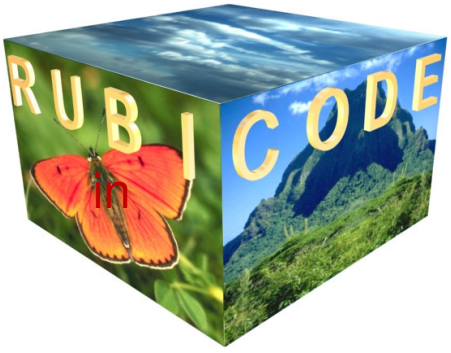

The **RUBICODE** Project

Rationalising Biodiversity Conservation Dynamic Ecosystems

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Ecosystem Services and Biodiversity Conservation: Knowledge gaps and roadmap for future research

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1. EXECUTIVE SUMMARY

The scientific and public interest in ecosystem services has increased since the Millennium Ecosystem Assessment (MA) demonstrated the importance of ecosystem services for human well-being. At the same time, this report shed light on the critical situation facing numerous ecosystems. A central message of the MA is the need to extend general awareness of the importance of conserving biodiversity to maintain our own quality of life. Progress in this fast-moving field reveals new challenges in the basic science on ecosystem services. Here, we deliver a "road-map" to guide future research on ecosystem services and to develop efficient research policies for biodiversity conservation in Europe. The research priorities listed in this review were compiled based on RUBICODE reviews. The results were discussed subsequently with scientists and stakeholders during workshops and conferences and were finally compared with research recommendation of international biodiversity research programs.

A detailed list of recommendations is presented in this report. In summary, there is an urgent need for research to:

- *Quantify the role of biodiversity, including uncharismatic and speciose groups of organisms such as invertebrates, lower plants and fungi, in ecosystem function and service provision.*

- *Develop trait-based approaches to ecosystem service assessment which include: (i) improved knowledge of trait-based multi-trophic linkages within ecosystems; (ii) trait-based thresholds for the provision of services; and (iii) trait-based indicators to assess and define quantitatively service provision at multiple scales.*

- *Develop improved methods for the integrated assessment of ecosystem services at different spatial and temporal scales, including methods for: (i) investigating interactions between the demand and supply of multiple ecosystem services; (ii) upscaling and downscaling; and (iii) integrating valuation processes and results in impact assessments and models.*

- *Identify thresholds in the relationships between biodiversity, ecosystem functioning, ecosystem services and human well-being to identify points beyond which the level of ecosystem service delivery changes dramatically and perhaps irreversibly.*

- *Identify and quantify the impact of direct and indirect socio-economic and environmental drivers on ecosystem services, and develop tools to design and evaluate policy options for ecosystem service management under uncertain futures.*

- *Improve understanding of the role of the cultural, economic and policy contexts in ecosystem service assessment, particularly in the choice of: (i) metrics, valuation and appraisal methods; (ii) stakeholder involvement; (iii) required levels of precision; and (iv) policy instruments and decision support tools.*

- *Develop an improved classification for ecosystem services and values, which includes values of flows of ecosystem services and stocks of ecosystem assets and allows for the distinction between final and intermediate services.*

- *Enhance the usefulness of value, price and cost estimates for ecosystem services by: (i) improving database coverage, quality, depth and access; (ii) filling key gaps in valuation evidence; (iii) investigating replication, validity and transfer of functional assumptions and values estimates; and (iv) developing agreed protocols for comparing and transferring value estimates.*

- *Develop tools, methods and decision-support systems to assist the multi-level governance of ecosystem services.*

- *Quantify the role of multifunctional land management and landscape patterns on the provision of ecosystem services and develop options to conserve biodiversity and maintain ecosystem integrity outside protected areas.*

- *Develop tools and methods to promote the uptake of business opportunities associated with the sustainable management of ecosystem service delivery.*

2. INTRODUCTION

Biodiversity loss caused by increasing pressures from human activities is far from being halted despite numerous efforts from regional to global political initiatives. On one hand, the implementation of conservation action remains slow and is often hindered by a shortage of financial resources. On the other hand, biodiversity conservation still follows traditional approaches which largely neglect the needs of human beings. However, humans strongly depend on functioning natural systems as they receive numerous essential services from them. Hence, the concept of ecosystem services has attracted increasing interest in the scientific literature (e.g. Costanza et al. 1997; Daily 1997; Luck et al. 2009). Ecosystem services are now widely recognized as additional arguments for the conservation of biodiversity although there remains substantial controversy over their use and misuse (Ghazoul 2007; Ridder 2008). Since the United Nations Millennium Ecosystem Assessment (MA 2005) inventory on the condition of the world's natural systems, it has become increasingly recognized that ecosystems services play a key role in the conservation and sustainable use of natural resources. Despite the popularity of the ecosystem service approach in the academic world, it has rarely been implemented in decision support systems for biodiversity conservation (Turner and Daily 2008). A series of mainly practical limitations may account for the present situation, for example trade-offs between different services and human beneficiaries, mismatches between political and ecological scales, or difficulties regarding the quantification and valuation of ecosystem services which cannot easily be translated into monetary units. In summary, the ecosystem service approach needs to be developed into a more practical and transparent framework in order to be useful for decision makers.

