. Internationally these services include biodiversity value and carbon storage, nationally forests are also important for the production of timber, while locally they provide bushmeat and other nontimber forest products for income and consumption, often to the poorest and most marginalized sectors of society (Bennett *et al*. 2007; Nasi *et al*. 2008). Although science can improve understanding of the underlying processes that govern the trade-offs between ecosystem services, and economics can determine the relationship between ecosystem services and human well-being, making trade-offs between the well-being of different users for policy implementation is a political, moral and ethical question.

Processes

Although knowledge of how ecosystem services affect well-being is important, understanding and modelling the underlying processes leading to service provision is essential for predicting and managing change in ecosystem services (Fig. 1). Most research to date has focussed on describing spatial patterns of stocks or flows of ecosystem services (e.g. stocks of forest value, flows of water), rather than attempting to understand the underlying processes that underpin the provision of multiple services (e.g. Schröter *et al*. 2005; Naidoo & Ricketts 2006; Troy & Wilson 2006; Nelson *et al*. 2008; Anderson *et al*. 2009). Ecological research has tended to employ either statistical, empirical models, based on associations between observed patterns and variables, or process-based models that focus on underlying mechanisms. Pattern-based models tend to be static and used for description, whereas process-based models include dynamics and are better suited for understanding and prediction (Clark & Gelfand 2006). For example, early biodiversity models simply described where species are found; these moved on to models of the dynamics of single species populations or simple systems with only a few species.

