Rationalising Biodiversity Conservation in Dynamic Ecosystems

RUBICODE International Workshop on

Ecosystem Services and Drivers of Biodiversity Change

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BACKGROUND REPORT

Foreword

This report summarises a series of reviews that were undertaken during the first phase of the RUBICODE project. Copies of the full reviews are available to download from http://www.rubicode.net/rubicode/outputs.html. Other documents that can be obtained from the same address include the RUBICODE glossary, which contains working definitions of key terms, the project flyer and newsletters, and reports from previous RUBICODE workshops.

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Concepts of dynamic ecosystems and their services

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Introduction

Many current conservation strategies are developed around a static and uniform view of nature and the environment. Ecosystems are however dynamic. Thus for successful current and future conservation objectives it is important that new conservation strategies are developed and implemented that concentrate on managing dynamic ecosystems for maintaining their capacity to undergo disturbance, while retaining their functions, services and control mechanisms. Ecosystems are also multifunctional systems which provide humanity with vital services for example, food, wood, water, soil protection, climate regulation as well as many cultural and aesthetic services. Ecosystems can only continue to provide these services in a rapidly changing world if multifunctionality is taken into account in their management. Additionally a key element in ecosystems which allows them to deliver a range of services is the level of biodiversity within them. While conservation of biodiversity is an important societal need, it is not the only one. The question therefore is how can society prioritise its varying and multiple needs. The full report reviews the current state-of-the-art with regard to concepts and frameworks for the assessment and quantification of ecosystem services in the context of biodiversity conservation.

Frameworks and concepts

The framework for ecosystem service assessment proposed by the Millennium Ecosystem Assessment (MA, 2005) is perhaps the most well known. The MA report categorises ecosystem services into four different classes: provisioning, regulating, cultural and supporting services. The literature was searched for evidence of services identified by the MA within these different service classes for six terrestrial (agro-ecosystems, forests, semi-natural grasslands, heath and shrubs, montane and soils) and three freshwater (wetlands, rivers and floodplains, and lakes) ecosystems. Some services are provided by all ecosystems for example food, fibre, fuel and genetic resources, climate regulation, primary production, nutrient and water cycling, and the provision of habitats for flora and fauna. Finally all ecosystems have aesthetic values and recreational importance. Services such as biochemical/natural medicines, pollination and disease regulation tend to be restricted to the terrestrial ecosystems, whereas the provision of fresh water, energy (through hydroelectric power) and water regulation are obviously more focused on the aquatic ecosystems. Only one ecosystem provides all the MA categories of services, montane, which itself comprises a variety of habitat types across its altitudinal variation.

The concept of 'service-providing units' (SPUs; Luck *et al.*, 2003) to link explicitly species populations with the services they provide to humans is central to this review. An SPU can be defined simply as the components of biodiversity necessary to deliver a given ecosystem service at the level required by service beneficiaries. This definition makes three assumptions. First, that the [human] need for an ecosystem function has been explicitly identified thereby re-classifying it as a service. Note that this detailed quantification of the level of need is rarely done. Second, that the rate of delivery of the service can vary, but it should meet some base level defined by service beneficiaries (i.e. humans; e.g. financial profits attributable to service provision are above a given threshold). And third, that the components of biodiversity providing the service can be identified and quantified.

The concept has been extended beyond the population level to include functional groups and ecological communities (Luck *et al.*, 2008). While it is clear that species and functional diversity *per se* can affect the provision of certain ecosystem services, the SPU approach argues for quantifying relationships between service provision and key service providers, whether these be populations, functional groups or ecological communities. In this sense, an SPU is a collection of individuals from one or more species that possess certain characteristics, or trait attributes, required for service provision.

The steps that need to be undertaken to identify and quantify an ecosystem service using the SPU concept are specified in Figure 1. However, it should be recognised that completion of all these steps represents best practice and data are rarely available to this standard. The steps can be divided into three stages of analysis, which are described in detail in the full review: (i) identify beneficiaries and providers of the ecosystem service; (ii) quantify demand and supply of the service; and (iii) appraise the service value and implications for management and policy.

To summarise the first two stages of analysis, we wish to know which sections of the human community use the service (the ESBs) and at what level is it required, what components of the ecosystem provide the service (the ESPs), and what characteristics of these components are required to provide the service at the desired level (SPUs). The third and final stage of analysis involves the valuation of the service as provided by the SPU and potential alternatives and the appraisal of trade-offs and implications for biodiversity conservation and policy.

A literature review was undertaken to identify case studies which could be used to test the framework for identifying and quantifying ecosystem services using the SPU concept and establish gaps in knowledge. Information on 64 case studies was gathered covering all nine ecosystems. The availability of good examples was more limited for montane and lake ecosystems, which seems to reflect a real gap in present knowledge. The case studies cover a range of scales from local to regional to broadscale although more examples were available at the local scale where the provision and use of services is often most easily recognised. Among the studies examined, regulating service examples were most common, though this may reflect to some extent the biodiversity focus of the review. Table 1 provides information for a small selection of examples; more are available from the full report.

