ECOLOGICAL ECONOMICS

Ecological Economics 41 (2002) 393–408

This article is also available online at:
www.elsevier.com/locate/ecolecon

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

A typology for the classification, description and valuation of ecosystem functions, goods and services

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Abstract

An increasing amount of information is being collected on the ecological and socio-economic value of goods and services provided by natural and semi-natural ecosystems. However, much of this information appears scattered throughout a disciplinary academic literature, unpublished government agency reports, and across the World Wide Web. In addition, data on ecosystem goods and services often appears at incompatible scales of analysis and is classified differently by different authors. In order to make comparative ecological economic analysis possible, a standardized framework for the comprehensive assessment of ecosystem functions, goods and services is needed. In response to this challenge, this paper presents a conceptual framework and typology for describing, classifying and valuing ecosystem functions, goods and services in a clear and consistent manner. In the following analysis, a classification is given for the fullest possible range of 23 ecosystem functions that provide a much larger number of goods and services. In the second part of the paper, a checklist and matrix is provided, linking these ecosystem functions to the main ecological, socio–cultural and economic valuation methods. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Classification of ecosystem functions; Typology of goods and services; Ecological and socio-economic valuation

1. Introduction

In the past few decades, the field of ecological economics has witnessed a spectacular rise of concern with the valuation of ecosystem functions, goods and services. Early references to the concept of ecosystem functions, services and their economic value date back to the mid-1960s and early 1970s (e.g. King, 1966; Helliwell, 1969; Hueting, 1970; Odum and Odum, 1972). More recently, there has been an almost exponential growth in publications on the benefits of natural ecosystems to human society (see for example, Pearce, 1993; Turner, 1993; De Groot, 1992, 1994; Bingham et al., 1995; Daily 1997; Costanza et al.,

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PII: S0921-8009(02)00089-7

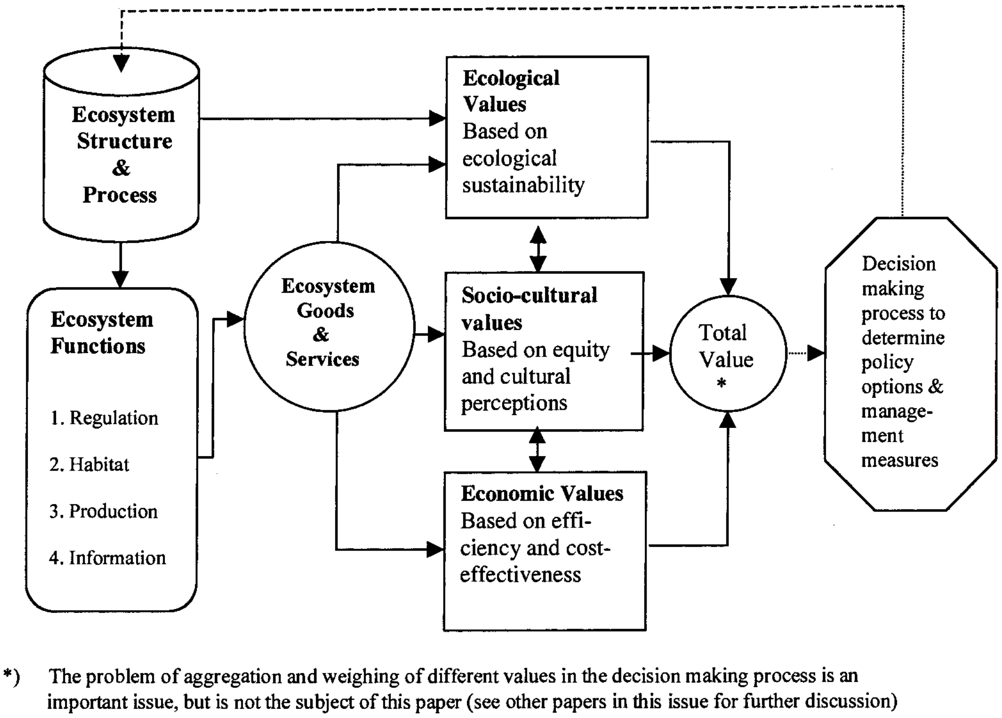

Fig. 1. Framework for integrated assessment and valuation of ecosystem functions, goods and services.

1997; Pimentel and Wilson, 1997; Limburg and Folke, 1999; Wilson and Carpenter, 1999; Daily et al., 2000). Despite the increase in publications on ecosystem goods and services, a systematic typology and comprehensive framework for integrated assessment and valuation of ecosystem functions remains elusive. This paper, therefore, aims to provide such an integrated framework, of which the main elements are presented in Fig. 1.

As Fig. 1 shows, the first step towards a comprehensive assessment of ecosystem goods and services involves the translation of ecological complexity (structures and processes) into a more limited number of ecosystem functions. These functions, in turn, provide the goods and services that are valued by humans. In the ecological literature, the term 'ecosystem function' has been subject to various, and sometimes contradictory, interpretations. Sometimes the concept is used to describe the internal functioning of the ecosystem (e.g. maintenance of energy fluxes, nutrient (re)cycling, food-web interactions), and sometimes it relates to the benefits derived by humans from the properties and processes of ecosystems (e.g. food production and waste treatment).

