SPECIAL ISSUE: The Dynamics and Value of Ecosystem Services: Integrating Economic and Ecological Perspectives

Designing an integrated knowledge base to support ecosystem services valuation

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Abstract

Quantifying the value of ecosystem services is important for the social recognition and acceptance of ecosystem management across multiple geographic scales. Yet, the data required to perform such quantifications and the dynamic models that allow the projection of policy changes into the future are currently scattered, incomplete, and difficult to use. We describe the design of the Ecosystem Services Database (ESD), an integrated, web-accessible knowledge base that links a relational database for temporally and spatially explicit data to dynamic simulation models. The ESD architecture supports unit standardization, scale translation in space and time, and statistical analysis. Process-based dynamic models and valuation methods can be run by end users either through a web-based simulation engine or on their own computers by means of open-source software. The knowledge base will serve as: (1) a communication tool for use by researchers in several fields; (2) an analytical tool for meta-analysis, synthesis, and prediction; (3) an educational tool to disseminate knowledge on ecosystem services and their valuation; (4) a collaborative tool for institutions involved in different aspects of ecosystem service valuation; and (5) a prototype for linking databases and dynamic models. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Quantifying the value of ecosystem services has become an important vehicle for assuring social recognition and acceptance of the public management of ecosystems (Costanza et al., 1997; Daily, 1997; Wilson and Carpenter, 1999). For example, in 1992 the environmental benefits database of the US EPA's Economic Analysis and Resource Branch contained at least 1600 studies related to

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the economic valuation of environmental benefits (Association of Environmental and Resource Economists, 1992). There is a rapidly growing literature on methods and case studies for economic valuation of particular ecosystems such as wetlands (Barbier et al., 1997), forests (Kramer et al., 1995), particular ecosystem commodities such as water (Smith and Desvousges, 1986; Postel and Carpenter, 1997), species such as the whooping crane (Bowker and Stoll, 1988), or even biodiversity (Pearce and Moran, 1994) and climate (Adams, 1989; RCG/Hagler Bailly, 1995; Glantz, 1992). These estimated values and their associated methodologies have been used in cost-benefit analyses for environmental management (Hanley and Spash, 1993), meta-analyses of ecosystems (Brouwer et al., 1997; Smith and Huang, 1995), and natural resource damage assessment (Kopp and Smith, 1993).

The ability to use this information will depend upon both its quality and accessibility. As valuation methodologies become established, we expect that more case studies will be published in working papers, government reports, and consultant studies. This will bring the challenge of information accessibility and data comparability into focus as decision makers are forced to extend their reach beyond peer-reviewed journals and library databases to quantify the value of ecosystem services.

In order to use existing information in new contexts, decision makers must also face the challenge of benefit transfers (Brookshire and Neill, 1992). For example, in developing countries and small communities, policy makers may be unable to fund valuation research, which is very expensive to initiate and maintain. As a result, they will need ways to transfer the results of studies from other contexts to their particular situation. Benefit transfers require information on methods and units of measurement, as well as the social, ecological and economic context of valuation studies.

To compare ecosystem service values across geographic regions we must, therefore, be able to verify all the components that went into their formulation—not just the results but also the raw data, the valuation methods and the documented analytic streams that produced the results. We

believe that establishing and encouraging open collaboration among users of a common knowledge base will greatly enhance ecosystem valuation research across multiple geographic scales. Open-source research (Schweik and Grove, 2000) describes a situation where scientists collaborate freely and share data, statistical analyses, and results on the World Wide Web. Under the 'open-source' vision, the creative and productive powers of numerous individuals and research groups can be harnessed with the common goal of quantifying the value of ecosystem services and natural capital stocks across broad geographic regions and multiple spatial scales. In the case of ecosystem service valuation, a major obstacle—the lack of available information for both human and ecological systems—might be overcome by fostering the open sharing of data sets, valuation techniques, and dynamic models.

To foster this vision, we have designed a fully transparent, web-accessible knowledge base, which will store and serve not only bibliographic information relative to environmental valuation studies, but also the actual raw data, algorithms, statistical models, and dynamic predictive models used. By using an innovative system design and interface, these elements can be reorganized and used to recalculate ecosystem service values using different methods, and the new results can be posted to the database for further review and revision. End-users will be able to replicate the original calculations, provide input at both the data and method level, and add new methods and estimation algorithms when new research makes them available.