The value of the SPU concept is greatly enhanced if some consideration is given to ecosystem dynamics. Ecosystems are in a constant state of flux and ensuring systems have the capacity to cope with likely changes is crucial if desirable ecosystem functions (i.e. services) are to be maintained. A permanent shift in conditions or an increase of stress (due to anthropogenic pressures such as climate change) can lead to changes in the balance between species, changes in species and/or functional composition and therefore to changes in (the composition of) SPUs, with possibly important consequences for conservation and management. A framework for quantifying and assessing these factors is discussed in the following summary paper on drivers that affect ecosystems and their services (Figure 2).

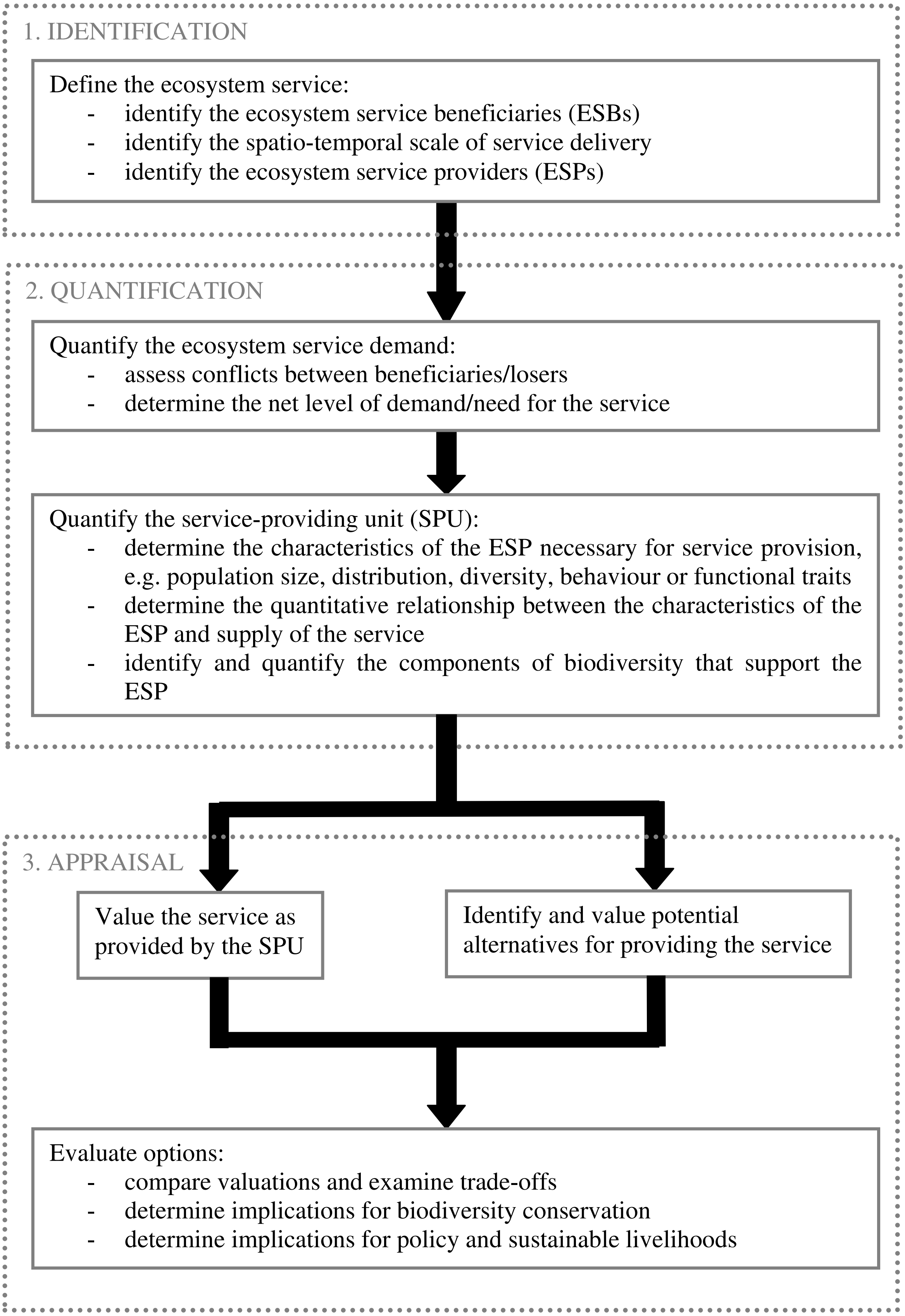

Figure 1: Guidelines for the identification and quantification of an ecosystem service.

Table 1: Examples from the literature where (some) quantification of ecosystem service demand and/or supply has been undertaken.