In this paper, we explicitly define ecosystem functions as 'the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly' (De Groot, 1992). Using this definition, ecosystem functions are best conceived as a subset of ecological processes and ecosystem structures (see Fig. 1). Each function is the result of the natural processes of the total ecological sub-system of which it is a part. Natural processes, in turn, are the result of complex interactions between biotic (living organisms) and abiotic (chemical and physical) components of ecosystems through the universal driving forces of matter and energy.

Although a wide range of ecosystem functions and their associated goods and services have been referred to in literature, our experience suggests that it is convenient to group ecosystem functions into four primary categories (De Groot et al., 2000).

1. *Regulation functions*: this group of functions relates to the capacity of natural and semi-natural ecosystems to regulate essential ecological processes and life support systems through bio-geochemical cycles and other biospheric processes. In addition to maintaining ecosystem (and biosphere) health, these regulation functions provide many services that have direct and indirect benefits to humans (such as clean air, water and soil, and biological control services).
2. *Habitat functions*: natural ecosystems provide refuge and reproduction habitat to wild plants and animals and thereby contribute to the (in situ) conservation of biological and genetic diversity and evolutionary processes.
3. *Production functions*: Photosynthesis and nutrient uptake by autotrophs converts energy, carbon dioxide, water and nutrients into a wide variety of carbohydrate structures which are then used by secondary producers to create an even larger variety of living biomass. This broad diversity in carbohydrate structures provides many ecosystem goods for human consumption, ranging from food and raw materials to energy resources and genetic material.
4. *Information functions*: Because most of human evolution took place within the context of undomesticated habitat, natural ecosystems provide an essential 'reference function' and contribute to the maintenance of human health by providing opportunities for reflection, spiritual enrichment, cognitive development, recreation and aesthetic experience.

Although the rank-order of the function categories is somewhat arbitrary, there is an underlying logic in their ordering. The first two function-groups (regulation and habitat) are essential to the maintenance of natural processes and components, and are, therefore, conditional to the maintenance of the availability of the other two function-groups. Since human life is quite impossible in the absence of any one of these function groups, however, the proposed hierarchy should not be interpreted too strictly.

Once the functions of an ecosystem are known, the nature and magnitude of value to human society can be analyzed and assessed through the goods and services provided by the functional aspects of the ecosystem. The ecosystem function-concept thus provides the empirical basis for the classification of (potentially) useful aspects of natural ecosystems to humans: observed ecosystem functions are reconceptualized as 'ecosystem goods or services' when human values are implied. The primary insight here is that the concept of ecosystem goods and services is inherently anthropocentric: it is the presence of human beings as valuing agents that enables the translation of basic ecological structures and processes into value-laden entities. As Fig. 1 shows, in our proposed framework, the form of this translation is not restricted to economic terms of 'consumption' but may also be ecological and/or socio-cultural (see further).

2. Classification of ecosystem functions, goods and services

Table 1 below provides an overview of the main functions, goods and services that can be attributed to natural ecosystems and their associated ecological structures and processes. The first column indicates a list of 23 functions and the second column lists the ecological structures and processes underlying these functions. The third column provides a more detailed list with examples of specific goods and services derived from these functions (not exhaustive).

In Table 1, only those goods and services are included that can be used on a sustainable basis[2], in order to maintain the ecosystem functions and associated ecosystem processes and structures.

Given these restrictions, important non-renewable natural mineral resources like gold, iron, diamonds, and oil are excluded from this list. Furthermore, energy sources that cannot be at-

[2] Ecological sustainability can be defined as 'the natural limits set by the carrying capacity of the natural environment (physically, chemically and biologically), so that human use does not irreversibly impair the integrity and proper functioning of its natural processes and components' (de Groot et al., 2000).