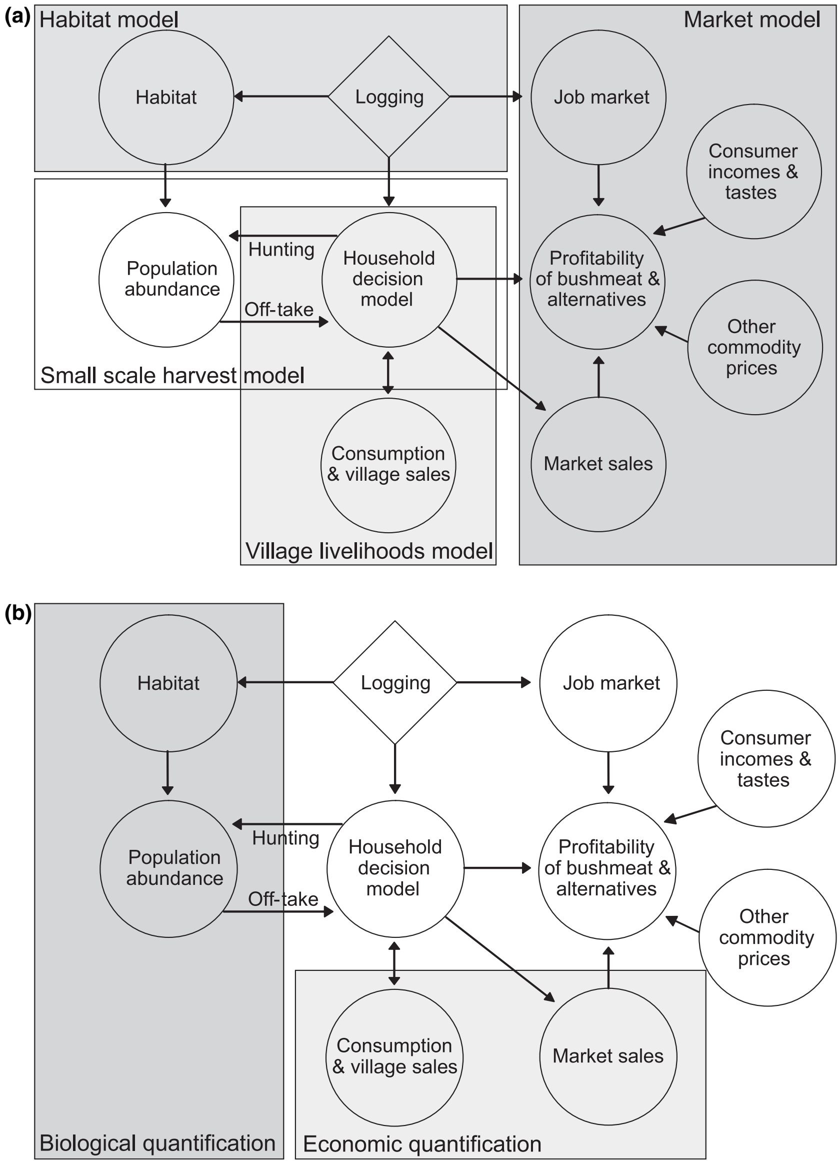

Fig. 1. (a) A simple conceptual diagram of some of the processes driving the direct use value of bushmeat. The hunting decision is made at the small scale by individual hunters, but this decision is influenced by village and market-level factors; for example consumer preferences and availability of substitutes influence consumer demand. Hunter off-take is a function of animal abundance, which is affected at a range of scales by habitat quality and availability. Modelling approaches to this system vary by scale and process type; for example small-scale harvest models, market models, habitat models and village livelihoods models. These different components of the bushmeat system have been modelled separately (shown in the shaded rectangles), but not in an integrated manner. (b) Accountancy-type approaches quantify ecosystem service value along separate axes depending on whether the stocks of an ecosystem service or the welfare benefits are being addressed, ignoring dynamics and interactions and thus excluding many changes that affect the provision of the service. A biological quantification would focus on the relationship between habitat characteristics (such as the amount and type of forest habitat), and the population abundance and level of harvesting of the exploited species, while an economic quantification would include local rates of consumption and the quantity and prices of market sales. Such patterns are unlikely to encapsulate the underlying processes (the rest of the diagram), which makes prediction of the effect of change on the system near-impossible.

Current research now includes models of the dynamics of whole assemblages and the interactions of multiple species within them.

Research in ecosystem services is following a similar process. For example, in bushmeat research, there is now a literature that describes patterns in the quantities and provenance of bushmeat entering markets in west/central Africa (e.g. Crookes, Ankudey & Milner-Gulland 2006; Albrechtsen *et al.* 2007), although knowledge of the size and dynamics of the source animal populations is still lacking. A few papers model the role of bushmeat in household decision making (e.g. Damania, Milner-Gulland & Crookes 2005) or the interaction between bushmeat consumption and components of the wider economy (e.g. Brashares *et al.* 2004; Wilkie *et al.* 2005). The need now is to link up these individual research areas into a process-based understanding that incorporates multiple scales in time and space (Fig. 1a). This would then allow us to investigate the potential effects of change at a range of scales on bushmeat hunting and to quantify the relative importance of both direct (such as habitat destruction) and indirect (such as changes in commodity prices) processes on the sustainability of bushmeat hunting in a given policy environment. Mapping accountancy-type quantifications of ecosystem services onto this same diagram demonstrates the inadequacies of this approach, with biologically based ecosystem service quantifications focussing on animal populations, whereas economically based quantifications focus on bushmeat use (Fig. 1b); neither of these is able to capture the broader processes that operate in this system.

The field of ecosystem services research is at a relatively early stage, and spatially explicit empirical research is still urgently required to counteract the dearth of information concerning patterns of ecosystem service provision. This is particularly true in areas where little social and ecological research has yet been undertaken, such as the tropical forests of west/central Africa. However, a focus on patterns alone without understanding the underlying mechanisms of service provision leads to poor predictive power (Tallis & Kareiva 2006; Carpenter *et al.* 2009). Therefore, we need to move towards a more process-based approach for multiple services if we are to make robust predictions, particularly given the prevalence and magnitude of environmental change, which is likely to alter the underlying processes in both quantitative and qualitative ways and may take many systems outside observed conditions. Data collection needs to be targeted towards testing hypotheses formulated from a model of the processes underlying the provision of ecosystem services. New statistical methods allow the integration of process-based models into statistically rigorous parameter estimation techniques, for example through Bayesian inference (Clark & Gelfand 2006), providing a strong framework for tackling complexity in understanding and predicting change in ecosystem services.