Service	**Ecosystem**	**ESBs**	**ESPs**	**SPU**	**Supporting system**	**Main drivers and pressures**
Fodder production[1]	Subalpine grasslands	Regional farmers in central French Alps	*Festuca paniculata* functional group (fibrous and nitrogen-poor leaves) and *Dactylis glomerata* functional group (tender and nitrogen-rich leaves)	Fodder quantity related to plant stature and abundance of the 2 ESPs. Fodder quality related to the community's average leaf nitrogen content.	Subalpine grassland plant communities.	Management intensity, land use change, nitrogen deposition, climate change.
Pollination of watermelons[2]	Agro-ecosystems	Local watermelon farmers in California	Native bees that pollinate watermelon crops	Functional group dynamics: sufficient diversity of bee species (20-30) and abundance of each species (not quantified) to cope with spatial and temporal environmental variation, and visitation rate and pollination effectiveness.	40% upland habitat (oak woodland and chaparral) within 2.4km of a farm site.	Market demand for product, deforestation, fragmentation, agricultural intensification, climate change, disease, competition with honeybee/ Africanised bee.
Water purification[3]	River and floodplain	General public	Multi-species-multi-zone riparian plant community (different trees, shrubs, herbs and grasses).	Nutrient and sediment filtration related to the number of constituent zones, and the density and width of the buffers.		Agricultural land use (food and biofuel demand), intensification.
Recreation and tourism[4]	Forest	Locals and tourists who visit the Stockholm National Urban Park	Eurasian Jay (*Garrulus glandarius*) provides a seed dispersal service for the oaks, which provide the direct service to humans.	Species abundance: minimum of 12 pairs of jays for the 2700 ha park.	Oak forest (where the species feeds and disperses acorns) and coniferous forest (where it breeds).	Epidemic oak disease, land use change, policy changes, forestry and timber demand, deforestation, fragmentation.
Water cycling[5]	Soils	The global population, particularly in arid and semi-arid regions with eroded soils at risk of desertification.	Soil macrofauna, in particular bioturbators (e.g. termites, ants and earthworms).	Species density: at least 30 termite macropores per square meter are necessary to assure water retention by significantly decreasing runoff.		Land abandonment, urban expansion, deforestation, agricultural intensification, climate change, overgrazing (and trampling by cattle).

References: (1) Quétier *et al.*, 2007; (2) Kremen *et al.*, 2002; 2004; (3) Correl, 2005; Dosskey, 2001; (4) Hougner *et al.*, 2006; (5) Leonard and Rajot, 2001

Discussion

This review has shown that the quantification of many services provided by ecosystems is most often minimal. If quantification is made then most often it is made as part of a monetary valuation of the relevant service. However quantification based purely on monetary values may be dangerous and our review suggests that even with the difficulties in identifying the relevant actors involved in the service (ESB, ESP and SPU), a standardised approach to the quantification of ecosystem services could provide a better methodology for the conservation of a range of ecosystem services.

The ecosystem service approach should never be considered as a replacement for traditional conservation strategies. However, there is great potential for the approach to add value to these traditional strategies and act as a powerful force for species conservation in human-dominated regions. When SPUs can be identified and protected, the magnitude of human reliance on ecosystems is likely to ensure that species populations are maintained at a level well above that required for species protection. Services provided by exotic species, or the notion of functional replaceability among species potentially undermines the contribution that the ecosystem service approach may make to conservation. A ranking of species or systems based on their service-providing 'value' must be reconciled with considerations of resilience to environmental change and contribution to the conservation of indigenous biodiversity. Only then can informed decisions about ecosystem management be made.

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Identifying and assessing socio-economic and environmental drivers that affect ecosystems and their services

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Change on earth has been taking place for billions of years, but of new concern is the scale, the magnitude and the speed at which change has been occurring since the industrial revolution and more recently over the last sixty years. Human activity has led to an increase in the risk of crossing critical thresholds that could result in abrupt changes to human and ecological systems. To prevent and reduce further environmental degradation, and reverse it where possible, it is important to understand how and why change is occurring. The identification of drivers of environmental change, which is embedded in the way humans live, encompasses detecting the rate of occurrence, the spatial and temporal scales of change and examining the changes in quantity and quality of ecosystems.

The RUBICODE project has set out to research existing knowledge about drivers of environmental change that has been reported in the literature. The review demonstrates that the majority of studies focus on one spatial scale exclusively, although drivers are known to act differently at different spatial (and temporal) scales. Demography is the most frequently cited indirect driver of environmental change, with land use and land cover change, and climate variability and change the most commonly cited direct drivers. Natural, physical and biological phenomena, diseases and wars are the least discussed direct drivers. The review highlighted the problems that arise from the use of different terminology in describing similar or even identical concepts. There is not, for example, a commonly accepted definition of the notion of a driver. Better defining and standardising terminology would help to reduce confusion and facilitate the rapid exchange of comparable information.

We propose a new conceptual framework based on coupling the DPSIR and SES concepts[1] as a means to investigate the complex dynamics of environmental change drivers as well as the identification of the internal and external perturbations that influence ecosystem services. Integration is desirable for a number of reasons: it creates a common framework for applications in different contexts; it standardises concepts and terminology; it makes explicit the exogenous and endogenous components of the system and it builds on well established approaches that are embedded in a number of policy and decision-making organisations. The DPSIR is specifically geared towards policy and management development, explicitly structuring statistics and indicators across the interactions between man and nature, which should ensure 'buy-in' from many stakeholder organisations involved in the monitoring of indicators related to demographic, socio-economic and environmental conditions.