The US National Science Foundation funded the design, implementation and deployment of the Ecosystem Services Database (ESD) in late 2000. This paper is the first published description of the ESD, its rationale, initial contents, management strategy, and the innovative conceptual and technical framework that will lead to the implementation of the ESD over the next years. An initial prototype of the ESD will be available to anyone interested in early 2002, at the Internet address http://esd.umces.edu.

2. The Ecosystem Services Database (ESD)

As part of a synthesis study supported by the National Center for Ecological Analysis and Synthesis (NCEAS, 2002 http://www.nceas.ucsb.edu) an initial estimate of the global value of ecosystem services was assembled (Costanza et al., 1997). This initial synthesis study stimulated much discussion, media attention, and debate. The methods used in the first synthesis were admittedly crude and imperfect, but they also pointed the way to improved assessments in the future. In particular, they pointed to the need to develop comprehensive ecological-economic databases and models that could adequately incorporate the complex interdependencies between human dominated ecosystems and natural ecosystems.

Currently, the data to support the valuation of ecosystem services are scattered and incomplete (Costanza et al., 1997). In response, the ESD project was envisioned at NCEAS to provide an integrated knowledge base coupling a relational factual database with a range of models—including statistical models and dynamic simulation models—in a form that is fully accessible from the World Wide Web. This will provide both a resource for the analysis and synthesis of ecosystem service values and a prototype for linking databases and models that can be applied to many other ecological problems. The ESD will need to represent diverse information (relating to data, processes, and values) in a highly integrated and accessible way. The most widely known web-accessible databases on ecosystem valuation are the Environmental Valuation Reference Inventory (EVRI, Canadian Ministry of the Environment Canada and EPA-USA: EVRI, 2002 URL) and ENValue (Environmental Protection Agency of New South Wales: EPA-NSW, 2002 URL). They are primarily bibliographic databases and do not contain raw data, models, or algorithms used for valuation. Furthermore, the development of ENValue seems to have been abandoned, while EVRI is being actively funded and maintained, but is only accessible to researchers outside Canada for a steep annual fee. Other comprehensive sites illustrate the theory and practice of ecosystem valuation (e.g. King and Mazzotta, 2002 URL)

but do not host searchable databases. The ESD, in contrast, will be an open-access database containing not only bibliographic references and usable data from studies and publications, but also explicit representation of functional ecological processes in a form directly suitable to incorporation in simulation models. The ESD engine and interface will have integrated dynamic modeling capabilities to enable the analysis of socio–economic and ecological values of natural capital. We will make computational and simulation services available directly over the World Wide Web, allowing users with standard web browsers to run and explore reasonably sized models remotely through the web interface; or to download working model descriptions for local simulation, after selecting process information and data from the database with standard query operations.

The following sections describe the principal classes of knowledge represented in the ESD, its innovative technical and conceptual infrastructure, and the conceptual background that allows the integration of very diverse and complex knowledge.

3. Classes of knowledge and their integration

Ecosystem valuation studies often require a very high level of aggregation of raw information, yet require very fine-grained and diverse information in order to be carried out. The classes of knowledge used by the ESD will reflect this duality by grappling with special representational challenges and careful conceptual planning to prevent incompatibilities. This section outlines the main typologies of knowledge that need to be represented in the ESD and some corresponding representational issues.

A quick overview of the data organization in the ESD is presented in Fig. 1 as a simplified, non-rigorous Entity-Relationship diagram (Harrington, 1988). It is important to note that the figure refers only to the factual component of the database, i.e. the static data. The dynamic, process-based knowledge component cannot be represented with a simple diagram; rather, the architectural principles that enable their storage

and use will be briefly discussed in the next section.

As Fig. 1 shows, named sectors in the data model represent different kinds of information. The user entry point for query and retrieval could be any of the sectors: for example, a user might want to conduct a search based on a reference to a published article, a particular biome, a specific ecosystem service, or all of these combined. The main classes of knowledge represented in Fig. 1 have peculiar representation needs and relevance within the ESD, and they are, therefore, given separate descriptions below.