Table 1
Functions, goods and services of natural and semi-natural ecosystems

	Functions	Ecosystem processes and components	Goods and services (examples)
	Regulation Functions	*Maintenance of essential ecological processes and life support systems*	
1	Gas regulation	Role of ecosystems in bio-geochemical cycles (e.g. CO_2/O_2 balance, ozone layer, etc.)	1.1 UVb-protection by O_3 (preventing disease). 1.2 Maintenance of (good) air quality. 1.3 Influence on climate (see also function 2.)
2	Climate regulation	Influence of land cover and biol. mediated processes (e.g. DMS-production) on climate	Maintenance of a favorable climate (temp., precipitation, etc) for, for example, human habitation, health, cultivation
3	Disturbance prevention	Influence of ecosystem structure on dampening env. disturbances	3.1 Storm protection (e.g. by coral reefs). 3.2 Flood prevention (e.g. by wetlands and forests)
4	Water regulation	Role of land cover in regulating runoff & river discharge	4.1 Drainage and natural irrigation. 4.2 Medium for transport
5	Water supply	Filtering, retention and storage of fresh water (e.g. in aquifers)	Provision of water for consumptive use (e.g.drinking, irrigation and industrial use)
6	Soil retention	Role of vegetation root matrix and soil biota in soil retention	6.1 Maintenance of arable land. 6.2 Prevention of damage from erosion/siltation
7	Soil formation	Weathering of rock, accumulation of organic matter	7.1 Maintenance of productivity on arable land. 7.2 Maintenance of natural productive soils
8	Nutrient regulation	Role of biota in storage and re-cycling of nutrients (eg. N,P&S)	Maintenance of healthy soils and productive ecosystems
9	Waste treatment	Role of vegetation & biota in removal or breakdown of xenic nutrients and compounds	9.1 Pollution control/detoxification. 9.2 Filtering of dust particles. 9.3 Abatement of noise pollution
10	Pollination	Role of biota in movement of floral gametes	10.1 Pollination of wild plant species. 10.2 Pollination of crops
11	Biological control	Population control through trophic-dynamic relations	11.1 Control of pests and diseases. 11.2 Reduction of herbivory (crop damage)
	Habitat Functions	*Providing habitat (suitable living space) for wild plant and animal species*	Maintenance of biological & genetic diversity (and thus the basis for most other functions)
12	Refugium function	Suitable living space for wild plants and animals	Maintenance of commercially harvested species
13	Nursery function	Suitable reproduction habitat	13.1 Hunting, gathering of fish, game, fruits, etc.
	Production Functions	*Provision of natural resources*	13.2 Small-scale subsistence farming & aquaculture
14	Food	Conversion of solar energy into edible plants and animals	14.1 Building & Manufacturing (e.g. lumber, skins). 14.2 Fuel and energy (e.g. fuel wood, organic matter). 14.3 Fodder and fertilizer (e.g. krill, leaves, litter).
15	Raw materials	Conversion of solar energy into biomass for human construction and other uses	15.1 Improve crop resistance to pathogens & pests. 15.2 Other applications (e.g. health care)
16	Genetic resources	Genetic material and evolution in wild plants and animals	16.1 Drugs and pharmaceuticals. 16.2 Chemical models & tools. 16.3 Test- and essay organisms
17	Medicinal resources	Variety in (bio)chemical substances in, and other medicinal uses of, natural biota	Resources for fashion, handicraft, jewelry, pets, worship, decoration & souvenirs (e.g. furs,
18	Ornamental resources	Variety of biota in natural ecosystems with (potential) ornamental use	feathers, ivory, orchids, butterflies, aquarium fish, shells, etc.)
	Information Functions	*Providing opportunities for cognitive development*	

Table 1 (*Continued*)

	Functions	Ecosystem processes and components	Goods and services (examples)
19	Aesthetic information	Attractive landscape features	Enjoyment of scenery (scenic roads, housing, etc.)
20	Recreation	Variety in landscapes with (potential) recreational uses	Travel to natural ecosystems for eco-tourism, outdoor sports, etc.
21	Cultural and artistic information	Variety in natural features with cultural and artistic value	Use of nature as motive in books, film, painting, folklore, national symbols, architect., advertising, etc.
22	Spiritual and historic information	Variety in natural features with spiritual and historic value	Use of nature for religious or historic purposes (i.e. heritage value of natural ecosystems and features)
23	Science and education	Variety in nature with scientific and educational value	Use of natural systems for school excursions, etc. Use of nature for scientific research

Adapted from Costanza et al. (1997), De Groot (1992), De Groot et al. (2000).

tributed to a certain ecosystem type are excluded, e.g. wind and solar-energy. On the other hand, some non-ecosystem specific functions that can be used without (permanently) affecting the other functions, such as the use of natural waterways for transportation, is included. Also some mineral resources that are renewable within a time-frame of 100–1000 years, like sand on beaches provided by dead coral and shells, are included. In (economic) valuation of these goods and services due account should be taken of these natural regeneration rates.

Since the use of one function may influence the availability of other functions, and their associated goods and services, the capacity of ecosystems to provide goods and services in a sustainable manner should be determined under complex systems conditions (see Limburg et al., 2002). The ecosystem processes and components described in the second column of Table 1 should, therefore, be used in dynamic modeling to make these interdependencies, and the implications for their valuation, more explicit (see Boumans et al., 2002).

It should be realized that ecosystem processes and services do not always show a one-to-one correspondence: sometimes a single ecosystem service is the product of two or more processes, whereas in other cases a single process contributes to more than one service. For example, the function 'gas regulation' is based on biogeochemical processes (like carbon and oxygen cycling) which maintain a certain air quality but also influence the greenhouse effect and thereby climate regulating processes. Furthermore, analysis of ecosystem functions and services involves different scales, notably the physical scale of the ecosystem function itself, and the scale at which humans value the goods and services provided. It is not a necessary condition that the two correspond. When valuing ecosystem functions, these inter-linkages and scale issues should be made clear, and on the next few pages each of the 23 functions are described in more detail.

2.1. Regulation functions and related ecosystem services

Natural ecosystems play an essential role in the regulation and maintenance of ecological processes and life support systems on earth. The maintenance of the earth's biosphere as humanity's only life support system in an otherwise hostile cosmic environment depends on a very delicate balance between many ecological processes. Some of the most important processes include the transformation of energy, mainly from solar radiation, into biomass (primary productivity); storage and transfer of minerals and energy in food chains (secondary productivity); biogeochemical cycles (e.g. the cycling of nitrogen and other nutrients through the biosphere); mineralization of organic matter in soils and sediments; and regulation of the physical climate system. All these processes, in turn, are regulated by the interplay of abiotic factors (i.e. climate) with living organisms through evolution and control mechanisms. In order for humans to continue to benefit from these functions, we need to ensure the continued existence and integrity of these natural ecosystems and processes. Because of the indirect benefits of regulation functions, they are often not recognized until they are lost or disturbed, but they are nevertheless essential to human existence on earth.

