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Ecosystem Services

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Introduction
Defining Ecosystem Services
Examples of Ecosystem Services
Capturing the Value of Ecosystem Services
Conclusions
Further Reading

Introduction

The world's ecosystems yield a flow of essential services that sustain and fulfill human life, from seafood and timber production to soil renewal and personal inspiration. Although many societies have developed the technological capacity to engineer replacements for some services, such as water purification and flood control, no society can fully replace the range and scale of benefits that ecosystems supply. Thus, ecosystems are capital assets, worthy of at least the level of attention and investment given to other forms of capital. Yet, relative to physical, financial, human, and social capital, ecosystem capital is poorly understood, scarcely monitored, and, in many cases, undergoing rapid degradation and depletion.

Recognition of ecosystem services dates back at least to Plato. This recognition of human dependence on ecosystems, in the past and today, is often triggered by their disruption and loss. Direct enjoyment of services, such as the extraction of timber, fish, and freshwater, can reduce the quantity and quality produced. The provision of ecosystem services can also be affected indirectly and inadvertently. Deforestation, for instance, has exposed the critical role of forests in the hydrological cycle – mitigating flooding and reducing erosion. Release of toxic substances has uncovered the nature and value of physical and chemical processes, governed in part by microorganisms that disperse and break down hazardous materials. Thinning of the stratospheric ozone layer has sharpened awareness of the value of its service in screening out harmful ultraviolet radiation.

Defining Ecosystem Services

Simply put, ecosystem services are the conditions and processes through which ecosystems, and the biodiversity that makes them up, sustain and fulfill human life. Ecosystem services are tightly interrelated, making their classification somewhat arbitrary. The Millennium Ecosystem Assessment (MA) – the formal international effort to elevate awareness and understanding of societal dependence on ecosystems – has suggested four categories.

First, 'provisioning services' provide goods such as food, freshwater, timber, and fiber for direct human use; these are a familiar part of the economy. Second, and much less widely appreciated, 'regulating services' maintain a world in which it is biophysically possible for people to live, providing such benefits as water purification, pollination of crops, flood control, and climate stabilization. Third, 'cultural services' make the world a place in which people want to live; they include recreation as well as esthetic, intellectual, and spiritual inspiration. Fourth, 'supporting services' create the backdrop for the conditions and processes on which society depends more directly. All of these services are provided by complex chemical, physical, and biological cycles, powered by the sun, and operate at scales ranging from

Table 1 A classification of ecosystem services. Examples of ecosystem services and how they can be categorized

Provisioning services: Production of...
Food
Seafood, agricultural crops, livestock, spices
Pharmaceuticals
Medicinal products, precursors to synthetic pharmaceuticals
Durable materials
Natural fiber, timber
Energy
Biomass fuels, low-sediment water for hydropower
Industrial products
Waxes, oils, fragrances, dyes, latex, rubber
Genetic resources
Intermediate goods that enhance the production of other goods
Regulating services: Generation of...
Cycling and filtration processes
Detoxification and decomposition of wastes
Generation and renewal of soil fertility
Purification of air and water
Translocation processes
Dispersal of seeds to sustain tree and other plant cover
Pollination of crops and other plants
Stabilizing processes
Coastal and river channel stability
Control of the majority of potential pest species
Carbon sequestration
Partial stabilization of climate
Protection from disasters:
regulation of hydrological cycle (mitigation of floods and droughts)
moderation of weather extremes (such as of temperature and wind)
Cultural services: Provision of...
Esthetic beauty, serenity
Recreational opportunities
Cultural, intellectual, and spiritual inspiration
Supporting services: Preservation of...
Processes underlying services in the classes above
Options
maintenance of the ecological components and systems needed for future supply of the goods and services above and others awaiting discovery

smaller than the period at the end of this sentence to as large as the entire biosphere (**Table 1**).

Tradeoffs in Managing the Flows of Ecosystem Services

Biophysical constraints on human activities, such as limited supplies of energy, land, and water, typically manifest themselves as tradeoffs between different uses. Thus, managing ecosystem services involves difficult ethical and political decisions about which services to develop and how to do so. At local scales, allocation of limited resources to alternative activities typically involves a zero-sum game, illustrated by the widespread redirection of water from agriculture to urban and industrial purposes. At global scales, different groups of people compete for use of Earth's open-access resources and waste sinks, such as the atmosphere's capacity to absorb CO_2 and other greenhouse gases without inducing climate change.