3.1. Bibliographic reference

One aim of the ESD is to provide access to background information derived from published valuation studies. To obtain this, storage and appropriate classification of bibliographic information will be necessary. For simplicity, in Fig. 1 we represent the corresponding data model as a single entity (or 'box'). In the actual database, we provide for non-redundant keyword storage, automatic thesaurus generation, and support structures to implement a multi-standard rating system for quality of data and studies (see the section on quality control below for more detail).

Bibliographic references will be linked to almost every other entity in the database and the corresponding information will be made accessible from query output pages. We will also provide the opportunity for users to create and operate upon views of the database that use only the information related to a particular set of references. In addition, since good bibliographic databases on environmental valuation exist (e.g. ENValue, EVRI), we are exploring the possibility of providing direct links with the information contained in them.

3.2. Geographic information and country indicators

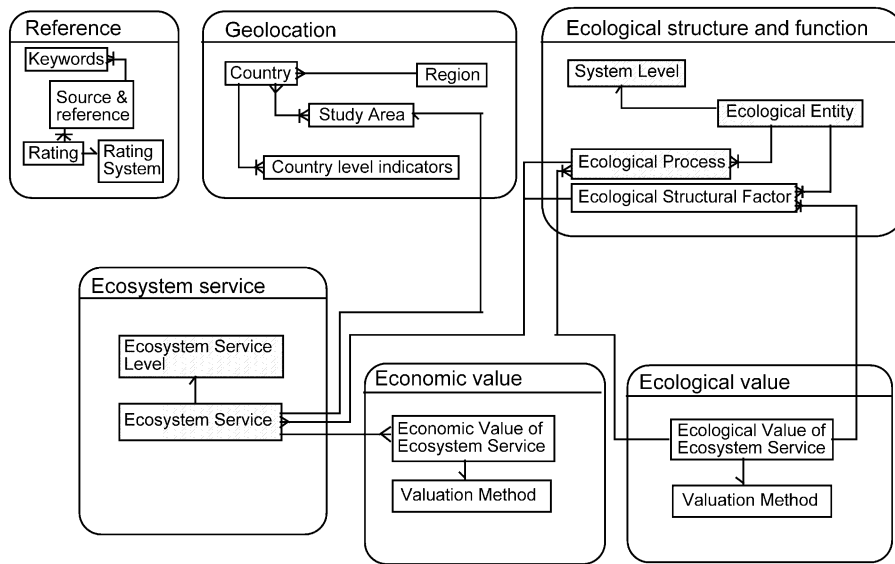This section contains geographical and statistical information specific to the different countries

Fig. 1. Simplified entity-relationship diagram of the factual data model. For clarity, obvious relationships (like the relationship of references with most other entities) have been omitted, and relationships are only indicated in one direction unless the reciprocal interaction is not obvious. The single arrow indicates one-to-one relationships, the three-pronged stands for one-to-many, and a vertical sign indicates that the link is optional.

of the world. The sources and contents of this information are detailed in the next section.

3.3. Ecosystem service

Ecosystem service is the central entity connecting diverse information within the ESD. Like other entities in the data structure, the storage of ecosystem services allows the representation of different levels of organization by incorporating structural information for single data entries. What Fig. 1 represents as a single box will correspond in the database to a tree—i.e. a data structure that represents an inclusive hierarchy of services with an arbitrary number of levels. Such a hierarchy will be explicitly referred to in user queries (through cascading selection menus) in order to obtain information at different levels of aggregation. For example, users will be able to refer to 'Gas regulation' in general—retrieving the aggregated values of different services like maintenance of CO_2/O_2 balance or UV-B protection—or to refer specifically to one of these services. Tables with added structural information of this kind appear elsewhere in the database and are represented in Fig. 1 with a hatched pattern.

3.4. Ecosystem structure and function

Information on ecosystem structure and function is important in several ways. If valuation is made in the context of sustainability, values must be determined based upon their contribution to that objective. This means, for example, determining the sustainable yield values of forest, which may differ substantially from forest yield values under existing management. Many ecosystem processes, such as energy transformation, biogeochemical cycling and food web interactions, have direct ecological values that can be estimated and stored in physical units along with their distribution parameters (e.g. kcal, C-budgets, and species diversity). Information on the underlying ecosystem structural components and processes provide clues to the substitutability of ecosystem services which, in turn, helps to determine the most appropriate economic valuation methods.