Our fundamental lack of understanding of many processes that underpin the dynamics of ecosystem services, even at a basic level, significantly hinders our capacity to develop predictive models. In particular, the linkage between biodiversity and ecosystem function is not well understood. For example, the dynamics of the soil microbial community still require substantial research if we are to understand and predict the processes underlying decomposition (Brussaard *et al.* 1997). Key complexities that need to be explicitly considered include the interdependencies between multiple ecosystem services and between ecosystem services and ecosystem characteristics (Chee 2004; Díaz *et al.* 2006), including thresholds and nonlinearities. In particular, we need to be able to identify thresholds of scale or levels of disruption that can result in rapid collapse or change of state of an ecosystem service (Walker & Meyers 2004; Tallis & Kareiva 2006; Biggs, Carpenter & Brock 2009; Koch *et al.* 2009), such as fish stock collapse due to over-harvesting, and lake eutrophication due to run-off from agricultural lands. Other important nonlinearities include the feedbacks between multiple services and the socio-economic system that can lead to nonlinear social and ecological responses to policies (Chee 2004). Modelling these requires an understanding of the drivers of human behaviour, demography, societal values and markets, which links back to the discussion of agendas above. A social–ecological approach addresses not only the dynamics within each of the social, economic and ecological components, but also explicitly deals with the linkage and feedbacks between them (Folke 2006). This approach is increasingly used as a basis for ecosystem service assessment (e.g. Walker & Meyers 2004; Folke 2006; Tallis & Kareiva 2006; Carpenter *et al.* 2009).

Although more than one service is typically provided by a given area, relatively few studies have developed process-based models of multiple ecosystem services. No study, to our knowledge, has integrated dynamic models of multiple ecosystem services to include feedbacks between different services, although pioneering studies on multiple services are moving closer (e.g. scenario analysis of multiple services including biodiversity conservation, carbon sequestration and water quality, as well as several marketed commodities in the Willamette Basin, Oregon, by Nelson *et al.* 2009); in particular none has considered the interactions between social and ecological components of a system (Tallis & Kareiva 2006). This is an important omission. Understanding and modelling linkages is hindered by the complexity of such interactions; even without including interactions, highly complex and data-intensive models have formed the basis of studies mapping multiple ecosystem services (e.g. Schröter *et al.* 2005; Naidoo & Ricketts 2006; Nelson *et al.* 2008, 2009). Nevertheless, given the importance of feedbacks demonstrated in small-scale or single service case studies, research directed at improving our understanding of interactions between multiple services is of critical importance, because such feedbacks are likely to change model predictions substantially.

A second issue is how to quantify the overall value of multiple ecosystem services provided by the same area and the trade-offs inherent in managing for one rather than another ecosystem service. Multiple ecosystem services can represent different facets of the same underlying ecosystem, and hence treating them independently can lead to potential double-counting of the benefits provided or the overlooking of synergistic properties of ecosystem functions (Chee 2004). Increased provision of some services reduces provision of others, and some services are substitutable one for the other while others are not. For example, Nelson *et al.* (2008) modelled potential trade-offs and synergies between carbon sequestration and biodiversity, both provided by forested areas; however, different types of forest provided these services to a greater or lesser extent, leading to trade-offs between the two services, neither of which was compatible with increased crop provision on the same land. Such trade-offs and interactions are often ignored in modelling studies due to their complexity.

Metrics

Metrics provide a means of quantifying the value of ecosystem services, valuing their impacts on well-being and constructing policy-relevant indicators of trends. In order to develop meaningful metrics for ecosystem services, the underlying processes need to be understood. For example, in the bushmeat system, the most commonly used metrics are market-based, due to the relative ease of collection of this information (Fig. 1b). The metrics are intended to detect overhunting and depletion of bushmeat populations, and include the distance travelled to market, based on the idea that the further the meat travels the more depleted the areas immediately surrounding the market are. However, these metrics are the product of two processes: depletion and market dynamics. In the case of a market in Ghana, the increase in travel distance is more likely to have been caused by price increases offsetting trader travel costs than by depletion (Crookes *et al.* 2006).