Another issue which is not sufficiently addressed in current conservation approaches is the dynamic nature of ecosystems. Most conservation strategies focus on protected areas and are still developed around a static and uniform view of their nature and environment. Yet, ecological research increasingly emphasizes dynamic processes within populations, habitats, and ecosystems. Furthermore, human activities which cause pressures on ecosystems and their associated services are also dynamic. Thus, innovative conservation approaches are required which ensure ecosystem resilience in response to disturbance and thereby the maintenance of ecosystem service delivery. The implementation of such new approaches appears to be particularly urgent in the face of rapid land use and climate changes.

The EU-funded project "Rationalising biodiversity conservation in dynamic ecosystems" (RUBICODE) was established to investigate the benefits which humans derive from terrestrial and freshwater ecosystems and their associated organisms. The project identifies those components of biodiversity which deliver specific services to human societies to provide a more rational basis for biodiversity conservation. By reviewing existing knowledge and developing and applying new concepts, RUBICODE aims to provide support for policy makers and decision processes.

This report provides an overview of gaps in knowledge and future research needs identified by RUBICODE activities while taking into account external initiatives for biodiversity conservation. The specific objectives are: (1) to identify critical gaps in knowledge which constrain the development of innovative large-scale conservation approaches, (2) to point out future research which is required to overcome these constraints, and (3) to evaluate whether existing European and national research strategies and initiatives are consistent with those research needs identified by RUBICODE.

3. METHODS

This review on gaps in knowledge and future research needs is based on research output from various sources. The first source is the extensive reviews performed by the RUBICODE project (available from the project website http://www.rubicode.net/rubicode/outputs.html):

- Review on concepts of dynamic ecosystems and their services (Vandewalle et al. 2008);
- Review on the dynamics of economic values and preferences for ecosystem goods and services (Kontogianni et al. 2008);
- Identifying and assessing socio-economic and environmental drivers that affect ecosystems and their services (Anastasopoulou et al. 2007);
- Assessing and monitoring ecosystems: Indicators, concepts and their linkage to biodiversity and ecosystem services (Feld et al. 2007; Feld et al. in press);
- Review of indicators targeting habitat area (Martins da Silva et al. 2007);
- Functional traits underlie the delivery of ecosystem services in different trophic levels (De Bello et al. 2008);
- European habitat management strategies for conservation: Current regulations and practices with reference to dynamic ecosystems and ecosystem service provision (Haslett et al. 2007); and
- The effectiveness and appropriateness of existing conservation policies and their integration into other policy sectors (Jongman et al. 2008).

Beyond these reviews, external expertise from the scientific and stakeholder community was attained during four workshops:

- Assessing and monitoring ecosystems: Concepts, policies and indicators (27 February - 1 March 2007, Essen, Germany);
- Establishing the link between threat and action (15-16 May 2007, Brussels, Belgium);
- Ecosystem services and drivers of biodiversity change (25-28 February 2008, Helsingborg, Sweden); and
- Habitat management and conservation policy: Strategies for a new dynamic approach focused on ecosystem service provision (29-30 April 2008, Kranjska Gora, Slovenia).

The main findings of the workshop on "Ecosystem services and drivers of biodiversity change" were further discussed in a two week long e-conference (31 March - 11 April 2008). The reports of these activities can likewise be downloaded from the project website.

The results obtained from the RUBICODE reviews, workshops and the electronic conference were then compared with outputs from previous and ongoing European and national biodiversity research strategies and initiatives, including DIVERSITAS (http://www.diversitas-international.org), Biodiversa (http://www.eurobiodiversa.org/) and EPBRS (The European Platform for Biodiversity Research Strategy, http://www.epbrs.org). The interim report "The economics of ecosystems and biodiversity", related workshop reports of the TEEB initiative (http://ec.europa.eu/environment/nature/biodiversity/economics/index_en.htm) and outputs from the EU-framework projects ALARM (Assessing Large Scale Risks for Biodiversity with tested Methods, http://www.alarmproject.net), ALTER-Net (A Long-Term Biodiversity, Ecosystem and Awareness Research Network, http://www.alter-net.info), and BioStrat (Developing the EU Biodiversity Research Strategy, http://www.biostrat.org) served as additional sources. The results obtained from this process are presented in Section 4 on "Research Needs".

The next step in the process of generating a roadmap for future research was a three day-long consultation with stakeholders. In order to provide a comprehensive list of tangible research priorities, 45 stakeholders from research-organising and research-funding organisations and 21 scientists discussed the importance of the proposed research needs during the workshop "The way ahead in ecosystem service & biodiversity research - Ecosystem services and biodiversity conservation: Knowledge gaps and roadmap for future research", which was held in Leipzig, Germany (12-14 January 2009). Gaps in knowledge and research needs identified by various RUBICODE activities were re-evaluated in different thematic working groups as well as during plenary and open discussions. The aim of this interactive process was to determine the five most important research needs within the different subject areas. Workshop participants were further asked to state reasons for their selection and to propose solutions as to how research needs could be addressed most effectively. These recommendations are presented in the workshop report (which can be downloaded from the website and is summarised in Annex 2).

These recommendations formed the basis for a final list of research priorities provided in Section 5 on "Synthesizing the Research Recommendations".