3.5. Economic value

The concept of economic value is key to the data model of the ESD. The economic values of ecosystem services are estimated using a wide range of available methods (see Farber et al., this issue). Not all valuation techniques are equally suited for all ecosystem services, and in some cases several techniques may need to be used jointly due to multiple scales of analysis and different data requirements (see DeGroot et al., this issue). Each valuation technique has different data needs and range of applicability across spatial and temporal scales. Moreover, some valuation methods are likely to need the support of projective or predictive dynamic models. Again, the ESD must contain, along with the valuation methods themselves, all the data and the models that are needed to support the valuation activity.

In addition to obvious issues like currency compatibility, several less intuitive aspects and distinctions are crucial and need to be part of the knowledge model. First, economic valuations can be welfare- or impact-based. Welfare-based valuations determine the difference that environmental services make to the well-being, incomes, or costs to people. Monetary valuations of welfare are often based on willingness to pay or to accept compensation for services. Impact valuations reflect how services change the economic or social context. For example, a loss of mangroves may result in the loss of 100 fishermen's jobs; at an income of $10 000 per fisherman, this is the equivalent of a $1 million economic impact, but if these fishermen were to obtain alternative employment, at $8000 per fisherman, the welfare loss in lost income would only be $200 000. The knowledge model must be able to make a clear distinction between these two types of values.

Second, the distinction between partial and general equilibrium valuations must also be maintained in the knowledge model. Partial valuations determine a welfare change or impact resulting from some small change in a system. For example, establishing the increased fishery catch from more mangroves in a local context, while holding fishing effort constant and economically valuing increased catch. General equilibrium valuations

are more complicated. More mangroves would not only result in greater catch per unit effort, but would likely induce more effort; so the total effect of increased mangroves has two parts, an efficiency effect (partial) and a scale effect (general equilibrium). Establishing general equilibrium valuations requires knowledge of how an entire system of interrelated activities will respond to some change in that system.

Third, large-scale services are not likely to be easily quantified on a partial valuation basis. For example, alterations in climate will have significant spatially distributed impacts on forested ecosystems. Understanding the economic implications of climate change for the world's forests requires a full equilibrium modeling of forest growth, harvest and trade. Simplistic, marginal alterations in localized forest supply and demand conditions will not adequately capture the full value of climate services for forests. Thus, general equilibrium models of interrelated forest markets will be necessary. Climate and forestry models may be able to predict the changes in tree growth regionally, but establishing the economic value of tree growth across regions is more complicated than simply multiplying the full welfare value of an acre of trees by the acre equivalent loss or gain in forest services. This becomes increasingly true for climate changes that substantially impact forest habitats.

Finally, it will be difficult to establish welfare valuation using simulation modeling of large scale changes in ecosystems, because such large-scale welfare valuations will likely be based on partial, or marginal, analyses. Instead, these simulations may have to be limited to impact valuations, such as impacts on GDP or some other aggregate indicator. Such valuations have found some usefulness in understanding the implications of large scale, all pervasive impacts such as climate change policies (Weyant, 2000).

These considerations invite care in developing the meta-information that will qualify and allow using the valuation methods included in the database. From the point of view of the ESD, valuation methods are an integral component of the data, and as such can be searched for, retrieved, added and modified just like any other data component.

4. Achieving interoperability: the integrating modeling architecture

The integration of a diverse knowledge base under a common user interface poses both a conceptual and a technical challenge. Interoperability between data and models raises relatively simple challenges such as units and numerical domain, to highly complex ones such as scale and representation of time, space, and behavior. These issues apply equally to 'static' information (data) and 'dynamic' information (models). The role of dynamic process information in the ESD is multifold. First of all, models of various kinds are necessary for projection of known phenomena, scenario generation and analysis. Patterns of global change and environmental processes can be simulated to analyze the effects of particular decisions or decision-making strategies, or to project the consequences of current situations into the future. In addition, support functions such as parameter search, sensitivity analysis, and optimization can all be described and included in the database as specialized dynamic content.

Second, dynamic models are, in many cases, necessary to provide context for the static data. Due to the complexity and variety of paradigms and spatio-temporal scales with which natural processes can be represented (Villa, 1992, 2001), data describing ecological processes often only make practical sense in the reference context of a fully specified dynamic model. Any data model implies a conceptual model of the phenomena described, and the knowledge relative to the processes inducing change in the data is often a substantial and inseparable component of the knowledge model. All rates and stocks in the ecological component of the proposed database can, therefore, serve as parameters and initial conditions for a corresponding process-based model, explicitly indicated at the level of transfer equations.