Making informed decisions about how to use ecosystem goods and services hinges on understanding these tradeoffs: knowing the joint products – the suite and level of services – that ecosystems can provide. For example, an ecosystem managed exclusively for agriculture may yield a greater return on agricultural products than one managed for multiple services, but understanding that diversified management may produce greater overall returns could influence management decisions (**Figure 1**).

Provision of biodiversity is one supporting service that has historically been discounted when managing for other ecosystem services. Biodiversity, however, can provide irreplaceable benefits. Genetic diversity, for example, allows for both the survival and evolution of the ecosystems we depend on for myriad benefits. Recent research indicates that diverse systems are more resilient, and therefore provide ecosystem services more reliably in the long term, than monocultures. While under optimal conditions managing for a single species may provide superior timber supplies or nutrient sequestration, given natural and human-caused variability in temperature, rainfall, and other environmental factors, managing for a diverse system will more consistently provide services in an uncertain world.

Examples of Ecosystem Services

Ecosystem services can be explored by focusing either on a single service that may be provided by various ecosystems or by looking at a single ecosystem that may provide a variety of services. Here we illustrate both approaches, considering first pollination services provided by bees then the suite of services provided by wetlands and forests. We highlight the differences in scale of delivery of services, from local to global, and explore the tradeoffs inherent in their management.

Pollination Services Provided by Bees

Pollination, the movement of genetic material in the form of pollen grains, is a key step in the development of most food crops. Even crops that do not rely on insect pollination – wind pollinated or self-pollinated crops – are sometimes more productive when visited by an insect pollinator. Bees are a particularly important group of insect pollinators, responsible for pollinating 60–70% of the world's total flowering plant species, including nearly 900 food crops worldwide, such as apples, avocados,

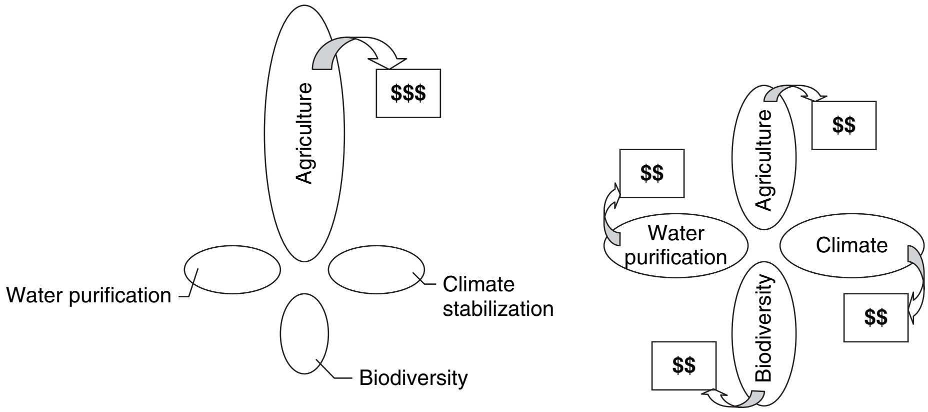

Figure 1 Joint products of ecosystems. Many ecosystems are currently managed to exploit only one service. Managing for multiple services can increase ecosystem benefits.

cucumbers, and squash. These crops comprise 15–30% of the world's food production, and bees are credited with \$4.2 billion in annual crop productivity in California alone. Bees are especially important pollen vectors in part because physical adaptations, such as hairs designed to pick up pollen, and behavioral adaptations, such as fidelity to a single species of plant on each pollen-gathering trip, ensure good pollen transport and cross-pollination.

In the US, most major agricultural enterprises that rely on bee pollination import managed bees, almost always the European honeybee *Apis mellifera*. The available stock of managed honeybees has declined dramatically, however, dropping by over 50% in the last 50 years, while demand for pollination services has increased in many areas. This decline in managed bee populations has many causes, including increased pesticide use, disease in the hives, and downsizing of stocks that have hybridized with Africanized bees, introducing traits that make managed bees more aggressive and thus a liability to the farmer.

The contribution of native, wild bees to agricultural pollination was ignored, and assumed to be negligible, until the early 2000s. Since then, research has shown that native bees serve an important role in pollination, picking up slack when managed bee pollination is insufficient and enhancing crop production in general. Farms with generous native bee habitat nearby may be able to fully or partially replace pollination by managed bees. In some cases, native bees are more efficient pollinators than European honeybees. The variety of wild bees, with distinct physical and behavioral traits, allows them, as a group, to pollinate a wide variety of flowering plants. Tomatoes, for example, have pollen that is accessible only by vibrating the flower, which bumble bees and some other native bees can, while honeybees cannot. Though tomatoes are self-pollinating and do not require an insect vector, native bees promote cross-pollination, which, for example, significantly increases the fruit set and size of Sungold cherry tomatoes.