2.1.1. Gas regulation

Life on earth exists within a narrow band of chemical balance in the atmosphere and oceans, and any alterations in that balance can have positive or negative impacts on natural as well as social and economic processes. The chemical composition of the atmosphere (and oceans) is maintained by bio-geochemical processes which, in turn, are influenced by many biotic and a-biotic components of natural ecosystems. Important examples are the influence of natural biota on processes that regulate the CO_2/O_2 balance, maintain the ozone-layer (O_3), and regulate SOx levels. The main services provided by the gas regulation function are the maintenance of clean, breathable air, and the prevention of diseases (e.g. skin cancer), i.e. the general maintenance of a habitable planet.

An important issue when trying to determine the service value from this ecosystem function is the scale at which the analysis is carried out. For example, the influence of 1 hectare of ocean, or forest, as a carbon-sink is difficult to measure. However, the cumulative effect of losing 50% of the earth forest-cover, or 60% of the coastal wetlands, and the reduction of algae-productivity in large parts of the oceans due to pollution, on the gas regulation function is considerable.

2.1.2. Climate regulation

Local weather and climate are determined by the complex interaction of regional and global circulation patterns with local topography, vegetation, albedo, as well as the configuration of, for example, lakes, rivers, and bays. Due to the greenhouse-properties of some atmospheric gases, gas regulation (see above) also plays an important role in this function, but reflectance properties of ecosystems are also important in determining weather conditions and climate at various scales.

The services provided by this function relate to the maintenance of a favorable climate, both at local and global scales, which in turn are important for, among others, human health, crop productivity, recreation and even cultural activities and identity.

2.1.3. Disturbance prevention

This function relates to the ability of ecosystems to ameliorate 'natural' hazards and disruptive natural events. For example, vegetative structure can alter potentially catastrophic effects of storms, floods and droughts through its storage capacity and surface resistance; coral reefs buffer waves and protect adjacent coastlines from storm damage. The services provided by this function relate to providing safety of human life and human constructions.

2.1.4. Water regulation

Water regulation deals with the influence of natural systems on the regulation of hydrological flows at the earth surface. This ecosystem function is distinct from disturbance regulation insofar as it refers to the maintenance of 'normal' conditions in a watershed and not the prevention of extreme hazardous events. Ecosystem services derived from the water regulation function are, for example, maintenance of natural irrigation and drainage, buffering of extremes in discharge of rivers, regulation of channel flow, and provision of a medium for transportation. A regular distribution of water along the surface is, therefore, quite essential, since too little as well as too much runoff can present serious problems.

2.1.5. Water supply

This ecosystem function refers to the filtering, retention and storage of water in, mainly, streams, lakes and aquifers. The filtering-function is mainly performed by the vegetation cover and (soil) biota. The retention and storage capacity depends on topography and sub-surface characteristics of the involved ecosystem. The water supply function also depends on the role of ecosystems in hydrologic cycles (see function No. 4), but focuses primarily on the storage capacity rather than the flow of water through the system. Ecosystem services associated with water supply relate to the consumptive use of water (by households, agriculture, industry).

2.1.6. Soil retention

The soil retention function mainly depends on the structural aspects of ecosystems, especially vegetation cover and root system. Tree roots stabilize the soil and foliage intercepts rainfall thus preventing compaction and erosion of bare soil. Plants growing along shorelines and (submerged) vegetation in near-coastal areas contribute greatly to controlling erosion and facilitating sedimentation.

The services provided by this function are very important to maintain agricultural productivity and prevent damage due to soil erosion (both from land slides and dust bowls).

2.1.7. Soil formation

Soil is formed through the disintegration of rock and gradually becomes fertile through the accretion of animal and plant organic matter and the release of minerals. Soil-formation usually is a very slow process; natural soils are generated at a rate of only a few centimeters per century and after erosion, soil formation (or regeneration) from bedrock takes 100–400 years per cm topsoil (Pimentel and Wilson, 1997).

Ecosystem services derived from soil formation relate to the maintenance of crop productivity on cultivated lands and the integrity and functioning of natural ecosystems.

2.1.8. Nutrient cycling

Life on earth depends on the continuous (re)cycling of about 30–40 of the 90 chemical elements that occur in nature. In addition to carbon (C), oxygen (O), and hydrogen (H) (which have been discussed in the gas-, climate- and water-regulation services) the most important nutrients are nitrogen (N), sulfur (S) and phosphorous (P). Other so-called macro-nutrients are calcium, magnesium, potassium, sodium and chlorine. Furthermore, a large number of so-called trace elements are needed to maintain life, including, for example, iron and zinc. The availability of these elements is often a limiting factor to the growth and occurrence of life forms and constant (re)cycling of these nutrients is, therefore, essential.