Within the broad conceptual framework of the ESD, there is no philosophical distinction between data and models: both are 'models of the world', differentiated only by the adoption of a representation of system behavior. Both need to contain explicit definitions of the corresponding

time and space domains, and must indicate clearly and unambiguously the representational paradigm adopted (e.g. grid or polygons for spatial data; difference equations or Markov chains for dynamic models). These concepts are at the core of the Integrating Modeling Architecture (IMA: Villa, 2001) project, whose foundations were laid in 1999 at the University of Maryland. The IMA allows integrated representation and use of multiple scale, multiple paradigm, static and dynamic knowledge models. The architecture ensures the interoperability of model component through formal specification of all the information needed to enforce it. The IMA model typologies can be extended at any time and in an uncoordinated way to support new representational paradigms.

The following paragraphs provide a brief introduction to the key architectural principles of the IMA and how they will be used in the ESD. The IMA web site (http://www.integrated-modelling.org) should be used as an up-to-date reference for further information and distribution of the available software.

4.1. A common representation for interoperability

The IMA uses the Extensible Markup Language (XML: Harold, 1998) to encode the details of every model component or module (representing data or dynamic models). XML, a trusted, industry-standard language framework applied in innumerable fields of science and engineering, allows coherent description of model components (modules) in a way that closely resembles the way web pages are laid out. The adoption of a tight declarative framework is the key to ensure clear, non-redundant specification of model components that can interoperate. Just like the DNA sequence provides a common language for the specification of all living beings, entities involved in a modeled system share an underlying uniform representation that allows them to be checked for compatibility, and when possible used together with full interoperability.

The IMA is designed to enforce discipline in model description and prevent misuse of reusable model components. The use of explicit units and explicit specification of time and space is impor-

tant in this sense: a module specifically developed to describe the dynamics of a watershed in China will not work blindly with data from the USA. Numerical boundaries and units can be specified for all required variables.

Similarly, documentation is an integral component of module specification. The format for references is compatible with common bibliography programs. Networked repositories such as the ESD can enforce that modules contain documentation for all their components.

4.2. Domains: beyond metadata

In conventional database applications, 'metadata' are defined as information that describes the relationship between raw numbers and the world (either physical, such as geographic coordinates, or disciplinary, such as bibliographic references). The IMA goes beyond the conventional idea of metadata by separating the representation of the world from the actual data objects: modules are exposed to aspects such as time and space by 'adopting' these aspects at the request of the user. The key abstraction allowing this is the domain, an evolution of the metadata concept. Domains are XML-specified objects that represent the way particular aspects of the world, such as time or space, are seen by a module. They are used in an IMA simulation to mediate and interpret the interaction between objects, allowing independence, consistency and generality in object specification. The adoption of the domain exposes a module to change and gives it virtual 'eyes' to look at the simulated world.

The most obvious domains are time and space. According to the domains adopted, modules will 'see' each other in different ways when used together. This includes making all simulation components scale-aware. If, for example, a nutrient model stored in the database sees time as a sequence of 1-s steps (time domain), and the database user chooses to input a temperature timeseries that only has data points every hour, interpolation will take place automatically (with full but optional control from the user) so that the ecosystem model can be run.

The same concept applies to other domains, such as space. A spatially explicit simulation using a grid- or polygon- based representation is trivial to create; it will suffice to retrieve the non-spatial model and to select spatially explicit data to satisfy its data requirements, from which the model will take the spatial extent, resolution and position. Modules whose spatial extent is larger than their resolution will be automatically replicated to cover the full extent. Such modules could be used unmodified in a grid- or polygon-based space, and in one, two, or three spatial dimensions.

The domain concept can be extended to provide existing objects with additional meaning and functionality without changing specification. For example, we can envision a validation domain that is qualified with data that the object is supposed to produce in the real world. At any given time, the state of the object with respect to 'reality' will be a measure of how the object's simulated behavior matches observation. This information can be used, e.g. by automatic optimizer services that drive the simulation towards acceptable parameter values. Another domain that will be instrumental in the ESD project will be the 'value' domain, qualified by attributes and priorities reflecting the definition of value, and using interoperable, automatically converted currency units.