The contributions of native bees to crop production are usually undocumented and underestimated, and they are always unpaid, at least directly. Though hives of managed honeybees must be rented or maintained, wild bees pollinate at no cost to the farmer. Populations of native bees are under great threat, however, by land management practices that promote the use of pesticides and the loss, fragmentation, and degradation of habitat. Protecting native bees without protecting the ecosystems in which they live is impossible. Native habitat, unlike agricultural monocropping, provides the year-round supply of blooming plants that wild bees require for sustenance. Native habitat also provides nesting areas; most wild bees are solitary, laying a single egg in a nest cavity dug into the ground or into dead wood, not forming social hives. In order to reap the benefits of native pollinators, food resources and nesting habitat must be available within a short distance of crops, possibly as hedgerows, in ditches, or around water ponds. A study of wild bee pollination of coffee in Costa Rica showed that farms closer to tropical forest remnants were visited by many more species of wild bees than those further away. Had the far sites been adequately pollinated, coffee yield would have been increased by nearly 20% and misshapen coffee beans reduced by 27%. A lower-bound estimate of the pollination services from these patches is US \$62 000 per year (in the early 2000s).

The diversity of the native bee population is one of its strengths. Many species of bees participate in pollination, and the abundance of different species varies year by year. This diversity allows the native pollinator community to be both resistant, maintaining functionality in the face of environmental upheaval, and resilient, able to reestablish itself in the wake of a destructive event. When the population of *Apis* declined dramatically in the second year of the Costa Rica study, sites close to forest fragments showed minimal loss of pollination while pollinator visits dropped by nearly 50% further away. Thus, as well as enhancing pollination services in conjunction with managed bees, native bee populations provide important insurance against the possibility that managed bee populations could fail because of disease, hybridization, or other causes.

Services Provided by Wetlands

Areas inundated by fresh, brackish, and salt water are all considered wetlands; among many wetland types are fens and bogs, tidal marshes, riparian zones, and lakeshores. Wetlands, which cover less than 9% of the Earth's surface, can be extremely productive and many are disproportionately large providers of ecosystem services. Three of the key services that wetlands provide are flood mitigation, water purification, and biodiversity support.

In the upper part of a watershed, many wetlands store water that flows overland toward rivers and streams. They can release this water into the main channel slowly, reducing and delaying flood peaks. Downstream, wetlands can absorb and reduce peak flood levels, providing area into which flood waters can spread, dissipating flood energy by slowing water movement, and removing flood water through transpiration and infiltration.

The same physical characteristics of wetlands that slow and absorb overland flow related to flooding can also provide a mechanism for storing and detoxifying urban and agricultural wastewater before it discharges directly into a main channel. Wetlands filter out various nutrients, other pollutants, and sediment: they support anaerobic bacteria that denitrify waste; the plants take up and store nutrients; and by slowing and redirecting water flow, wetlands enhance sedimentation – the accreting sediments can effectively bury pollutants. While many wetlands can purify water very economically, their effectiveness depends on many factors, including rate of inflow, amount of sediment and organics in the wastewater, residence time of wastewater in the wetland, and total surface area.

A wide variety of animals rely on wetlands for survival. Plant species that deliver flood abatement and water purification can also support biodiversity, providing varied food and shelter. A riparian wetland, for example, might provide food plants and underground burrows for muskrats; seeds, food plants, and nest-building materials for ducks; and food and shelter for fish and invertebrates.

Wetlands provide a variety of other services as well. Major products associated with wetlands are peat, timber, and mulch. Regulating services in addition to flood mitigation and water purification include waste detoxification, carbon storage, and control of pests and diseases. Wetlands provide many cultural services as well, particularly recreation services such as bird watching, boating, and hunting. Wetlands also provide key supporting services, such as soil formation and buffering freshwater aquifers from saltwater intrusion.

Worldwide, wetlands are estimated to provide many billions of dollars in services each year. They are recognized by the international treaty, the Ramsar Convention on Wetlands, and regulated by domestic law in many countries. Nonetheless, they have historically undergone widespread losses in favor of other land uses; worldwide, 50% of wetlands are estimated to have been lost since 1900.

