Linking Ecology and Economics for Ecosystem Management

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This article outlines an approach, based on ecosystem services, for assessing the trade-offs inherent in managing humans embedded in ecological systems. Evaluating these trade-offs requires an understanding of the biophysical magnitudes of the changes in ecosystem services that result from human actions, and of the impact of these changes on human welfare. We summarize the state of the art of ecosystem services–based management and the information needs for applying it. Three case studies of Long Term Ecological Research (LTER) sites—coastal, urban, and agricultural—illustrate the usefulness, information needs, quantification possibilities, and methods for this approach. One example of the application of this approach, with rigorously established service changes and valuations taken from the literature, is used to illustrate the potential for full economic valuation of several agricultural landscape management options, including managing for water quality, biodiversity, and crop productivity.

Keywords: ecosystem services, valuation, ecosystem management, LTER, trade-offs

The history of environmental and resource manage- ment has been influenced by the degree of incorporation of ecological processes and functions, the importance of human welfare in decisions, and the processes of decisionmaking (Andrews 1999, Mangun and Henning 1999). Decisionmaking approaches tied to evaluations of environmental impact have been proposed in the past, but they have not explicitly taken an ecosystem services perspective, nor have they joined that perspective with economic valuation methods (Dee et al. 1973, Westman 1985, Treweek 1999). The ecosystem services approach addresses recent calls for the explicit incorporation of economic valuations in ecological management decisions (Carpenter and Turner 2000, WRI 2005). For example, Treweek (1999) notes that "while there are well-developed techniques for economic appraisal and social assessment, little progress has actually been made in integrating these techniques with those for EcIA [ecological impact assessment] in order to reach balanced decisions about the overall acceptability of ecological change. This is a deficiency that urgently needs to be addressed" (p. 205). The tragic consequences of Hurricane Katrina on the Gulf Coast, and in New Orleans in particular, have highlighted the importance of addressing ecosystem services—such as the storm protection that wetlands provide—in management decisions involving coastal settlement and infrastructure policies. Knowledge of the enhanced storm protection services of rebuilt coastal wetlands is critical to assessing the ability to use natural system services in addition to humanmade protection, altered coastal settlement patterns, and coastal infrastructure design. Also evaluating trade-offs between coastal marsh area and fisheries require an understanding of these ecosystem services and their values.

The ecosystem services approach integrates ecology and economics to help explain the effects of human policies and impacts both on ecosystem function and on human welfare (Costanza et al. 1997, Daily 1997, NRC 2005). Here we illustrate the potential applicability of an ecosystem services–based approach using coastal, urban, and agricultural LTER (Long Term Ecological Research) sites.

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What is ecosystem services–based management?

Ecosystem services are the benefits humans receive, directly or indirectly, from ecosystems (Costanza et al. 1997, Daily 1997). Alterations of ecosystems change the mix of services through changes in ecosystem structures and processes. Services may increase or decrease; for example, increasing the land mass of wetlands for storm protection may diminish fishery habitat by reducing the marsh–water edge. Ecosystem management decisions inevitably involve trade-offs across services and between time periods, and weighing those trade-offs requires valuations of some form.

Ecosystem services assessments. Ecosystem services can be categorized in a variety of ways (NRC 2005). Table 1 reproduces the Millennium Ecosystem Assessment (WRI 2005) categories and illustrates a variety of these services. All ecological services are the consequence of supporting processes working at various temporal and spatial scales. For example, carbon dioxide (CO_2) gas regulatory cycles work at small and rapidly changing local scales, but carbon (C) sequestration services have value at global and long-term scales. To be effective, management must focus on the health of appropriately scaled ecosystems and landscapes, and on integrating knowledge about ecological and economic systems across multiple scales (Costanza et al. 1992, Rapport et al. 1998).

Assessments of ecosystem services require estimates of changes in ecosystem processes and structures, and in the resulting levels of services. For example, changes in forest tree species lead to changes in C sequestration, which can be measured (Balvanera et al. 2005). The resulting change in forest cover also leads to changes in evapotranspiration, affecting local climate regulation services. Forested ecosystems provide for the regulation of water cycling through the landscape, streams, and rivers. The movement of water through the forested landscape has been modeled and the implications for river flows estimated (Guo et al. 2000). The regulation of river flows is an ecological service that has economic value. The forest cover examples illustrate the "joint products" implications of changing ecological structures and functions. Another example is the relationship between primary production and fishery yields across a variety of aquatic ecosystems (Nixon 1988). Kremen (2005) provides a useful summary of several service measures. Ecosystem services–based management requires connecting these quantified services to human welfare.