Many structural and functional aspects of natural ecosystems facilitate nutrient cycling at local and global scales. For example, soil organisms decompose organic matter thereby releasing nutrients to both local plant growth, but also to the atmosphere; algae in coastal waters perform this same function. Also, migration (of birds, fish and mammals) plays an important role in the distribution of nutrients between ecosystems.

Ecosystem services derived from nutrient cycling are mainly related to the maintenance of 'healthy' and productive soils. Furthermore, nutrient cycling plays an important role in the gas-, climate- and water-regulation functions (see above).

2.1.9. Waste treatment

To a limited extent, natural systems are able to store and recycle certain amounts of organic and inorganic human waste through dilution, assimilation and chemical re-composition. Forests, for example, filter dust particles from the air, and wetlands and other aquatic ecosystems can treat relatively large amounts of organic wastes from human activities acting as 'free' water purification plants.

2.1.10. Pollination

Pollination is essential to most plants for reproduction, including commercial crops. This ecosystem function is provided by many wild pollinator-species (including insects, birds and bats). Without this function, many plant species would go extinct and cultivation of most modern crops would be impossible. The service provided by this function can be derived from the dependence of cultivation on natural pollination. Without wild pollinator species, current levels of agricultural productivity could only be maintained at a very high cost through artificial pollination (Daily, 1997).

2.1.11. Biological control

As a result of millions of years of evolutionary processes, the biotic communities of natural ecosystems have developed many interactions and feedback mechanisms that led to more or less stable life-communities and prevent the outbreak of pests and diseases. According to Ehrlich (1985), natural ecosystems control more than 95% of all the potential pests of crops and carriers of disease to human beings.

2.2. Habitat functions and related ecosystem services

Natural ecosystems provide living space for all wild plant and animal species on earth. Since it is these species, and their role in the local and global ecosystem that provide most of the functions described in this paper, the maintenance of healthy habitats is a necessary pre-condition for the provision of all ecosystem goods and services, directly or indirectly. The habitat, or refugium function, can be split in two distinct sub-functions, each providing different services:

2.2.1. Refugium function

By providing living space to wild plants and animals, both for resident and transient (migratory species), natural ecosystems are essential to the maintenance of the biological and genetic diversity on earth. Natural ecosystems can thus be seen as a ‘storehouse’ of genetic information. In this ‘genetic library’ the information of environmental adaptations acquired over 3.5 billion years of evolution is stored in the genetic material of millions of species and sub-species. To maintain the viability of this genetic library (through evolutionary processes), maintenance of natural ecosystems as habitats for wild plants and animals is essential.

2.2.2. Nursery function

Many ecosystems, especially coastal wetlands, provide breeding and nursery areas to species which, as adults, are harvested elsewhere for either subsistence or commercial purposes.Unfortunately, the nursery services of many ecosystems are often unknown or ignored and in many instances nursery areas are, and have been, transformed to other more direct ‘economic’ uses with disastrous ecological and socio-economic consequences (e.g. draining of mangrove lagoons) (Gilbert and Janssen, 1997).

2.3. Production functions and related ecosystem goods and services

Natural and semi-natural ecosystems provide many resources, ranging from oxygen, water, food, medicinal and genetic resources to sources of energy and materials for clothing and building. However, a fundamental distinction should be made between the use of biotic resources (i.e. products from living plants and animals) and abiotic resources (mainly sub-surface minerals). One important difference between biotic and abiotic resources is their renewability. Generally speaking, biotic resources are renewable, while most abiotic resources are not (although it may be possible to recycle them). In this paper, production functions are limited to *renewable* natural resources.

Over time, humans have learned to manipulate the biotic productivity of natural ecosystems to provide certain resources in greater quantities than available under natural conditions. When discussing the contribution of nature to (biotic) production functions, a distinction must, therefore, be made between products taken directly from nature, like fish, tropical hardwoods, so-called ‘minor’ forest products (e.g. fruits, leaves), and products from cultivated plants and animals. In this paper, biotic production functions are limited to that part of natural Gross Primary Production that can be harvested on a sustainable basis and for which people only need to invest minimal time, labor and energy to harvest the goods provided.[3]

[3] One service not included in Table 1 is bio-energy fixation although it actually is the most important service provided by natural ecosystems: without their capacity to convert (mainly) solar energy into biomass there would be no life on earth. Primary Productivity can be used to determine maximum sustainable use levels: as a general rule-of-thumb, not more than 50% of Gross PP (or 10% of Net PP) should be harvested by man (Odum, 1971) to maintain the integrity of the supporting ecosystems.

2.3.1. Food

Although today most foods are derived from cultivated plants and domesticated animals, a substantial part of the global human diet still comes from wild plants and animals. Natural ecosystems are an almost unlimited source of edible plants and animals, ranging from game and bush meat, fish and fowl, to vegetables, fungi, fruits, and such exotic items as birds' nests and sponges. Certain forms of small-scale subsistence farming and aquaculture, with minimal external inputs, can also be included in this function, as long as it does not interfere with the other services provided by the ecosystem in question. The forest, grassland or aquatic ecosystem that is partly or temporarily being used or converted for food production must maintain most, preferably all, other functions or be able to recover in a reasonable time period.