While the services provided by wetlands are widely recognized, simultaneously maximizing multiple services may not be possible. In some cases this is related to location: upland watersheds may be very important for flood control but may be too far upstream to have an impact on water purification. In other cases one service may thrive to the detriment of another: a wetland that is absorbing a heavy nutrient load may be overtaken by a single, aggressive plant species and thus fail to be an effective reservoir for biodiversity. Finally, it can be costly to measure function and hence difficult to judge how effectively a wetland is performing a given service or how to manage for that particular service.

Services Provided by Forests

Forests provide a wide array of services, such as timber production, climate stabilization, provision of water quantity and quality, and cultural benefits, such as recreation. Some management options increase the supply of several services, but often one service is enhanced to the detriment of others.

Forests are often managed for provisioning services, particularly for timber. But even within the category of provisioning services, management options differ. If a forest is considered exclusively a supplier of timber, managers will encourage the growth of only certain kinds of trees, possibly nonnative fast-growing trees, and will cultivate them so that they grow in a uniform way, typically straight and tall. When the trees are deemed mature, they will be cut down, often all at once. By contrast, if a forest is regarded as a supplier of diverse benefits, it may be managed to nurture a wide array of valued species that would not be available in the monocrop forest described above.

Forests also have both short-term and medium-term impacts on climate. Temperature regulation happens in forests when the canopy shades the ground and when dark-colored foliage absorbs heat. Forests can in certain circumstances also influence precipitation – in cloud forests, for example, trees and epiphytes intercept and condense water directly from the air, and that water runs down trunks to plants and soil below. On a longer timescale, forests play a role in carbon cycling and sequestration; when forest plants, bacteria, and algae respire, they take CO_2 out of the atmosphere. Plants, soils, and the animals that eat them in forests, grasslands, and other terrestrial ecosystems store ~2000 billion tons of carbon worldwide, about half the amount of carbon stored in the ocean and nearly three times that stored in the atmosphere. However, if these ecosystems are burned or destroyed, as happens when timber is harvested, the carbon they are sequestering is released to the atmosphere. Although most organic compounds do return to the atmosphere as CO_2 when living organisms die and decompose, in a functioning forest ecosystem some is buried and sequestered. About 25% of the human-caused increase in CO_2 concentration in the atmosphere during the past 20 years resulted from land-use change, primarily deforestation.

Forests in a watershed, on the hillslopes that drain into a river, influence the water quality in that river. In part this is because higher-intensity uses, such as agriculture input pollutants like nutrients and pesticides into a system while forests do not. Forests themselves also reduce sediment and nutrient runoff. Clearing trees can have an impact as soon as the next rainy season on sediment and nutrient loads in streams, as demonstrated in the classic Hubbard Brook experiment. In some cases, water users have invested in forests to keep their water supplies clean. New York City recently invested US$ 250 million to acquire and protect land in the Catskills watershed that supplies water to the city. By working with landowners to reduce pesticide and fertilizer application and to plant buffer strips along waterways, New York City reduced potential contamination of its drinking water. In conjunction with related conservation investments amounting to ~US$ 1.5 billion, the city thereby obviated the need to build a filtration plant projected to cost between US$ 6 and US$ 8 billion.

Forests can also play an important role regulating the timing and quantity of runoff. The economic value of forests in the watershed of the Yangtze River above Three Gorges Dam, in western Hubei Province, Central China, was quantified in a study published in 2000. Here, the Gexhouba Hydroelectric Power Plant, the largest hydro-facility in China, producing 15.7 billion kW annually, requires a narrow range of flows on the Yangtze in order to run at full power. If the water level is too high, then water must be released through the sluice gates, causing the water level below the dam to rise, reducing the amount of power that can be produced; at very high flows, turbines are drowned and cannot work at all. If the water is too low, then generators cannot run at full power.

The goal of the hydroelectric facility's managers is for the river to have flow depths that vary as little as possible, as this has been shown to be much more important for power generation than the total flow. Upstream forests damp fluctuations in stream flow by reducing runoff in wet periods through canopy interception, leaf litter absorption, and soil and groundwater storage; increased infiltration provides base flow in dry periods through groundwater discharge. Though water flow regulation is a function of vegetation, soil type, and slope, which occur in a heterogeneous mix through the watershed, forests and even shrubs with all types of soils and slopes consistently provided better water regulation than grasses, orchards, and crop agricultural fields. This study estimated the value of electricity produced by the hydro-facility due to water regulation by the forest at over US$ 600 000 per year (in the early 2000s), or about 2.2 times the income derived from forest product services in this area. Because trees lose water to the atmosphere through transpiration, however, the total water available downstream was decreased by the forest.