Integrated ecological–economic models provide a useful approach to quantifying the trade-offs in ecosystem services in complex, dynamic systems. The Patuxent landscape model links spatially explicit human, land use, hydrologic, biogeochemical, and food web models. It allows systematic analyses of the interactions among the physical and biological dynamics of the Patuxent River watershed (Costanza et al. 2002, Costanza and Voinov 2003). The socioeconomic model of regional land use dynamics captures complex feedbacks between ecological and economic systems. The model was designed to address the effects of various spatial patterns of human settlements and agricultural practices on hydrology, plant productivity, and nutrient cycling in the landscape. Nalle and colleagues (2004) developed a spatially explicit "production-possibilities frontier" model to simulate the trade-offs between timber harvest value and the population viability of two wildlife species. Production-possibilities frontiers represent the maximum feasible combinations of services from an ecosystem depending upon management options. This model is useful in illuminating the trade-offs between economic (timber) and ecological (biodiversity) services, and in selecting cost-effective management options.

Full ecological–economic models may be the gold standard for establishing the full range of ecosystem service possibilities and management options. Establishing the production-possibilities frontiers, along with social values, makes it possible to determine the global optimum across the feasible set of services. However, full modeling is costly in terms of data and measurability requirements. A practical alternative is to consider service changes, or gradients, from the status quo provided by a finite set of management options. This may not provide for a global optimum, but may result in the choice of superior management options within a viable set of those options. In addition, management efforts are often addressed at relatively small spatial scales, at which it would be impractical to develop costly ecological–economic models. An alternative is to narrow the scope of analysis and focus only on locally important ecosystem services and their changes (Guo et al. 2000).

Evaluation of services. Information about trade-offs that people are willing to make across alternative ecological services within the suite of feasible ecological services can be used to assess the desirability of different management outcomes (Heal et al. 2001, Nalle et al. 2004). These trade-offs can be measured using both individual and collective values, and can be in monetary or nonmonetary units (scores, ratings, rankings). Evaluations of trade-offs are critical to finding management options that provide for the highest-value service flows from an ecosystem. For example, a management option that increases coastal wetlands area but reduces marsh–water edge would be evaluated by comparing the values for storm protection gained with the values for fishery habitat lost.

Although a focus on trade-offs suggests that economic efficiency is an important criterion for measuring impacts on social welfare, other considerations—equity, sustainability, ecological stewardship, and cultural and ethical values—also provide important foundations for the decisionmaking process (Costanza and Folke 1997). Equity analyses require an estimation of who receives the service benefits or costs of management options, while sustainability and stewardship analyses focus on the intertemporal distribution of those services. Cultural and ethical considerations may place constraints on acceptable decisions.

There is meaningful debate surrounding the role that human, utilitarian values should play in making environmental management decisions, pitting anthropocentrism against

Table 1. Ecosystem functions and services.

Ecosystem functions and services	Description	Examples
Supportive functions and structures	Ecological structures and functions that are essential to the delivery of ecosystem services	See below
Nutrient cycling	Storage, processing, and acquisition of nutrients within the biosphere	Nitrogen cycle; phosphorus cycle
Net primary production	Conversion of sunlight into biomass	Plant growth
Pollination and seed dispersal	Movement of plant genes	Insect pollination; seed dispersal by animals
Habitat	The physical place where organisms reside	Refugium for resident and migratory species; spawning and nursery grounds
Hydrological cycle	Movement and storage of water through the biosphere	Evapotransporation; stream runoff; groundwater retention
Regulating services	Maintenance of essential ecological processes and life support systems for human well-being	See below
Gas regulation	Regulation of the chemical composition of the atmosphere and oceans	Biotic sequestration of carbon dioxide and release of oxygen; vegetative absorption of volatile organic compounds
Climate regulation	Regulation of local to global climate processes	Direct influence of land cover on temperature, precipitation, wind, and humidity
Disturbance regulation	Dampening of environmental fluctuations and disturbance	Storm surge protection; flood protection
Biological regulation	Species interactions	Control of pests and diseases; reduction of herbivory (crop damage)
Water regulation	Flow of water across the planet surface	Modulation of the drought–flood cycle; purification of water
Soil retention	Erosion control and sediment retention	Prevention of soil loss by wind and runoff; avoiding buildup of silt in lakes and wetlands
Waste regulation	Removal or breakdown of nonnutrient compounds and materials	Pollution detoxification; abatement of noise pollution
Nutrient regulation	Maintenance of major nutrients within acceptable bounds	Prevention of premature eutrophication in lakes; maintenance of soil fertility
Provisioning services	Provisioning of natural resources and raw materials	See below
Water supply	Filtering, retention, and storage of fresh water	Provision of fresh water for drinking; medium for transportation; irrigation
Food	Provisioning of edible plants and animals for human consumption	Hunting and gathering of fish, game, fruits, and other edible animals and plants; small-scale subsistence farming and aquaculture
Raw materials	Building and manufacturing Fuel and energy Soil and fertilizer	Lumber; skins; plant fibers; oils; dyes Fuelwood; organic matter (e.g., peat) Topsoil; frill; leaves; litter; excrement
Genetic resources	Genetic resources	Genes to improve crop resistance to pathogens and pests and other commercial applications
Medicinal resources	Biological and chemical substances for use in drugs and pharmaceuticals	Quinine; Pacific yew; echinacea
Ornamental resources	Resources for fashion, handicraft, jewelry, pets, worship, decoration, and souvenirs	Feathers used in decorative costumes; shells used as jewelry
Cultural services	Enhancing emotional, psychological, and cognitive well-being	See below
Recreation	Opportunities for rest, refreshment, and recreation	Ecotourism; bird-watching; outdoor sports
Aesthetic	Sensory enjoyment of functioning ecological systems	Proximity of houses to scenery; open space
Science and education	Use of natural areas for scientific and educational enhancement	A "natural field laboratory" and reference area
Spiritual and historic	Spiritual or historic information	Use of nature as national symbols; natural landscapes with significant religious values