Figure 2 illustrates the proposed framework for this integration. The boundary of the socio-ecological system is represented by the large hashed-line box. Everything within the box is endogenous to the system. The Drivers (or Indirect Drivers in the MA) are exogenous to the system. This means they are influenced primarily by factors, processes and interactions that occur outside of the ecosystem under consideration. The Pressures (or the MA's Direct Drivers) represent the variables that act upon the ecosystem state. The states change in response to the Pressures, and these dynamics (in time and space) are characterised by concepts such as resilience, robustness, durability and stability (Stirling, 2007). As the state changes it may reach a certain threshold (the SPU) that has negative (or positive) consequences for the service provision demanded by the service

[1] The Drivers-Pressures-State-Impact-Response (DPSIR) framework used by the European Environment Agency (EEA, 1999) and the concept of Socio-Ecological Systems (SES; Berkes and Folke, 1998).

beneficiary. Thus, the SPU is a function of: (i) the attributes of the biology of the species providing the service (the ESPs); (ii) the attributes of the supporting system; and (iii) the attributes of the service beneficiaries (the ESBs). If any of these attributes change there could be a different SPU. The impact is assessed using valuation techniques, including for example, trade-offs with alternative (non-biological) approaches to service provision. The nature of the impact on the provision of multiple services within a habitat will influence conflicts between ESBs and thus the desired response. Responses, such as policy measures and/or conservation management, are then implemented in accordance with the measured costs of the impact. These responses act on the Pressures, as these are endogenous to the system. Policy cannot act on the Drivers in any meaningful way as these are exogenous to the system and, therefore, are beyond the influence of the human actors operating within the system. It could be argued that, for example, C sequestration at a regional scale feeds back to the (broader) climate system, but at the scale of an individual ecosystem this feedback would be trivial. The integration of the DPSIR and SES frameworks can promote insight into the properties of socio-ecological systems and their responses to a variety of drivers and pressures, and thus aid understanding of sustainable conservation strategies.

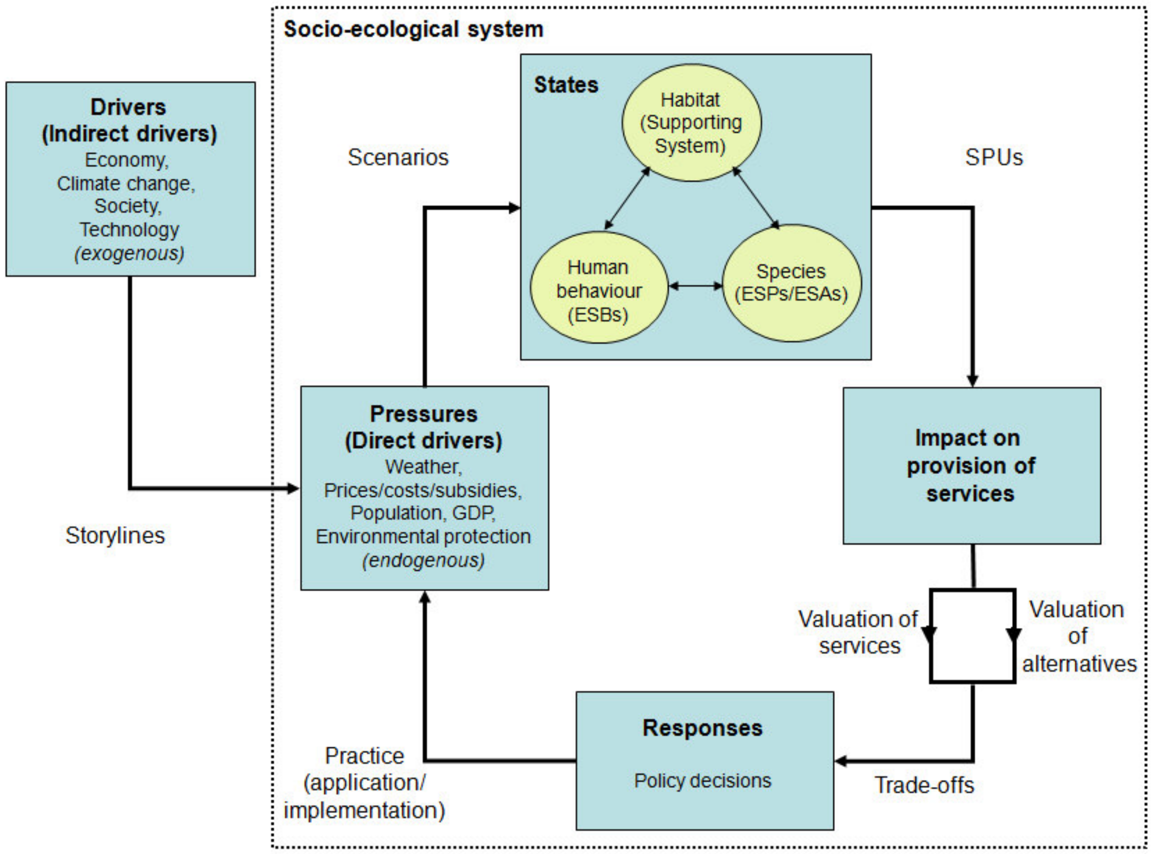

Figure 2: A proposed coupled DPSIR and SES framework for the assessment of the effects of environmental change drivers on ecosystem services. ESB = Ecosystem Service Benficiary; ESP = Ecosystem Service Provider; ESA = Ecosystem Service Antagoniser; SPU = Service Providing Unit.