Different management regimes will yield different suites of services. Some services can never be co-produced; other services will almost always be produced in tandem, though often to differing degrees. For the hypothetical forest illustrated in Figure 2, cattle and timber cannot be produced on the same parcel of land – conversion to pasture optimizes livestock but reduces timber output dramatically. Under timber maximization, once trees are harvested they are not available for climate or hydrologic regulation, though before harvest those services will be produced, as well as some habitat and hiking trails. Carbon sequestration, hydropower, recreation, and preservation of biodiversity tend to be co-produced, but there are tradeoffs in their optimal supply. Maximizing biodiversity, for example, produces all four to their fullest extent but allows for no timber supply. Bringing selective logging back into the management regime reduces supply of the other services somewhat; maximizing timber yield reduces them much more dramatically.

Tradeoffs between services are also tradeoffs between consumers, such as local recreationalists, regional users of hydropower, and global beneficiaries of carbon sequestration and biodiversity conservation. These tradeoffs underscore the importance of valuation, making explicit who benefits from ecosystem services and who pays for them. Conceiving of ecosystem functions as services and assigning a monetary value to them provides a tool for decision-makers to weigh different management options.

Capturing the Value of Ecosystem Services

Despite their obvious importance to human well-being, people tend to think of ecosystems as being economically productive in narrow terms, often assigning value only to the production of conventional commodities or to real estate development. Provision of ecosystem services is only rarely considered in cost–benefit analyses, preparation of environmental impact statements, or other assessments of alternative paths of development. There is no shortage of markets for ecosystem goods (such as clean water and watermelons), but the services underpinning these goods (such as water purification and bee pollination) often have no monetary value. This is in part because ecosystem services are

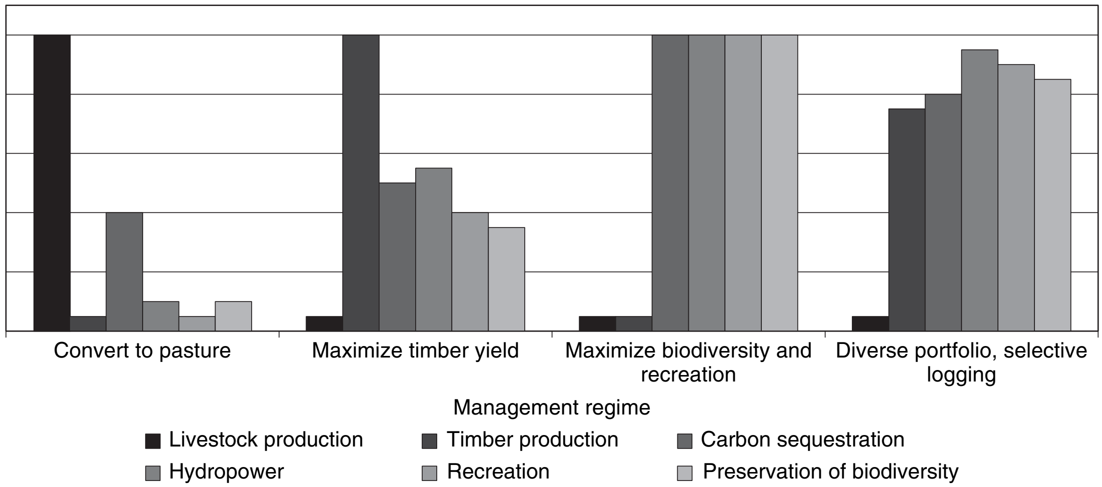

Figure 2 Tradeoffs associated with alternative management objectives for a hypothetical forest ecosystem.

generally public goods, free to any user, and therefore difficult to value. Because people mostly do not pay for them, it can be difficult to discern what the supply, demand, and willingness to pay for services actually are. As a result, there are no direct price mechanisms to signal the scarcity or degradation of these public goods before they fail.