biocentrism, and human values against moral obligations and intrinsic rights (Goulder and Kennedy 1997, NRC 2005). One possible compromise is that intrinsic rights and moral obligations establish constraints within which further management decisions can be based on utilitarian values. A full consideration of the role of all ecosystem components in providing useful services may result in the conservation of the same species and processes that would be demanded for reasons of morality, intrinsic rights, and stewardship.

The changes in services caused by ecological change may be large or small. Small changes in ecological conditions may lead to large changes in valued services. The margins at which valuations of changes must be made can be large or small. If margins of change are small, partial equilibrium analyses of ecological and economic systems may be adequate for valuation. For example, increasing wetland area by a few hundred hectares (ha) may have little effect on the marsh–water edge and may increase fishery yields without substantially altering market prices or general economic conditions. At larger margins (e.g., saving the coastal wetlands of Louisiana), a general equilibrium analysis or ecological–economic modeling analysis would be necessary, as such a large change would have substantial local and national implications. Future research should focus on the scale of change at which partial equilibrium analyses are no longer reasonable for some services.

Basic approaches for assessing the value of changes in ecological services are shown in box 1. Ecological services that have a supportive function (WRI 2005) or that have indirect or less commonly understood effects on individual welfare (biodiversity, nutrient cycling, soil formation, etc.) are problematic for the use of valuation techniques that require direct expressions of value. In these circumstances, it may be necessary to construct values indirectly, by tying services to things people directly value; for example, soil formation values may be measured in terms of increased crop yields and resulting income increases or consumer savings. *Replacement-cost* methods can be problematic when the cost of replacing a service exceeds its value, as in the case of early wetlands valuations based on the cost of replacing the tertiary wastewater treatment services of wetlands. Very few municipalities used tertiary treatment at the time because it was too costly. However, a reasonable use of replacement cost was in determining the value of preserving and restoring the pristine character of the Catskills watershed, measured by the cost savings to New York City of not having to build a multibillion-dollar water treatment system (Heal 2000). *Avoided-cost* methods similarly assume that the costs would actually be incurred in the absence of the service, suggesting the need to understand behavioral responses to changes in service availability.

Economic valuation tools provide monetary measures of service values, reflecting the value of services relative to other things that people spend money on. Nonmonetizing methods do not require a connection between values and money, but still provide information about relative values, equivalencies, or rankings. The equivalencies and relative rankings can be used to weight the changes in ecological services resulting from management decisions.

Some valuation methods are more appropriate for an ecosystem service than for others. Table 2 illustrates possible methods for the valuation of different services. For example, gas regulation, such as C sequestration, can be valued on the basis of the costs the economy would incur to remove the same volume of C in the absence of natural sinks (replacement cost), but only if it is reasonable to assume that removal would take place in the absence of the natural service. Nutrient regulation, such as the uptake of nitrogen (N) by streamside vegetation, can be valued for its beneficial impacts on water quality and measured by downstream treatment costs avoided (avoided cost), but only if it is reasonable to assume that polluted water would be treated in the absence of the natural service. Recreationists' *contingent valuations* of enhanced fishing opportunities can also be used.

When ecological services or their valuations are interdependent, it may be necessary to jointly value the entire

Box 1. Valuation methods.

Methods of valuing ecosystem services include conventional economic valuation (Freeman 1993, Willis and Corkindale 1995, O'Connor and Spash 1999, NRC 2005) and nonmonetizing valuation or assessment (Renn et al. 1995, Kahn 2005).