4. RESEARCH NEEDS

The research needs were grouped in the following seven sections, which reflect the thematic areas considered during the RUBICODE project.

4.1. Concepts of ecosystem services

It is now widely recognised that ecosystems services play a key role in the conservation and sustainable use of natural resources. However, much remains to be understood in terms of how ecosystem services are provided and the factors influencing the provision of ecosystem services.

The following research needs therefore focus on the ecological underpinnings of service provision, ecosystem dynamics, and methodologies and tools for ecosystem service assessment:

A) Improve knowledge on the ecological underpinnings of service provision through:

- Assessing the current status of ecosystems in terms of their capacity to deliver services and identifying which services are most under threat.
- Quantifying the characteristics of biodiversity (from populations to communities, habitat types and landscapes) required to provide ecosystem services, i.e. their service provider characteristics.
- Understanding how incremental changes in service provider characteristics affect service provision.
- Understanding interactions between service providers, supporting habitat and ecosystem service delivery, and determining whether minimum habitat area thresholds for the sustainability of services can be defined.
- Understanding the impact of intra- and interspecific species interactions on ecosystem service provision, including circumstances where organisms might provide multiple ecosystem services, support the provision of ecosystem services by other organisms or adversely affect ecosystem service providers.
- Examining 'bundles' of ecosystem services whereby multiple services are provided by a collection of organisms.
- Quantifying the supply of ecosystem services relative to thresholds of service demand defined in relation to the needs of beneficiaries of these services.
- Quantifying the effects of invasive species on ecosystem structure, function and services.

B) Improve knowledge on the dynamic nature and responses of ecosystems through:

- Understanding the intricate and dynamic linkages between ecosystems and the importance of these interactions in terms of resistance and resilience to stress.
- Exploring relationships between ecosystem service providers and the socio-economic and environmental drivers of biodiversity change.
- Obtaining evidence on whether increased biodiversity *per se* contributes positively to ecosystem stability and the secure continuation of ecosystem services.
- Understanding environmental limits of ecosystems and identifying non-linear responses and thresholds beyond which the level of ecosystem service delivery changes dramatically and perhaps irreversibly.
- Assessing the implications of ecosystem service disruption for human well-being.
- Evaluating management strategies that ensure the continued provision of multiple ecosystem services under the influence of socio-economic and environmental drivers of change.

C) Improve methodologies for assessing ecosystem services at multiple scales through:

- Quantifying the most appropriate scale for study and management of different ecosystem services.
- Understanding interactions between biotic, abiotic, and human factors that influence ecological processes and ecosystem services at multiple landscape scales.
- Developing methods for upscaling local impacts and responses to landscapes and regions.

- Developing spatially-explicit mapping studies which account for the location of ecosystem service generation, the location of service beneficiaries and their demands for ecosystem services, and the flow of ecosystem services between them.
- Understanding temporal dynamics and time scale mismatches between impacts on ecosystem services and their governance.

D) Improve approaches and tools for ecosystem service assessment, including:

- Experiments on the effects of different components of biodiversity on ecosystem services at a management scale and 'natural experiments' based on real land-use situations.
- Models of interactions between ecosystem service providers, supporting habitats, service beneficiaries and service delivery.
- Frameworks and models for analysing trade-offs between multiple ecosystem services across nested scales.
- Scenarios for projecting trends in drivers and pressures which can be applied to models or frameworks for ecosystem services at multiple scales.
- Decision support systems to make information readily available to land managers.
- Case studies to understand interactions between biodiversity and ecosystem services from which consistent trends can be identified that can be applied more broadly.
- Methods to delineate and assess sensitivities, uncertainties and risks associated with ecosystem service assessment.
- Promotion of interdisciplinary research between the natural and social sciences on ecosystem service assessment to pool knowledge, data and methodologies.

4.2. Drivers that affect ecosystems and their services

Despite the important role of biodiversity in providing essential ecosystem services, biodiversity is increasingly being threatened by fast-paced global change, mostly due to anthropogenic drivers such as land use change, pollution, and climate change. It is essential for continued human well-being to understand how various drivers are affecting ecosystem services and to develop tools to predict how these changes might affect the provision of ecosystem services in the future.

Future research should therefore focus on socio-economic and environmental drivers, scenario development and methods for assessing uncertainties associated with scenarios:

A) Improve information and knowledge on socio-economic and environmental drivers that affect ecosystem services through:

- Understanding potential changes in indirect socio-economic drivers such as science and technology, culture and religion, and their influence on ecosystem services.
- Further research on less well understood direct drivers (pressures) such as natural, physical, and biological phenomena, diseases and wars.
- Improving understanding of the fundamental relationships between species community diversity and composition and ecosystem services to assist in understanding responses to a range of pressures.
- Evaluating the effect of agriculture and forestry practices on biodiversity and ecosystem services, through, for example, the use of biomass and energy crops.

B) Improve methods for developing scenarios of changing drivers and pressures of relevance to ecosystem services through:

- Development of scenarios of drivers and pressures that affect ecosystem service beneficiaries.
- Development of participatory approaches to scenario construction that build on a range of stakeholder perspectives and policy relevance.