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The dynamics of economic values and preferences for ecosystem goods and services

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Introduction

Valuation of environmental assets has been practiced actively since the 1970s. Although a pure academic curiosity at its beginnings, this particular line of research has gained momentum since the popularisation of the concept of ecosystem services by the Millennium Ecosystem Assessment. It is considered to be a cornerstone of sustainability assessment procedures both within national and international agencies as well as by private business and conservation practitioners. At present, research on ecosystem service valuation is rooted mostly on economic premises and methods. Alternative approaches based on either multi-criteria approaches and deliberative/inclusionary approaches are also being developed.

Ecosystem valuation is a highly controversial issue not only because of its technicalities but foremost because of the underpinning philosophical and moral strands.

The present review's main objective is to contribute to an understanding of the state-of-art in the design, empirical application and policy relevance of valuation exercises. It is important to stress that we are concerned with valuation of ecosystem services, not assets. Its main objective accordingly lies in reviewing peer-reviewed literature on ecosystem service valuation in relation to the following main questions:

1) How do valuation studies define and communicate changes in ecosystem service provision?
2) How are changes in ecosystem service provision linked to human welfare?
3) How do the dynamics of ecosystem service provision and demand enter into play?
4) What do average value estimates of specific ecosystem services reveal?
5) What are the relative merits of alternative approaches and methods?

Methods

Several studies on ecosystem valuation, mostly post 2000, were identified through several Internet based searches. A total of 89 cases were considered relevant for the present review and entered in a specific MS Access© database. Each entry provides information on a number of key characteristics of the studies, such as:

i) Authorship and publication date
ii) MA service category valued, ecosystem type and region
iii) Method used, categories of value investigated, welfare measure applied
iv) Value estimate and unit measurement
v) Policy rationale of the study
vi) Treatment of uncertainty and temporal stability of estimates

The resulting database contained 120 rows as studies valuing multiple services were defined by one row for each service. The material produced was evaluated qualitatively in order to reveal persistent practices in the studies and trends in value estimates.

Results

Simple descriptive statistics indicate that cultural and provisioning services are the most often-valued ecosystem services; regulating and supporting follow. The most widely applied economic valuation method is Contingent Valuation. Regional dispersion of valuation studies indicates a clear dominance of northern American studies while those in Asia are multiplying rapidly. The rationale for undertaking a valuation study of an ecosystem service has been mostly to raise awareness either in the public or among decision-makers. Only in a few cases was the aim of the study explicitly to facilitate an investment decision.

Uncertainty in the provision of ecosystem services under different management regimes and scales is rarely integrated into the valuation context. The definition and communication of changes in service provision is rather simplistic; most studies lack a clear quantitative expression of change in the service provision. In stated preferences approaches photos represent the usual reference and visualisation material. Studies with spatially explicit changes informed through geo-referenced maps represent a distinctive improvement in this direction. Most studies focus on multiple services.

Linking changes in service provision with human welfare is a central point in valuation design. Willingness To Pay (WTP) for a gain (compensating variation) is the usual welfare measure applied followed by cost estimates. Uncertainty related to future preferences is customarily addressed through option prices as presented and discussed in the review *in extenso*. The dynamics of preferences was addressed only once through the study of their temporal stability. Taken into account the concept of ecosystem services, it is not surprising that the majority of cases estimate (direct) use values. Social acceptability of the valuation process can be assessed through protest bids, whereas payment vehicle rejection is a strong indicator of its institutional conformity. Distributional conflicts are, as expected, not handled.

Value estimates are most often expressed in annual, per capita terms. In cases where a temporal aggregation of future benefits streams is attempted, a time period of 20 years and discount rates appr. 3-5% are applied. We present average value estimates of specific ecosystem services (expressed in Euros 2006) although they reveal at best a preliminary ranking of their importance in terms of human preferences.

The review concludes with a discussion of the relative merits of alternative approaches and methods.

Functional traits underlie the delivery of ecosystem services in different trophic levels

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Abstract

Functional traits of organisms can serve as tools for predicting and quantifying ecosystem service delivery in response to biodiversity loss. We collected published studies (~250) showing effects of functional traits on various ecosystem services, and the underlying ecosystem processes, at single trophic levels. The majority of studies considered plants and soil invertebrates, but relationships have been documented for a range of other organisms and habitats. Within each trophic level, specific processes and services are often affected by a combination of traits. At the same time, particular traits are involved simultaneously in the control of different processes, resulting in predictable clusters of traits and services. Multivariate analyses showed clear associations between traits of plants and soil organisms that underlie ecosystem nutrient economy, herbivory control and fodder and fibre production. The review demonstrates the potential for integrating the functional traits approach into predictive models of ecosystem services.

Introduction

Most ecosystem services can be provided by more than one species (or genotype within species) and the balance of species (or genotypes) responsible varies in time and space. Therefore it is useful to consider ecosystem service provision in terms of the traits, rather than the taxonomy, of service providers. Very little is known about how measures of the diversity of such functional traits relate to service provision. The objective here is to review literature linking functional traits to ecosystem service delivery as a step towards using measures of functional diversity to predict ecosystem service levels, and towards using links between these `effect traits' and the `response traits' which determine organisms' responses to change, to predict the impact of change on service delivery. We answer the following questions:

- What is the empirical evidence for links between functional traits of organisms and ecosystem service delivery?
- How is this knowledge spread across taxa, habitats and categories of service?
- Are certain combinations of functional traits linked to certain combinations of ecosystem services?