2.3.2. Raw materials

Here, only renewable biotic resources are taken into account, such as wood and strong fibers (for building), biochemicals or biodynamic compounds (latex, gums, oils, waxes, tannins, dyes, hormones, etc.) for all kinds of industrial purposes. Nature also provides many energy resources such as fuelwood, organic matter, animal power and biochemicals (hydrocarbons, ethanol, etc.), and animal-feed (e.g. grass, leaves, krill). Abiotic resources like minerals, fossil fuels, wind- and solar energy are not considered since they are usually non-renewable and/or cannot be attributed to specific ecosystems.

2.3.3. Genetic resources

Many biotic resources which were once collected in the wild are now obtained from cultivated plants and domesticated animals. Yet, many important crops could not maintain commercial status without the genetic support of their wild relatives. In order to maintain the productivity of these cultivars, or to change and improve certain qualities such as taste, resistance to pests and diseases, and adaptation to certain environmental conditions, regular inputs of genetic material from their wild relatives and primitive (semi-) domesticated ancestors remains essential. These inputs may vary from simple cross-breeding between wild and cultivated varieties of important crop-species to complicated manipulations of genetic resources through biotechnological research and genetic engineering (Oldfield, 1984).

2.3.4. Medicinal resources

Nature contributes to the maintenance of human health in many ways: by providing chemicals that can be used as drugs and pharmaceuticals, or which may be used as models to synthesize these drugs. Animals are used to test new medicines or may even serve as medical tools (such as medicinal leeches (*Hirundo medicinalis*) which are applied to reduce blood pressure), or as student specimens.

2.3.5. Ornamental resources

The use of wild plants and animals (and a-biotic resources such as precious minerals and stones) for ornamental purposes is extensive and varied. Nature provides many kinds of raw materials which are used for fashion and clothing (notably animal skins and feathers), handicrafts (e.g. wood and ebony for carving), and objects of worship (i.e. products associated with cultural, tribal and religious ceremonies). Wild plants and animals are also collected and traded as pets or for decoration (e.g. ornamental plants) in private households or to supplement the collections of zoological and botanical gardens. Many plants and animals and their products are used and traded as souvenirs, or as collector's items (e.g. orchids, butterflies, aquarium fish, birds, feathers, skins, ivory).

2.4. Information functions and related ecosystem goods and services

Natural ecosystems provide almost unlimited opportunities for spiritual enrichment, mental development and leisure. Because, the longest period of human evolution took place within the context of undomesticated habitat, the workings of the human brain for gathering information and a sense of well-being are very strongly tied to the experience of natural landscapes and species diversity (Gallagher, 1995). Nature is, therefore, a vital source of inspiration for science, culture and art, and provides many opportunities for education and research. As Forster (1973) put it already 25 years ago: '...natural environments provide a highly inspirational and educative form of re-creative experience, with opportunities for reflection, spiritual enrichment and cognitive development through exposure to life processes and natural systems'.

2.4.1. Aesthetic information

Many people enjoy the scenery of natural areas and landscapes which is reflected in, for example, the preference many people have for living in aesthetically pleasing environments and the demarcation of 'scenic roads'. Aesthetic information can have considerable economic importance, for example, through the influence on real estate prices: houses near national parks or with a nice ocean view are usually much more expensive than similar houses in less favored areas (Costanza et al., 1997).

2.4.2. Recreation and (eco)tourism

Natural ecosystems have an important value as a place where people can come for rest, relaxation, refreshment and recreation. Through the aesthetic qualities and almost limitless variety of landscapes, the natural environment provides many opportunities for recreational activities, such as walking, hiking, camping, fishing, swimming, and nature study. With increasing numbers of people, affluence and leisure-time, the demand for recreation in natural areas ('eco-tourism') will most likely continue to increase in the future.

2.4.3. Cultural and artistic inspiration

Nature is an important basis for folklore and culture as humans have developed different means of coping and interacting with nature. In other words, human culture is embedded within natural systems. Without nature, life would be very dull indeed or, as Van Dieren and Hummelinck (1979) state: 'There is hardly any province of culture to which nature does not give shape or inspiration'. Nature is used as a motive and source of inspiration for books, magazines, film, photography, paintings, sculptures, folklore, music and dance, national symbols, fashion, architecture, advertising, etc. Interestingly, although we are almost constantly using nature for all these (and other) purposes, we do not seem to be very conscious of this service and there is very little quantitative information on the economic value of all these activities in literature.

2.4.4. Spiritual and historic information

Natural ecosystems and natural elements (such as ancient water falls or old trees) provide a sense of continuity and understanding of our place in the universe which is expressed through ethical and heritage-values. Also religious values placed on nature (e.g. worship of holy forests, trees or animals) fall under this function-category.

2.4.5. Scientific and educational information

Natural ecosystems provide almost unlimited opportunities for nature study, environmental education (e.g. through excursions) and function as 'field laboratories' for scientific research, leading to thousands of publications each year. Natural areas also serve as important reference areas for monitoring environmental change.

3. Valuing ecosystem functions, goods and services

The importance (or 'value') of ecosystems is roughly divided into three types: ecological, socio-cultural and economic value (see Fig. 1). The papers by Farber et al. (2002), Limburg et al. (2002), Howarth and Farber (2002), Wilson and Howarth (2002) discuss these three concepts of value in more detail. In this paper we focus on the linkages between these valuation methods and the goods and services identified in the previous section.