C) Improve methods for capturing uncertainty in socio-economic and environmental drivers through:

- Developing conditional probabilistic futures for different sectors.
- Developing shock or 'wildcard' scenarios as explorations of extreme events and 'surprises'.
- Identifying those components of scenarios where uncertainty can be quantified and identifying which variables have high or low uncertainty.

4.3. Valuation of ecosystem services

The valuation of ecosystem services is essential in terms of communicating the importance of these services and developing effective policy tools. Although methodologies for the valuation of ecosystem services exist, there is a real need for more research to develop adequate classifications of services and values, enhance value estimates and incorporate the dynamic nature of ecosystems in valuation methodologies.

The following research priorities focus on improving knowledge on, and methodologies for, the valuation of ecosystem services:

A) Develop improved taxonomies for ecosystem services and values, including better understanding and expression of distinctions between final and intermediate services, and between values of flows of ecosystem services and stocks of ecosystem assets.

B) Enhance the availability and usefulness of value estimates by:

- Improving database coverage, quality, depth and access.
- Adopting a strategic research programme to fill key gaps in valuation evidence, including studies on transfer of value estimates.
- Developing agreed protocols for comparing and transferring value estimates.

C) Improve methods for assessing dynamic aspects of ecosystem service valuation, including:

- Risk and uncertainty in ecosystem service provision.
- Thresholds in ecosystem service provision.
- Scaling up and down across ecosystems and economic systems, in space and time.
- Changes in economic systems, preferences and technologies.

D) Improve understanding of the cultural and political acceptability of different approaches to the estimation, communication and uses of ecosystem service values.

4.4. Biological traits and ecosystem services

Most ecosystem services can be provided by more than one type of organism (species, or genotype within species) and the identity of suitable organisms (ecosystem service providers or ESPs) varies in time and space. Therefore it is useful to consider ESPs in terms of their traits, rather than their taxonomy. Certain traits will determine the ability of organisms to provide a given ecosystem service (effect traits). Certain traits will determine the response of organisms to environmental change (response traits). It is likely that, if traits in these two groups are the same or are linked in some way, the environmental change will have an impact on the provision of the service. Trophic interactions are almost always important in service provision and thus traits affecting relationships between organisms in different trophic levels must be considered when linking environmental change to service provision.

In order to investigate these linkages within and between trophic levels and to assess their relevance to predicting the impact of environmental changes on ecosystem service provision, the following research is required:

A) Improve knowledge on traits across organisms through:

- Developing trait concepts, trait lists and protocols for trait assessments in organisms other than plants.
- Assembling trait databases, including organisms other than plants.
- Identifying effect traits, particularly for organisms other than plants.

B) Improve knowledge on multi-trophic linkages and the response of ecosystem services to environmental change through:

- Identifying traits that act as linkages across trophic levels.
- Describing trait-based interactions that contribute to the delivery of key ecosystem services.
- Understanding the flow of pressures for change through trophic linkages.
- Analysing how trait-based interactions control the delivery of bundles of ecosystem services, i.e. the ecological basis for multifunctionality.
- Identifying sources of vulnerability of service delivery relating to trait interactions.

C) Improve knowledge on the potential for using traits as indicators of ecosystem services through:

- Quantifying linkages between components of functional diversity and ecosystem services.
- Identifying thresholds and benchmark values for traits in relation to ecosystem service delivery in a range of ecosystems.
- Developing databases for vegetation and traits, including algorithms to couple them, and quantifying functional diversity (e.g. trait means, functional divergence) in key European plant communities.

4.5. Indicators of ecosystem services

Indicators represent a fundamental requirement for monitoring ecosystems and for measuring the success of conservation actions. They also represent an essential tool for communicating complex patterns and processes to decision makers. Therefore, indicators should be robust, repeatable, widely accepted, and easily understood (Balmford and Bond 2005).

In order to improve indicators of biodiversity, including indicators of habitat area and ecosystem services, and their application across different ecosystems, the following research is required:

A) Improve indicators of biodiversity and ecosystem services through:

- Developing indicators of genetic diversity, particularly those that indicate the adaptive capacity of organisms to changing environments.
- Developing indicators of ecosystem services, rates of ecosystem service delivery and of ecological processes underlying ecosystem service delivery.
- Developing indicators for biodiversity at large spatial scales to address conventions and agreements at the international level.
- Developing indicators that incorporate economic and other values of ecosystem services.

B) Improve the suitability of habitat area indicators for biodiversity assessment through:

- Increasing the resolution of data, e.g. CORINE-land cover maps (CLC), which form the basis for habitat area indicators in order to obtain reliable estimates in trend analysis.
- Creating common definitions and baseline data sets which combine national inventories with CLC calculations.
- Improving data quality by using standardised protocols for sampling and information processing.
- Verifying satellite images of all ecosystem types in the field.
- Combining habitat area indicators with other indicators of biodiversity to improve information on habitat quality.
- Validating the links between indicators of habitat area and other indicators of biodiversity for different ecosystems and investigating the scale dependency of this relationship.

4.6. Habitat management and ecosystem services

In general, there is a need for research to develop a more dynamic approach to habitat management that takes account of ecosystem change in space and time rather than the present rather static approach. There is also a need to further investigate the sustainable provision of ecosystem services within the bounds of management for conservation. This approach has the benefit of acting as an "early warning system" for biodiversity loss, whereby service provision will cease before the extinction of service providers.