4.3. Search and retrieval

The domains used by models also provide the key to efficiently searching the database. Each domain will correspond to a search page where a user of the ESD will be able to define the search domain in (e.g.) space, time, value, or documentation. Search pages will use intuitive interfaces to make searching simple and efficient. As an example, the space domain will use interactive selection of areas from GIS maps. Simpler, quick-loading search pages will also be available as options for use in locations with poor network connectivity.

The modular nature of the IMA-driven ESD enables new search pages to be added whenever new domains are developed. The user will restrict the search space in the domains that are relevant to the purpose. For example, by browsing through the available domains, it will be possible to select all the GIS coverages relative to North America that are relevant to global warming, or all dynamic models of denitrification that have been tested in marshes and forests.

4.4. Incremental composition of models

Each piece of information retrieved by the ESD user will be stored as part of a temporary, higher-level model. As new modules are retrieved, they become part of the temporary model. The user will then be able to visualize, modify, delete, or run the incrementally defined model at any time. The web-based IMA engine will take care of linking the information retrieved and keep the user informed of the model structure as it develops. At the request of the user, it will also be able to create a simulation world (time, space, and other domains) and make the model accessible; a static model (e.g. a timeseries of GIS data) will just be displayed in the user's browser, a dynamic model will be run and results displayed as the simulation progresses.

At any time, the user will be able to download the XML code of the model, which can then be emailed, placed on a web site for others to use, or downloaded to be simulated locally at the user's leisure by means of freely available IMA software. However, users will not need to see the XML code unless they want to. The ESD will not contain material whose copyright would prevent the free exchange of the knowledge obtained and developed using it.

The IMA, like the ESD, is an open source project whose software is available to the public. Freedom of use and modification is guaranteed by the General Public License (FSF, 2002 URL). Contribution from interested parties is strongly encouraged both at the design and implementation levels.

5. A web-accessible, multi-paradigm knowledge base.

This section describes the anticipated contents of the first release of the ESD, planned for 2003. We also describe our proposed strategy for quality control and management of data submission.

5.1. Economic values from published studies

The database will be initially populated with the data that were used in the original Costanza et al. (1997) synthesis study. This will allow users to replicate the original study and to update it as new data are entered into the database. These data consist of about 120 independent published studies, carefully checked for relevance and consistency, and about 200 estimates of value for ecosystem services at the global and biome scales, expressed in both original and standardized units.

5.2. Geographic information and country indicators

To provide users of the ESD with important background information and to allow calculation of social and ecological indicators within the database post-processing engine, we will include and maintain a comprehensive database of country-level statistical information for the whole globe. This information will be obtained from the World Bank's World Development Indicators (a data CD published by the World Bank) providing basic economic statistics such as purchasing power parity, national and per capita GDP, basic demographic statistics such as population, age structure, fertility rates, and other health and quality of life statistics such as infant mortality and education rates. An attempt will also be made to provide information on measures related to environmental quality as they relate to health and infrastructure (e.g. water and air quality, freshwater availability, or sewage treatment infrastructure).

5.3. The global unified metamodel of the biosphere (GUMBO)

Possibly the most intuitive way for a user to start exploring ecosystem services valuation is to use a global-scale model that can use available data for the whole planet. GUMBO (Boumans et al., this issue) is a global simulation model aimed at assessing the dynamics of ecosystem services. It is a metamodel in the sense that it represents a simplified version of several well-established global models. Its resolution and complexity were chosen to meet the conflicting criteria of (1) enough complexity to capture the dynamic aspects and interconnections among the major global ecosystem services as listed in Costanza et al. (1997), and (2) enough simplicity to be distributed and run with limited computational resources and by a broad range of users.

GUMBO consists of five sectors or 'spheres': atmosphere, lithosphere, hydrosphere, biosphere, and anthroposphere (human systems). It is also divided into and calibrated for 11 biomes or ecosystem types which encompass the entire surface area of the planet: open ocean, coastal ocean, forests, grasslands, wetlands, lakes/rivers, deserts, tundra, ice/rock, croplands, and urban. These 11 biomes are an aggregation of the 16 biomes used in Costanza et al. (1997). The paper by Boumans et al. (this issue) provides extensive detail about the model's structure, scope and application.