Methods

We found 247 references which showed an effect of traits of ecosystem services or on ecosystem processes with a clear link to services. Each reference was classified according to ten criteria:

1) Whether the study was a review or presented an original data analysis.

2) The Millennium Ecosystem Assessment service category assessed.

3) The specific ecosystem service assessed.

4) The ecosystem process underlying the service.

5) At which level of organisation the traits were considered:

a) species level, i.e. species with different traits differed in service provision;

b) functional group level, i.e. different functional groups differed in service provision;

c) the presence of dominant traits, or the weighted average of traits, in a community; or

d) the divergence in traits in a community (using functional group richness or other available indices of trait diversity).

6) The specific trait(s) considered.

7) Whether traits were assessed in combination with other traits or individually.

8) The relationship (+ve, -ve or unknown) of trait values with ecosystem services.

9) The organisms providing the service.

10) The ecosystem type in which the study was undertaken.

The resulting database contained 548 rows, as studies assessing multiple traits or processes/services, were defined by one row for each trait/service combination.

Detrended Correspondence Analysis (DCA) was used to show the similarity among ecosystem processes/services in terms of the traits that provide them. The association between services and traits was based on contingency tables (Chi-squared) and visually represented by the distance between points in multivariate space.

Results

Numbers refer to the criteria examined, see `Methods':

1) 25% of the examples came from reviews as opposed to original data.

2, 3) Most services examined were in the `regulating' or `supporting' categories.

4) The processes for which trait effects have most often been reported were decomposition/mineralization (171), productivity (66), nutrient retention/sedimentation (45), evapotranspiration (27) and herbivory (27).

5) Effect traits were most frequently reported at the level of functional groups and the dominant traits in a community.

6) These traits referred mostly to the morphological and chemical structure of plants, and to feeding habit and substrate type for fauna and microbes.

7) Most studies examined traits individually, rather than in combination, even though different studies identified different traits in provision of particular services. Several key traits appear to influence simultaneously a range of ecosystem services; for example leaf chemistry and morphology with canopy and root architecture in plants, and body size with feeding habit in soil invertebrates.

8) In 69% of studies the value of the traits considered was positively correlated with service provision. In most other cases, the relationship was not stated.

9) 50% of studies focussed on vascular plants and 20% on soil macrofauna, with other groups poorly represented.

10) In descending order of frequency, studies examined grassland, soil, freshwater, forest, shrubland, agricultural and wetland ecosystems.

The involvement of a given trait in multiple service delivery and the dependence of each service on a range of traits resulted in clumps of associated traits and services (Figure 3). In particular, the DCA analysis considering all main processes and services from the database was strongly driven by differences in the specific functions associated with different types or organisms, therefore discriminating services mediated by plant and soil organisms (top left cluster of Figure 3A), from those mediated by aquatic organisms (bottom left) and by other insects (centre right). When considering only plant and soil invertebrate traits (top left cluster in Figure 3A), particularly close associations were found among those traits that underlie nutrient economy, herbivory control, and fodder and fibre production (provided mostly by different plant traits) and among the services related to water flow and soil formation (provided mostly by soil invertebrate traits). When considering only plant traits and the related processes (Figure 3B), the analysis discriminated mostly between processes related to pollination (first axis) and other processes affected by traits relating to processes and services at smaller vs. larger spatial scales (second axis; e.g. fertility and nutrient cycling vs. water and climate regulation).