To improve the management of habitats and ensure the sustainable provision of ecosystem services, the following research is therefore needed:

- Quantify change in spatial habitat mosaic heterogeneity over time and its role in mitigating the effects of climate change.
- Evaluate the function of ecological corridors in dynamic ecosystems and the appropriateness of corridors and networks in conservation management.
- Place a greater emphasis on research needed to conserve invertebrates, including a better understanding of their role in ecosystem function and provision of ecosystem services.

- Combine research on different major taxonomic groups to provide integrated practical management practices, strategies and policy.
- Develop methods to balance the conflicts between economic service provision and biodiversity conservation management.

4.7. Conservation policy and ecosystem services

In order to incorporate an ecosystem services approach into policy, it is important that any research on ecosystem services be closely linked with the governance context in which it is embedded. To achieve this, it is essential to carry out research on the links between governance, public perceptions and attitudes, planning and communication.

Research should focus on the governance and institutional context to incorporate an ecosystem services approach into conservation policy as well as communication and planning:

A) Improve the political and institutional knowledge base through:

- Understanding the ways in which human societies, enterprises and well-being depend upon, or can be enhanced by, ecosystem services.
- Assessing the contribution that the protection of ecosystem services will make to biodiversity conservation.
- Investigating the risks associated with conservation based on ecosystem service delivery.
- Developing and evaluating participatory adaptation strategies for sustainable service delivery at national, regional and local scales.
- Improving knowledge of how the ecosystem services approach could be integrated into other policy sectors to develop a more integrated approach to policy-making and delivery.
- Analysing local knowledge, perceptions, attitudes and preferences of ecosystem services and understanding how these factors affect individual and community behaviour.
- Understanding the impacts of governance and conflict management at different scales on the provision of ecosystem services.
- Understanding the institutional context of ecosystem service change and how different institutional structures and property rights regimes impact on the behaviour of individual and collective beneficiaries.
- Designing dynamic institutions that help to maintain different ecosystem services.
- Developing interdisciplinary methodologies that support capacity building for public involvement in conservation and sustainable use of ecosystem services and biodiversity.

B) Improve communication about ecosystem services through:

- Identifying good practices to encourage two-way communication with the public and stakeholders in order raise awareness of the key importance of natural systems and the risks and projected impacts of ecosystem services change.
- Promoting public participation to set objectives for ecosystem service delivery in relation to stakeholder preferences and values.
- Developing tools to facilitate communication within and between sectors, ministries and institutions, and policy communities.

C) Improve methods and knowledge for incorporating ecosystem services into planning through:

- Developing mechanisms for factoring ecosystem service change into rural development planning and conservation planning, including the design of nature reserves and protected areas.
- Developing tools for understanding and integrating ecosystem service conservation into corporate environmental management systems.
- Integrating considerations of biodiversity and ecosystem services into impact assessments, particularly into environmental impact assessment and strategic environmental assessment processes.

5. SYNTHESIZING THE RESEARCH RECOMMENDATIONS

The short list of recommendations presented in this section is an attempt to synthesize the more specific recommendations presented in the above section, and to capture the priorities identified in the Leipzig workshop report (Annex 2). This list does not replace the list given in the preceding section, which provides much of the detail necessary to implement the overarching recommendations presented in this section. The research recommendations listed below are not presented in priority order.

Research is needed to:

1. *Quantify the role of biodiversity, including uncharismatic and speciose groups of organisms such as invertebrates, lower plants and fungi, in ecosystem function and service provision.*

Ecosystem services may be provided by individual species, functional groups of species or entire ecological communities. Further research is needed to identify and quantify the role of biodiversity in ecosystem service provision. This will help to inform strategies for managing services through managing the underpinning biodiversity. There is also an urgent need to place a new and much greater emphasis on understanding the importance of uncharismatic but species-rich groups of organisms to ecosystem service delivery. Invertebrates, lower plants and fungi form not only by far the greatest portion of biodiversity, but they also have a wide range of essential roles in ecosystem function and provide an equally wide range of ecosystem services, the majority of which have not yet been considered. The vast numbers of species involved means that it will be necessary to identify proven indicator or surrogate groups of species or species traits that can be used in policy decisions.

2. *Develop trait-based approaches to ecosystem service assessment which include: (i) improved knowledge of trait-based multi-trophic linkages within ecosystems; (ii) trait-based thresholds for the provision of services; and (iii) trait-based indicators to assess and define quantitatively service provision at multiple scales.*

Ecosystem services are rarely provided exclusively by a single species. Different species possessing the traits underlying service provision are important at different times and in different places. Furthermore, service delivery is almost always dependent on interactions between trophic levels. Traits underlying ecosystem service provision (effect traits) need to be compiled in trait databases using standardised protocols. The quantification of threshold

values for traits of species in a community which are necessary for the maintenance of service delivery at the level required is necessary to assess how far an ecosystem is from a functioning state. It sets goals and, therefore, represents a precondition for habitat and ecosystem management. Case studies, as well as empirical and modelling approaches, are considered as suitable tools. There is an unmet demand for ecosystem service indicators. By transferring traits into tangible, communicable and relevant indicators (for example, indices and multimetrics) applicable across different scales, ecosystem assessment by various decision makers and stakeholders could be facilitated substantially.