GUMBO will be integrated in the first release of the ESD. ESD users will be able to run global change scenarios of their choice through the web-based interface.

6. Update and quality control

We want the ESD to be as flexible and dynamic as possible, incorporating new knowledge and offering a data model that is compatible with the future development of ecosystem service valuation theory. The ESD should be a reference for wide spatial and temporal scales as a central repository of information and models for valuation of natural capital. At the same time, for the ESD to be useful it is of utmost importance that the quality of the information is carefully controlled. For this reason we envision a multiple-stage data entry process, open to all interested parties, but incorporating peer review and careful evaluation of submissions by an independent advisory board. We view the peer-review process as a necessary step towards building a system of incentives to promote the open-source research vision advocated by Schweik and Grove (2000).

6.1. Input of new information

In general, researchers will be able to submit new information through secure web forms, which will guide and organize the input of new information in different categories. The forms will not update the database directly, but will notify the submission to a database manager for review and possible incorporation into the ESD. We consider this process the only way to maximize security and ensure referential integrity. Issues to be considered for submission guidelines are: (1) unit and value standardization; (2) formats for submitted factual information, references and dynamic models; (3) integrity and proper reference to the hierarchical characterizations developed for ecological services, entities and processes. In general, only entries that contain all the information required to comply with the appropriate IMA constructs will be accepted. The translation into XML will be done by the database maintainers, with the help of automated software interfaces able to handle the most common data and model formats.

6.2. Quality control

Quality control is a critical issue for the success of the ESD. As a guideline, we will employ the following:

1. an Advisory Board will be established before the deployment of the fully operational ESD, including reviewers and representatives of the main users of the database (coming from science, policy-making, industrial advisory bodies and NGOs) to ensure adequate design, management and access system for the database.
2. A database manager will be responsible for entering data into the database, supported by a group of reviewers and technical staff to physically enter the data into the database. Data will be obtained both through active searches in libraries, other databases, etc. and through a submission form that will be available on the database web site. The database manager will distribute submitted data and publications to a network of reviewers, covering the main biomes and services (see point 3).
3. An international Review Committee will be involved in the review process, supported by a set of standardized guidelines to ensure comparability of the quality control and rating system, which we will produce during the first year. This review committee will consist of a representative selection of individuals and organizations that are knowledgeable about ecosystems (e.g. wetland or coral reef experts), their functions and services (e.g. system ecologists) and/or economic valuation (e.g. resource economists). Before data are entered into the database, at least several members of the committee must have reviewed the quality and validity of the submitted data.

The Advisory Board and Review Committee are important instruments to establish effective working relationships with the main organizations active in collecting and storing data on ecosystem services and values (e.g. EPA, IUCN, the World Bank, Conservation International, LTER network).

7. Conclusions

The web-accessible ESD will provide several important benefits, outlined below with a description of its most important roles.

7.1. Communication tool

The ESD will provide a dynamic link between ecological and socio–economic data within the global system. By enabling meta-analysis and synthesis, it will contribute to the further development of the theory and practice of ecological economics, fostering communication between practitioners of the physical sciences, the social sciences and policy makers.

7.2. Analytical tool

The ESD, in combination with a physical archive, will provide a powerful tool for conducting meta-analysis and synthesis of ecological–economic data on ecosystem services and benefits (what-if projections, synthesis, cross-country com-

parisons, benefit transfer). It will greatly facilitate and help standardizing the use of ecological–economic information in project evaluations and cost-benefit analysis.

7.3. Education and dissemination

The ESD will constitute an important tool for education and dissemination of knowledge about the valuation of natural capital and ecosystem services, both for educational institutions and the general public.

7.4. Collaboration

The ESD will stimulate collaboration and linkages between national and international institutions engaged in ecological-economics studies of the natural environment, both through collaborative networks and the international scientific advisory group.

7.5. Prototype for linking databases and models

The ESD will serve as a prototype for linking relational databases and dynamic simulation models. The need for this kind of linkage is expanding rapidly as models become more complex and collaborative, and become a more and more established component of ecosystem knowledge. There are many potential uses for this kind of computational structure in several different disciplines. The modular nature of the ESD and the IMA will enable the easy transfer of the ESD engine to other research contexts. In addition, the open-source nature of the project will allow anyone with access to the World Wide Web to implement and, if necessary, adapt the system for different needs.

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