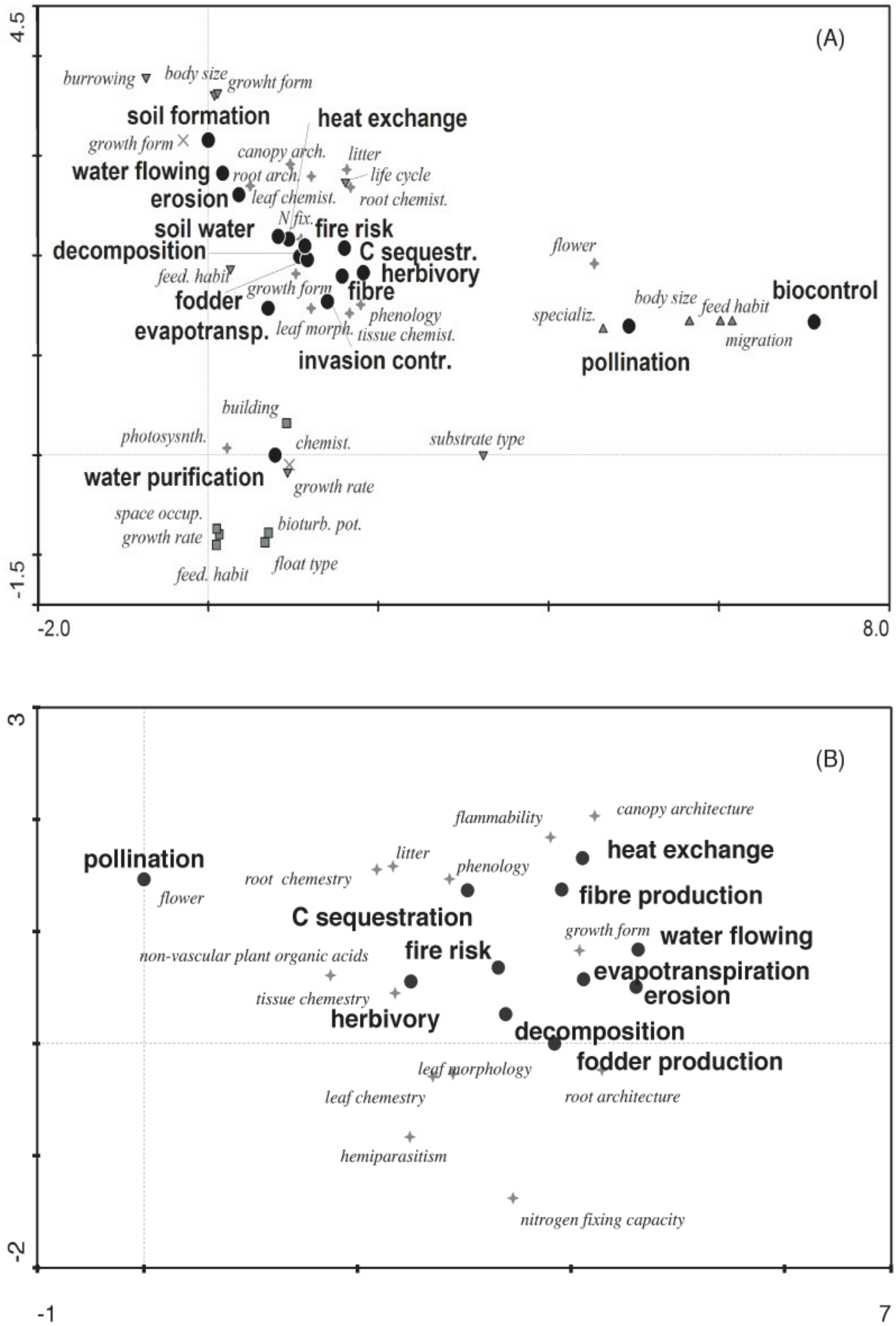
Discussion

The review shows that functional traits are key constituents of biodiversity underlying a range of ecosystem services across different trophic levels and habitats. It shows the combined effect of various traits on bundles of ecosystem services and their underlying processes. The same trait contributes simultaneously to the control of different processes, whilst given processes are controlled by a range of traits.

Future research needs

It is clear from the above where the main gaps are in terms of ecosystems, service types and organism types studied. This review has involved studies examining single trophic levels. Given that ecosystem processes and services rely on organisms from different trophic levels, the match between traits and services will benefit from consideration of interactions among different trophic levels, i.e. top down and bottom up effects. This will be the topic of our next review.

Figure 3: Association between traits and ecosystem processes (A, including all organisms; B, only plants). The DCAs show the similarity among ecosystem processes (black circles) in terms of the traits (different symbols for different organisms) that predict them (distance between two points reflects contingency). Only those processes with more than ten entries in the literature were considered. The first two DCA axes, accounting around 40% variance for each analysis, are shown. Symbols are: "star" for vascular plants, "cross" for non-vascular plants (only in A), "downward-triangle" for below-ground invertebrates, "upward-triangle" for above-ground invertebrates, "square" for all different aquatic organisms.



Assessing and monitoring ecosystems – indicators, concepts and their linkage to biodiversity and ecosystem services.

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Introduction

The Millennium Ecosystem Assessment (MA) raised the need for indicators, particularly those linked to biodiversity and its role in providing and sustaining ecosystem services. According to the MA's Biodiversity Synthesis the most important direct drivers of biodiversity loss and ecosystem service changes are habitat changes (such as land use changes, physical modification of rivers or water withdrawal from rivers), climate change, invasive alien species, overexploitation of resources, and pollution.

Appropriate indicators are needed to assess and monitor ecosystem services and their underlying functions and processes. However, current indicators are subject to several drawbacks: i) they do not fully cover the major components of biodiversity, i.e. genetic, compositional, structural and functional biodiversity; ii) they do not address the full range of spatial scales needed for local, national, regional, sub-global and global assessment, monitoring and management; iii) they do not sufficiently address ecosystem functions and processes; iv) they do not account for ecosystem uniqueness; v) they do not sufficiently distinguish between managed and natural ecosystems and related "managed" and "natural biodiversity".

Methods

We collected 617 published studies from the *Science Citation Index Expanded* (SCIE, time span: 1997–May 2007) in order to review the state-of-the-art for ecosystem indicators and to identify major gaps in knowledge. Each reference was classified according to the following indicator characteristics:

- Ecosystem(s) addressed by the indicator.
- Type of indicator (numerical type, abiotic, biotic, landscape).
- Rationale behind, and purpose of, indication.
- Relation to biodiversity and ecosystem services.
- Spatial scale of application.
- Related policies "driving" the development of indicators.
- Validation and standardisation of indicator/indication system.

The resulting database contained 534 indicators covering six ecosystems (forests, grasslands and shrublands, agro-ecosystems, soils, wetlands and rivers; see Figure 4) and landscapes (landscape-level indicators). Each indicator is related to 72 indicator characteristics, which are classified into the seven groups defined above.