3. *Develop improved methods for the integrated assessment of ecosystem services at different spatial and temporal scales, including methods for: (i) investigating interactions between the demand and supply of multiple ecosystem services; (ii) upscaling and downscaling; and (iii) integrating valuation processes and results in impact assessments and models.*

Ecosystem service assessment requires a multi-disciplinary approach which can be delivered through integrated assessment modelling involving physical, ecological and socio-economic methods. Demand from ecosystem service beneficiaries and the supply of services by biodiversity operate and interact at different scales emphasizing that scaleable models are required covering local, regional and continental scales. Methods are required that enable better use of valuation results across different scales and take account of how values at one scale may be dependent on factors at other scales. Future research in these areas should focus on developing interfaces between valuation or benefits-transfer methods and various integrated assessment and modelling tools. In addition, assessment of synergies (positive feedbacks) and conflicts between different services and different ecosystems should be addressed.

4. *Identify thresholds in the relationships between biodiversity, ecosystem functioning, ecosystem services and human well-being to identify points beyond which the level of ecosystem service delivery changes dramatically and perhaps irreversibly.*

Ecosystem services are characterised by non-linear relationships between service provision and ecosystem changes. Therefore, we need to understand the sensitivity and dynamics of ecosystems to environmental change by analysing the non-linear dynamics, thresholds and tipping points. Moreover, the components of biodiversity required for service delivery and the effects of ecosystem service disruption on society remain poorly understood. Further research should investigate ways in which these factors can be better incorporated within ecosystem service assessment frameworks and models, valuation methodologies, and accounting or decision support frameworks.

5. *Identify and quantify the impact of direct and indirect socio-economic and environmental drivers on ecosystem services, and develop tools to design and evaluate policy options for ecosystem service management under uncertain futures.*

Policy tools and frameworks are needed which deal with uncertainty and explore trade-offs. Relevant approaches include participatory scenario development, probabilistic approaches to uncertainty assessment, frameworks or models for assessing multiple ecosystem services, identification of species' response traits to environmental pressures, and methods for enabling decision-making based on incomplete knowledge.

6. *Improve understanding of the role of the cultural, economic and policy contexts in ecosystem service assessment, particularly in the choice of: (i) metrics, valuation and appraisal methods; (ii) stakeholder involvement; (iii) required levels of precision; and (iv) policy instruments and decision support tools.*

Methodologies can influence outcomes, and the most appropriate choices will vary with cultural, social, economic and policy factors. The strengths and weaknesses of different methodological approaches in different societies and policy contexts is required, e.g. comparative ex-post evaluation of the process and outcomes in different cases across Europe, including views of researchers, decision makers and stakeholders. Qualitative and semi-quantitative methodologies (i.e. fuzzy cognitive mapping, Bayesian belief networks, and deliberative techniques) should be integrated with economic valuation approaches. Better, expectation-based validity tests for stated-preference methods (scope sensitivity, substitutes and complements, influence of access regime on value estimates) should also be developed and the utility of combining quantitative information on ecosystem service providers with stated preference methods explored. Social science methods (e.g. agent-based modelling) should increasingly be developed and applied to explore the social values associated with biodiversity and ecosystem services. This should advance understanding of human perceptions of ecosystem services and how human behaviour changes demand for services.

7. *Develop an improved classification for ecosystem services and values, which includes values of flows of ecosystem services and stocks of ecosystem assets and allows for the distinction between final and intermediate services.*

Economic incentives are a potentially powerful tool to improve ecosystem management. However, most ecosystem services are not marketed. The lack of prices and values is a basic impediment for the development of policy tools (Carpenter et al. 2006). Appropriate classification schemes that avoid double-counting or under-counting of services, and standardised reporting practices are thus urgently required.

8. *Enhance the usefulness of value, price and cost estimates for ecosystem services by: (i) improving database coverage, quality, depth and access; (ii) filling key gaps in valuation evidence; (iii) investigating replication, validity and transfer of functional assumptions and values estimates; and (iv) developing agreed protocols for comparing and transferring value estimates.*

Primary valuation studies are expensive. Fuller reporting of the details of primary studies, including development of agreed standards and protocols, and their transfer to public databases, would make valuation results available for cases in which the costs of primary studies would be disproportionate to the policy problem. Continued research on benefits-transfer methods, including meta-analyses of valuation studies, are necessary. A strategic approach to funding primary studies to fill key gaps in coverage, and investment in making existing studies and meta-analyses easily available, is needed at the European level.

9. Develop tools, methods and decision-support systems to assist the multi-level governance of ecosystem services

Levels of ecosystem service provision are in part driven, and are otherwise strongly influenced by policies and decision-making at different levels of governance, from local to national, European and global. Understanding how these drivers and levers interact is

essential for efficient communication between all parties involved and for influencing decisions relating to ecosystem service provision and conservation needs. Further research should investigate ways in which these factors can be incorporated within toolkits to inform decision-making. A decision-support system would enable simultaneous and integrated consideration and comparison of all aspects of ecosystem services, including sustainable development. The toolkit could include the use of a public benefit scoring system, multi-agent simulation models, multi-criteria analysis and an instrument selection tree.