3.1. Ecological value

To ensure the continued availability of ecosystem functions, the use of the associated goods and services should be limited to sustainable use levels. The capacity of ecosystems to provide goods and services depends on the related ecosystem processes and components providing them (column 2 in Table 1) and the limits of sustainable use are determined by ecological criteria such as integrity, resilience, and resistance. The 'Ecological Value' or importance of a given ecosystem is, therefore, determined both by the integrity of the Regulation and Habitat Functions of the ecosystem and by ecosystem parameters such as complexity, diversity, and rarity (De Groot et al., 2000). Since most functions and related ecosystem processes are inter-linked, sustainable use levels should be determined under complex system conditions (see Limburg et al., 2002), taking due account of the dynamic interactions between functions, values and processes (Boumans et al., 2002).

3.2. Socio-cultural value

In addition to ecological criteria, social values (such as equity) and perceptions play an important role in determining the importance of natural ecosystems, and their functions, to human society (see Fig. 1). In a report by English Nature (1994), social reasons are mentioned as playing an important role in identifying important environmental functions, emphasizing physical and mental health, education, cultural diversity and identity (heritage value), freedom and spiritual values. Natural systems are thus a crucial source of non-material well-being and indispensable for a sustainable society (Norton, 1987). The socio-cultural value mainly relates to the Information Functions (see Table 1).

3.3. Economic value

Economic valuation methods fall into four basic types, each with its own repertoire of associated measurement issues: (1) direct market valuation, (2) indirect market valuation, (3) contingent valuation, (4) group valuation.

3.3.1. Direct market valuation

This is the exchange value that ecosystem services have in trade, mainly applicable to the 'goods' (i.e. production functions) but also some information functions (e.g. recreation) and regulation functions: New York City, for example, has sought to use natural water regulation services of largely undeveloped watersheds, through purchase or easements, to deliver safe water and avoided a $6 billion water filtration plant. This implies those watersheds are worth up to $6 billion to New York City. Wetlands trading programs allow property owners to capitalize on the demand for wetlands banks, with wetlands being sold in banks for $74 100–$4 93 800 per ha (Powicki, 1998).

3.3.2. Indirect market valuation

When there are no explicit markets for services, we must resort to more indirect means of assessing values. A variety of valuation techniques can be used to establish the (revealed) Willingness To Pay (WTP) or Willingness To Accept compensation (WTA) for the availability or loss of these services.

- Avoided Cost (AC): services allow society to avoid costs that would have been incurred in the absence of those services. Examples are flood control (which avoids property damages) and waste treatment (which avoids health costs) by wetlands.
- Replacement Cost (RC): services could be replaced with human-made systems; an example is natural waste treatment by marshes which can be (partly) replaced with costly artificial treatment systems.
- Factor Income (FI): many ecosystem services enhance incomes; an example is natural water quality improvements which increase commercial fisheries catch and thereby incomes of fishermen.
- Travel Cost (TC): use of ecosystem services may require travel. The travel costs can be seen as a reflection of the implied value of the service. An example is recreation areas that attract distant visitors whose value placed on that area must be at least what they were willing to pay to travel to it.
- Hedonic Pricing (HP): service demand may be reflected in the prices people will pay for associated goods; an example is that housing prices at beaches usually exceed prices of identical inland homes near less attractive scenery.

3.3.3. Contingent valuation (CV)

Service demand may be elicited by posing hypothetical scenarios that involve the description of alternatives in a social survey questionnaire. For example, a survey questionnaire might ask respondents to express their willingness to pay (i.e. their stated preference as opposed to revealed preference, see above) to increase the level of water quality in a stream, lake or river so that they might enjoy activities like swimming, boating, or fishing (Wilson and Carpenter, 1999).

3.3.4. Group valuation

Another approach to ecosystem service valuation that has gained increasing attention recently involves group deliberation (Wilson and Howarth, 2002; Jacobs, 1997; Sagoff, 1998). Derived from social and political theory, this valuation approach is based on principles of deliberative democracy and the assumption that public decision making should result, not from the aggregation of separately measured individual preferences, but from open public debate.

As the extensive literature on ecosystem service valuation has shown, each of these methods has its strengths and weaknesses (see Farber et al., 2002; Wilson and Howarth, 2002). Based on a synthesis study by Costanza et al. (1997), using over 100 literature studies, Table 2 gives an overview of the link between these valuation methods and the 23 functions described in this paper.

Table 2 shows that for each ecosystem function usually several valuation methods can be used. The table also shows that in the Costanza study (Costanza et al., 1997) for each function usually only one or two methods were used primarily. There also seems to be a relationship between the main type of function and the preferred valuation methods: Regulation Functions were mainly valued through Indirect Market Valuation techniques (notably Avoided Cost and Replacement Cost), Habitat Functions mainly through Direct Market Pricing (i.e. money donated for conservation purposes), Production Functions through Direct Market Pricing and Factor Income methods, and Information Functions mainly through Contingent Valuation (cultural and spiritual information), Hedonic Pricing (aesthetic information) and Market Pricing (recreation, tourism and science).