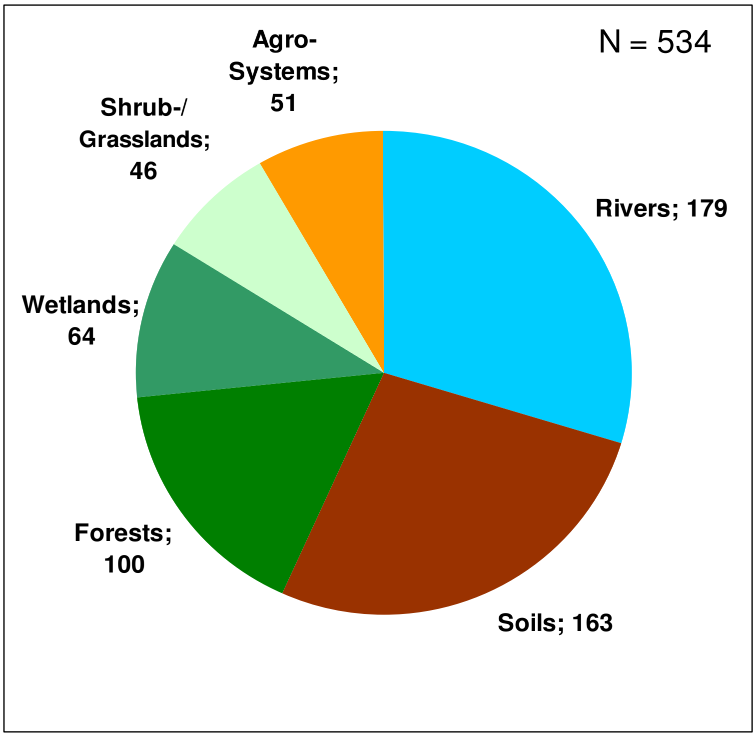

Figure 4: Allocation of indicators to ecosystems.

<u>Results</u>

Analysis of the database revealed that bioindication is frequently applied in all ecosystems. Indicators to assess the impact of environmental stress and its effect on biodiversity have been developed for all ecosystems, and many indicators are being widely applied across ecosystems, such as the number of endangered species, the number of sensitive taxa or Shannon-Weaver/Simpson diversity indices. Yet, biodiversity is most often referred to as 'species diversity' or simply as the 'number of taxa' present. According to current concepts of biodiversity, this only covers the compositional aspect of diversity. Other components, such as genetic, structural and functional diversity, remain unconsidered. However, measures of functional diversity, in particular, would be useful for assessing ecosystem services, and their underlying ecosystem processes. Decomposition of organic material, for instance, is a key supporting service in many ecosystems performed by numerous organisms at different trophic levels. The service is likely to be maintained as long as the systems are functioning, i.e. the processes are running at the rates needed. The linkage of the latter to biodiversity, however, is not well-known. The provision of goods and fuel might be indicated by their market prices and other monetary values, which is presumably widely applied, even if not reflected by our database. Regulatory and supporting services, in contrast, belong to indirect services and cannot be converted directly into monetary values. We hardly found any indicators that accounted for the latter service categories and the underlying ecological processes, respectively.

In terms of spatial scale, results show that bioindication is almost limited to comparatively small areas for all ecosystems. Species-based indicators, for instance, are restricted for bio-geographical reasons, while the large-scale use of metrics (taxa number, abundance, etc.) is confined because of ecoregional and ecosystem type-specific differences, i.e. different natural reference conditions. Species traits potentially provide the solution to this spatial limitation of bioindication, since they rather account for ecosystem (community) functions and processes and, thus, may be applicable in comparable ecosystems at larger scales. They also may provide more insight into the diversity of functions and processes linked to them. However, the use of traits in ecosystem assessment and monitoring is still infrequent.

Large-scale monitoring is used to address the landscape-level, but this is based mainly on abiotic indicators: area, spatial composition, fragmentation, land use, etc. These metrics can be easily derived by remote sensing using GIS systems and, thus, provide a means to cover large geographical areas. On the other hand, their applicability is still limited at small spatial scales and also restricted with respect to bioindication, in particular to biodiversity.

Evaluation of the criteria associated with the purpose of indication showed that habitat quality, monitoring and biodiversity evaluation play a chief role for all ecosystems. For agro-ecosystems, biodiversity-related indicators were most frequently cited, whilst for rivers indicators of ecological quality were the most extensive. The latter is owed to the European Water Framework Directive (WFD), which stimulated the development and application of bioindicators all over Europe. Likewise, the references on grasslands, forests and agro-ecosystems frequently referred to the Convention on Biological Diversity (CBD). The high number of soil indicators seems to be related to the European Soil Directive awaited in the near future. Environmental policies are likely to be a major driver of indicator development.

<u>Future research needs</u>

The review on ecosystem indicators and landscapes revealed the following gaps that should be addressed by future concerted actions of ecologists, economists and decision makers:

- Indicators accounting for genetic biodiversity.
- Indicators accounting for ecosystem functions and processes.
- Indicators accounting for regulatory and supporting services and service rates.
- Indicators derived from predictive models.
- Socio-economic indicators, in particular with respect to monetary values of regulatory and supporting services.
- Bioindicators addressing assessment and monitoring at large spatial scales (regional, sub-global, global).