10. *Quantify the role of multifunctional land management and landscape patterns on the provision of ecosystem services and develop options to conserve biodiversity and maintain ecosystem integrity outside protected areas.*

Landscapes and ecosystems are multifunctional, providing a wide variety of services simultaneously. Sustainable provision of these services at the levels required by the beneficiaries requires conservation of biodiversity to maintain ecosystem integrity over the wider landscape. A more holistic and integrated approach needs to be developed to integrate conservation into sectoral policy (e.g. agriculture, transport, industry, etc) and rural development *outside* existing protected area networks. To achieve this will require taking account of different scales of perception (e.g. human versus other organisms) in maintaining landscape heterogeneity and in monitoring and reacting to changes in service provision levels and ecosystem dynamics. The work may involve such areas as integrated modelling of land management and biodiversity cost/benefit analyses while also continuing to advocate the application of the precautionary principle to avoid inadvertent loss of still undocumented services and to safeguard more traditional conservation objectives.

11. *Develop tools and methods to promote the uptake of business opportunities associated with the sustainable management of ecosystem service delivery.*

Businesses have an increasing interest in ecosystem service management. Tools and methods are needed to help engage business stakeholders, appraise business opportunities, analyse trade-offs between different management options, evaluate incentives for ecosystem service management, and explore externalities.

6. DISCUSSION

The development and dissemination of a research agenda for a cross-disciplinary subject area such as ecosystem services and biodiversity is a challenging process. The research priorities presented in this report are the product of a long consultation process involving over a hundred scientists. Such an interdisciplinary approach may have a number of limitations. The majority of institutions were represented by only one member, which may result in individual views. In addition, contrasting views between members of different disciplines or even between members of the same discipline were also evident. The cross-disciplinary aspect of the exercise may however represent one of the strengths of this approach. Motivated by the strong interest of the public in sustainably conserving biodiversity, the full integration of stakeholders during all phases of the project represents the attempt to accelerate knowledge transfer between science and policy-makers. Consequently, the research needs presented in this report were developed in close cooperation with a broad range of research funding and research-organising governmental and non-governmental organisations.

The research needs outlined in this report very closely complement recent research initiatives, including the Millennium Ecosystem assessment (MA), The Economics of Ecosystems and Biodiversity (TEEB) initiative and the European Platform for Biodiversity Research Strategies (EPBRS). The latter produces bi-annual research recommendations following a different theme under each European Presidency. The results presented in this RUBICODE report represent a continuation and refinement of these research recommendations. For example, in its 2005 declaration on climate change and biodiversity conservation, the EPBRS stressed the need to understand the interactions between climate change and ecosystem components. It concluded that quantifying the impact of climate change on the provision of services and the development of strategies to increase the resistance and resilience of ecosystems was an important challenge which needed to be addressed (EPBRS 2005). EPBRS also emphasized the importance of cross-sectoral research and acknowledged that valuation of ecosystem services differed across cultures and stakeholder groups and that these different perceptions needed to be incorporated into valuation efforts. The EPBRS meeting organised under the German Presidency of the EU in 2007 had a sub-theme addressing "Biodiversity and ecosystem services – the Millennium Ecosystem Assessment framework in a European perspective". It stressed the need for improved knowledge on the contribution of biodiversity to ecosystem services, the influence of drivers and pressures, improved methodologies for the valuation of ecosystem services and an improved political and institutional knowledge base (EPBRS 2007). Finally, the EPBRS meeting under the French Presidency of the EU in 2008 addressed the theme of "Biodiversity and Industry" and presented a timely analysis of business practices and ecosystem services (EPBRS 2008). The development of concepts for the payment for ecosystem services (PES), incentive measures and risk assessment were not ranked as high priority research needs by the final RUBICODE workshop, but may represent important tools for making substantial progress in biodiversity conservation, for example, in agricultural landscapes.

The integration of ecosystem incentives into conservation management is an issue stressed also by Carpenter et al. (2006; 2009), who emphasize the importance of research attempts that bring together ecological and economic information, arguing that such information is essential if any assessment or management of the flow of multiple ecosystem services provided by a region or ecosystem is to be made. As few ecosystem services are marketed, we still lack important information pertaining to the prices that reflect the social value of services (Carpenter et al. 2006; 2009). As such, concepts and practical attempts to value ecosystem services (especially regulating services) are urgently needed and could result in important future decision-support tools for practitioners and policy-makers (Carpenter et al. 2006; CBD 2008).

The research needs identified by the RUBICODE project do not reveal entirely new challenges for the understanding and management of ecosystem services. However, this research agenda demonstrates the need to continue and to extend the framework provided by the MA and to increase the efforts to understand and to maintain ecosystem services for human well-being.

We hope that this roadmap for future research clarifies research requirements and stimulates research funding organisations, donors and research planning institutions. The agenda also demonstrates that new coalitions of disciplines among researchers are necessary – as well as research funding programs that promote even stronger institutional and trans-disciplinary cooperation.