To avoid double counting, and to make valuation studies more comparable, ideally a type of 'rank ordering' should be developed to determine the most preferred valuation method(s). Table 2 can be seen as a first attempt for such a rank ordering, but much more research is needed.

4. Discussion

We have attempted to provide a comprehensive and consistent overview of all functions, goods and services provided by natural and semi-natural ecosystems, and we have described their linkages with available valuation methods. From this analysis it shows that there are several important theoretical and empirical issues that remain to be resolved.

1. Ecological functions and services can overlap, leading to the possibility of economic 'double-counting'. For example, gas-regulation functions (and associated services) have influence on the climate and can, therefore, be valued separately, or as an integral part of the climate regulation service. Similar problems can occur when accounting for 'disturbance prevention' and 'water regulation' services: excessive runoff can lead to flooding and thereby larger disturbances. The interconnectedness of certain ecological functions, and associated ecosystem services, highlights the need for the development of dynamic models that take account of the interdependencies between ecosystem functions, services and values (see Boumans et al., 2002).
2. By matching the proposed typology against the best available valuation methods, we have shown that for all types of ecosystem functions it is possible, in principle, to arrive at a monetary estimation of human preferences for the availability and maintenance of the related ecosystem services. However, while several valuation methods can be used alongside each other (Table 2), it may ultimately be necessary to identify a rank ordering from the least to most preferred valuation methods for each

Table 2
Relationship between ecosystem functions and monetary valuation techniques

Ecosystem functions (and associated goods and services (see Table 1)	Range of monetary values in US$/ha year[a]	Direct market pricing[b]	Indirect market pricing					Contingent valuation	Group valuation
			Avoided cost	Replacement cost	Factor income	Travel cost	Hedonic pricing		
Regulation functions									
1. Gas regulation	7–265		+++	0	0			0	0
2. Climate regulation	88–223		+++	0	0			0	0
3. Disturbance regulation	2–7240		+++	++	0		0	+	0
4. Water regulation	2–5445	+	++	0	+++		0	0	0
5. Water supply	3–7600	+++	0	++	0	0	0	0	0
6. Soil retention	29–245		+++	++	0		0	0	0
7. Soil formation	1–10		+++	0	0			0	0
8. Nutrient cycling	87–21 100		0	+++	0			0	0
9. Waste treatment	58–6696		0	+++	0		0	++	0
10. Pollination	14–25	0	+	+++	++			0	0
11. Biological control	2–78	+	0	+++	++			0	0
Habitat functions									
12. Refugium function	3–1523	+++		0	0		0	++	0
13. Nursery function	142–195	+++	0	0	0		0	0	0
Production functions									
14. Food	6–2761	+++		0	++			+	0
15. Raw materials	6–1014	+++		0	++			+	0

Table 2 (*Continued*).

Ecosystem functions (and associated goods and services (see Table 1)	Range of monetary values in US$/ha year[a]	Direct market pricing[b]	Indirect market pricing					Contingent valuation	Group valuation
			Avoided cost	Replacement cost	Factor income	Travel cost	Hedonic pricing		
16. Genetic resources	6–112	+++		0	++			0	0
17. Medicinal resources		+++	0	0	++			0	0
18. Ornamental resources	3–145	+++		0	++		0	0	0
Information functions									
19 Aesthetic information	7–1760			0		0	+++	0	0
20 Recreation and tourism	2–6000	+++		0	++	++	+	+++	
21 Cultural and artistic insp.		0			0	0	0	+++	0
22 Spiritual and historic inf.	1–25					0	0	+++	0
23 Science and education		+++			0	0		0	0

[a] Dollar values are based on Costanza et al. (1997) and apply to different ecosystems (e.g. waste treatment is mainly provided by wetlands and recreational benefits are, on a per hectare basis, highest in coral reefs). In the columns, the most used method on which the calculation was based is indicated with +++, the second most with ++, etc.; open circles indicate that that method was not used in the Costanza study but could potentially also be applied to that function.

[b] Based on added value only (i.e. market price minus capital and labor costs (typically about 80%).

service to avoid double counting and enhance data comparability. While the resolution of this problem is beyond the scope of this paper, our analysis can serve as a useful starting point for future investigations, both with respect to gathering new, empirical data in a consistent manner, and by providing a framework for analyzing and processing existing information as input in data base development (Villa et al., 2002).

The proposed framework, in combination with such a comprehensive data base of ecosystem services and values, can help identify information gaps in the literature and could serve as a launching point for future collaboration and research strategies in the field of ecosystem service valuation. Once operational, it would be an important tool for more integrated cost-benefit analysis and greatly enhance more balanced decision-making regarding the sustainable use and conservation of natural ecosystems and their many goods and services.

Acknowledgements

This work was conducted as part of the Working Group on the Value of the World's Ecosystem Services and Natural Capital; Toward a Dynamic, Integrated Approach supported by the National Center for Ecological Analysis and Synthesis, a Center funded by NSF (Grant # DEB-0072909), the University of California, and the Santa Barbara campus. Additional support was also provided for the Postdoctoral Associate, Matthew A. Wilson, in the Group.

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