Two broad categories of metrics can be distinguished: those that allow us to measure, value and track changes in the stocks and flows of ecosystem services themselves; and those that allow us to monitor and detect the dynamics of the underlying processes that generate these flows. Both require process-based understanding, but they differ in the directness of their relationship to the ecosystem services themselves. Direct metrics for flows of ecosystem services require more research into how best to incorporate uncertainty and trade-offs into existing physical and value measures, and also how to translate highly complex scientific information into metrics of effects on human well-being (which are not just monetary). Metrics that focus on underlying processes would allow the detection of potential changes in ecosystem services before it is too late, and require an understanding of the relationship between ecosystem service value and underlying ecosystem composition, processes and biodiversity. Critical to detecting impending state changes will be the development of indicators of approaching thresholds or tipping points towards alternate states, which might be derived from meta-analyses of case studies or modelling studies (Walker & Meyers 2004; Biggs *et al.* 2009).

Uncertainty

Uncertainty, in the sense of stochasticity, is a feature of all natural systems, and one that can be fundamental to system functioning (e.g. Anderies & Beisner 2000). A process-based understanding of ecosystem services must therefore include an understanding of the role of uncertainty in the dynamics of a social–ecological system. However, we also need to address the uncertainties created by our own lack of understanding of the system. Most of the current research in ecosystem services fails to address the different sources of uncertainty in our understanding of system state and dynamics, and thereby conceals unquantified biases. Uncertainty in the quantification of ecological and socio-economic systems includes errors in measurement, systematic errors from biased sampling, and natural variation and stochasticity that result in uncertain data and parameter estimates in models (Regan, Colyvan & Burgman 2002). A neglected but potentially greater source of uncertainty stems from model uncertainty, particularly in assumptions about system dynamics or processes. For example the conceptual model outlined in Fig. 1 contains only the few linkages that we deem most important based upon our current understanding of the system. Model uncertainty is difficult to quantify and eliminate, although approaches include being explicit about developing competing models to confront with data, and using tools such as graphical models, structural equation modelling and model averaging (Mitchell 1992; Hilborn & Mangel 1997; Regan *et al.* 2002; Clark & Gelfand 2006). Linguistic uncertainty, including vagueness, context dependence and ambiguity (Regan *et al.* 2002), can also pose a significant problem, especially in interdisciplinary research such as is required for ecosystem services.

These uncertainties and complexities can be reduced; extensive sampling and increasingly sophisticated statistical methods can allow a greater understanding of the distribution of variability and uncertainty, as well as a better understanding of the underlying processes (Regan *et al.* 2002; Clark & Gelfand 2006). Identifying where key uncertainties lie is the first step towards their quantification and minimization where possible. Using a structured decision-making approach, ideally within an adaptive management framework, would improve our ability to integrate uncertainty into policy debates and the wider management process (Shea *et al.* 1998).

Conclusion

A major research effort is now underway to quantify, value and manage ecosystem services that may inform fundamental changes in society's approach to the environment. Without explicit recognition of the complexity of the issues that we face and the inherent sources of uncertainty, there is a danger of producing policy recommendations that are misleading or flawed. A process-based research approach that treats ecosystem service provision within the context of a linked social–ecological system, and which directly focuses on the causality from change in ecosystem services to human well-being, provides a robust basis for decision-making. Much of the difficulty and research interest lies in the interactions between the four areas of research we have highlighted, for example how metrics can be better designed to reflect changes in underlying processes. Such research requires a strongly interdisciplinary approach, which is fully engaged with policy makers and stakeholders. Achieving interdisciplinarity presents a significant research challenge in itself; the novelty often lies not in sourcing the techniques from each discipline but in the integration of multiple areas of research, and in crossing communication barriers, which is rarely a trivial endeavour. Yet it is vital that we achieve increasingly sophisticated levels of integration between disciplines if we are to succeed in providing robust and effective policy recommendations for managing our use of ecosystem services in a changing world.

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