While for some goods and services price reflects value or importance, when ecosystem services are assigned monetary value they tend to be priced much lower than their importance suggests. This is true in part because when supply is much larger than demand, prices are low, no matter how necessary the good. The pricing of diamonds and water is illustrative. Lost in the desert, a traveler would happily trade all the diamonds in the world for a single cup of water; back in the marketplace, our traveler would find that diamonds are many, many times more costly than water. Water is inexpensive or free because, like many ecosystem goods and services, it tends to be far more abundant than the volume demanded by people; when ecosystems are functioning well, even more is available.

Ecosystem services are also often undervalued because prices are based on current supplies and demands, so the amount we are willing to pay for continued nutrient retention in a wetland may be low today even if we can predict that nutrient-laden runoff from increased agriculture will threaten a downstream fishery tomorrow. Further, prices are based on marginal utility – for example, the amount someone would be willing to pay for the carbon stored in one more tree in a forest. If that forest is clear-cut, we lose all of the carbon storage and, since the loss of each tree changes the value of the next, we cannot account for the whole loss using the price of the first tree.

Precise valuation of ecosystem services is often not required to provide appropriate economic incentives for protecting the ecosystems that supply them. Incentives need only make it more economically appealing to a landowner to maintain hedgerows as habitat for native pollinators than to cultivate every last square meter of a field, for instance, or make it pay to preserve a wetland rather than filling it to build houses. A farm, as illustrated below, might generate enough income from nonagricultural commodities to alter its land management regime (Table 2). Incentives to protect and maintain ecosystems can be provided by the government, privately through markets, or through hybrid institutions such as cap-and-trade systems supported by government policy.

A variety of tools for valuing ecosystem services and creating incentives for their conservation are currently being developed, including capital markets such as the Chicago Climate Exchange, wetland mitigation banks, and outright payments, often involving private–public partnerships, for services, as is occurring in Australia, Costa Rica, and Mexico. These market-based approaches provide a much better indication of value than early, more theoretical attempts to quantify the value of ecosystem services. While valuation is not necessarily a solution or end in itself, it is a powerful way of organizing information and an important tool in the much larger process of decision making.

Table 2 A hypothetical farm business in 15 years

Commodity	*Share of farm business (%)*
Wheat	40
Wool	15
Water filtration	15
Timber	10
Carbon sequestration	7.5
Salinity mitigation	7.5
Biodiversity	5

In this model, traditional agricultural commodities account for 55% of revenues, as opposed to 100% today. Nonagricultural income is supplied by a mature market for ecosystem goods and services.

Conclusions

Because ecosystem services explicitly invoke human beneficiaries, basic scientific understanding of the ecosystem processes producing goods and services is meaningful only in the context of economic valuation and institutional structures. There is still much to learn on many fronts. Important questions include: Which ecosystems supply which services? What levels and types of ecosystem protection are required to sustain service supply? Can we develop robust methodologies for the valuation of ecosystems? Even if clear answers are absent to all of these questions, numerous and diverse efforts are now underway worldwide to protect vital ecosystem services, often using innovative economic incentives.

Explicitly identifying and valuing the goods and services provided by ecosystems has two obvious benefits. First, understanding the role of ecosystem services powerfully justifies habitat preservation and biodiversity conservation as vital, though often overlooked, policy objectives. While a wetland surely provides existence and option values to some people, the benefits provided by the wetland's nutrient retention and flood mitigation services are both universal and undeniable. Tastes may differ over beauty, but they are in firm accord over the high costs of polluted water and flooded homes. Second, if given the opportunity, natural systems can in many cases quite literally pay their own way. Market mechanisms and institutions that can capture and maximize service values can effectively promote environmental protection at the local, regional, national, and international levels. In some cases, however, protection of ecosystem services will not justify conservation of natural habitats. In other cases, the services will be largely irrelevant to environmental protection efforts. While a focus on ecosystem services provides great potential to promote environmental protection, its practical implications remain largely unexamined.

See also: Agroforestry; Biodegradation; Biodiversity; Biomass, Gross Production, and Net Production; Climate Change 1: Short-Term Dynamics; Coastal Zone Management; Conservation Biological Control and Biopesticides in Agricultural; Deforestation; Denitrification; Ecological Economics 1; Ecosystem Health Indicators ; Environmental Impact Assessment and Application Part 1; Erosion; Forest Management; Industrial Ecology; Lake Restoration Methods; Natural Wetlands; Resilience; Resistance and Buffer Capacity; Riparian Wetlands; Sediment Retention and Release; Stream Management; Sustainable Development; Water Availability; Water Cycle Management; Watershed Management; Wetland Models.

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