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Annex 1

Definitions of key terms

Term	Definition
Dynamic ecosystem	The concept of a dynamic ecosystem, central to RUBICODE, acknowledges the temporal and spatial variability in ecosystem characteristics due to natural or anthropogenic changes affecting the organisms individually or collectively, and hence the reality that a given ecosystem service cannot be maintained indefinitely at a given location. However, as all ecosystems are dynamic, the term is tautological and just serves as a reminder that a static approach to conservation will have limited usefulness.
Ecosystem services	The benefits that humans obtain from ecosystems that support, directly or indirectly, their survival and quality of life. They include provisioning, regulating and cultural services that directly benefit people, and supporting services that are necessary for the production of all other services (MA 2005).
Ecosystem service beneficiary (ESB)	A stakeholder who benefits from, or is affected positively by, an ecosystem service.
Ecosystem service provider (ESP)	An organism, species, functional group, population or community, or trait attributes (*defined below*) thereof, that contributes to ecosystem service provision.
Ecosystem service antagoniser (ESA)	The organism(s) that disrupts the provision of ecosystem services and the functional relationships between them and ecosystem service providers.
Service-providing unit (SPU)	The collection of individuals from a given species and their characteristics necessary to deliver an ecosystem service at the desired level.
Driver	Any natural or human-induced factor that directly or indirectly causes a change in an ecosystem. Direct drivers (sometimes referred to as pressures) are physical, biological or chemical processes that tend to influence directly changes in ecosystem services. Indirect drivers are factors that operate more diffusely than direct drivers, often by altering one or more of the direct drivers (MA 2005).
Functional trait (Response and Effect trait)	An attribute of an organism that has demonstrable links to the organism's function. This includes its response to the environment (response trait) or effect on ecosystem processes (effect trait).
Functional trait attribute	The value/state of a functional trait. It may be categorical (*e.g.* C3 vs C4 for plant photosynthetic pathway) or quantitative.
Functional group	A collection of organisms with similar functional trait attributes.
Indicator	A simple, measurable and quantifiable characteristic responding in a known and communicable way to a changing environmental condition, to a changing ecological process or function, or to a changing element of biodiversity.

Annex 2

Research recommendations from Workshop on Ecosystem Services and Biodiversity Conservation: Knowledge gaps and roadmap for future research

Research priorities on ecosystem services and drivers of change:

- Integrated assessment methodology for investigating interactions between the demand and supply of multiple ecosystem services across different scales.
- Investigation of tipping points beyond which ecosystem service delivery changes dramatically and perhaps irreversibly by quantifying the relationships between biodiversity, ecosystem functioning, ecosystem services and human well-being.
- Tools for designing and evaluating policy options for ecosystem service management under uncertain futures.
- Impacts of human perception and behaviour on the maintenance of biodiversity and ecosystem services.
- Business opportunities associated with the sustainable management of ecosystem service delivery.

Research priorities on quantification and valuation of ecosystem services:

- Develop improved classification for ecosystem services and values, including better understanding of distinctions between final and intermediate services, and between values of flows of ecosystem services and stocks of ecosystem assets.
- Improve understanding of the role of the cultural, economic and policy contexts in the choice of: (i) metrics, valuation and appraisal methods; (ii) stakeholder involvement; (iii) required levels of precision; and (iv) policy instruments and decision support tools.
- Enhance the usefulness of value, price and cost estimates by: (i) improving database coverage, quality, depth and access; (ii) filling key gaps in valuation evidence; (iii) studies to investigate replication, validity and transfer of functional assumptions and values estimates; and (iv) developing agreed protocols for comparing and transferring value estimates.
- Improve methods for taking account of, and communicating, dynamic aspects, including: (i) risk/uncertainty in service provision; (ii) ecological thresholds, tipping points and irreversibility; (iii) evolutionary change of the system under valuation; and (iv) changes in economic systems, preferences and technologies.
- Improve methods for the valuation of services at different scales, including methods for: (i) upscaling and downscaling; (ii) incorporating integrated assessment (long term and global) in valuation methods; and (iii) integrating valuation processes and results in impact assessments (EIA, SEA, SIA, etc) and IA models.

Research priorities on indicators and traits-based approaches for ecosystem service assessment:

- Improve knowledge of trait-based multitrophic linkages within ecosystems by improving knowledge of traits underlying ecosystem service provision (traits lists, databases and protocols).
- Quantify changes in ecosystem service provision as a result of pressures.
- Develop traits-based approaches, including traits-based thresholds (SPUs), to to define quantitatively what constitutes adequate service provision and to predict changes in ecosystem service provision as a result of environmental pressures.

- Identify where trait-based indicators can fill existing gaps in indication of ecosystem service provision by transferring traits into tangible, communicable and relevant indicators to address the target audience (indices, multimetrics, etc).
- Scale up trait-based indicator approaches to broader scales by establishing and validating links between on-site data and remote sensing data.

Research priorities on habitat management and conservation policy:

- Multi-level governance of ecosystem services – understanding drivers and levers.
- Tools, methods and decision-support systems for ecosystem service assessment integrated into a multifunctional toolkit.
- Multifunctional landscapes and ecosystem integrity.
- Recognition of the role of small invertebrates, lower plants and fungi in ecosystem function and service provision.
- Linking landscape pattern and processes (ecosystem services) with land management.