Conventional economic valuation

Revealed-preference approaches

- Travel cost: Valuations of site-based amenities are implied by the costs people incur to enjoy them (e.g., cleaner recreational lakes).
- Market methods: Valuations are directly obtained from what people must be willing to pay for the service or good (e.g., timber harvest).
- Hedonic methods: The value of a service is implied by what people will be willing to pay for the service through purchases in related markets, such as housing markets (e.g., open-space amenities).
- Production approaches: Service values are assigned from the impacts of those services on economic outputs (e.g., increased shrimp yields from increased area of wetlands).

Stated-preference approaches

- Contingent valuation: People are directly asked their willingness to pay or accept compensation for some change in ecological service (e.g., willingness to pay for cleaner air).
- Conjoint analysis: People are asked to choose or rank different service scenarios or ecological conditions that differ in the mix of those conditions (e.g., choosing between wetlands scenarios with differing levels of flood protection and fishery yields).

Cost-based approaches

- Replacement cost: The loss of a natural system service is evaluated in terms of what it would cost to replace that service (e.g., tertiary treatment values of wetlands if the cost of replacement is less than the value society places on tertiary treatment).
- Avoidance cost: A service is valued on the basis of costs avoided, or of the extent to which it allows the avoidance of costly averting behaviors, including mitigation (e.g., clean water reduces costly incidents of diarrhea).

Nonmonetizing valuation or assessment

Individual index-based methods, including rating or ranking choice models, expert opinion

Group-based methods, including voting mechanisms, focus groups, citizen juries (Aldred and Jacobs 2000, Howarth and Wilson 2006), stakeholder analysis (Gregory and Wellman 2001).

Table 2. Categories of ecosystem services and economic methods for valuation.

Ecosystem service	Amenability to economic valuation	Most appropriate method for valuation	Transferability across sites
Gas regulation	Medium	CV, AC, RC	High
Climate regulation	Low	CV	High
Disturbance regulation	High	AC	Medium
Biological regulation	Medium	AC, P	High
Water regulation	High	M, AC, RC, H, P, CV	Medium
Soil retention	Medium	AC, RC, H	Medium
Waste regulation	High	RC, AC, CV	Medium to high
Nutrient regulation	Medium	AC, CV	Medium
Water supply	High	AC, RC, M, TC	Medium
Food	High	M, P	High
Raw materials	High	M, P	High
Genetic resources	Low	M, AC	Low
Medicinal resources	High	AC, RC, P	High
Ornamental resources	High	AC, RC, H	Medium
Recreation	High	TC, CV, ranking	Low
Aesthetics	High	H, CV, TC, ranking	Low
Science and education	Low	Ranking	High
Spiritual and historic	Low	CV, ranking	Low

AC, avoided cost; CV, contingent valuation; H, hedonic pricing; M, market pricing; P, production approach; RC, replacement cost; TC, travel cost.

bundle of ecological services, using methods such as *conjoint analysis,* rather than sum the values of individual service levels (Goulder and Kennedy 1997). For example, valuation of water quality for impacts on salmon would require the joint valuation of other species connected to salmon, such as grizzlies. The interdependence of ecosystem services across members of a community may require joint valuation as a community exercise. This may be the case for services that enhance the social capital or cultural structure of a community, as opposed to services that have individualistic benefits such as increased crop yields.

The ability to transfer valuations from one context to another may be critical to the cost-effective use of services-based valuations. Some ecosystem services, such as the avoided greenhouse gas costs of C sequestration, may be provided at scales at which benefits are easily transferable. Other services are available at local scales but are so general that valuation in one context may be meaningfully transferred to another, such as the value of fish caught. Other local-scale services may have limited transferability, such as flood control values. Table 2 provides guidance for transferring service values from one context to another.

Decision processes. As the LTER case studies reviewed below illustrate, effects of management options on the level of ecological services can be represented as increases or decreases in those services from the status quo. The ideal measurement of service changes would be quantification of magnitudes, such as volumes of C stored, changes in runoff volume, and net primary productivity. Ratio and interval scaled data may not be possible, because of measurability, incomplete knowledge, and cost considerations. Some services, such as aesthetics, may not be quantifiable but can be characterized as qualitative improvements or degradations. Scoring or ranking systems can be used to quantify service changes (Westman 1985, Treweek 1999).

Similar measurement issues arise in the valuation of ecological services. Some service values can be quantified by magnitudes, such as the costs avoided by C sequestration or water uptake, the increased incomes from improved crop yields, or the value of water quality improvements from nutrient uptake services. In some circumstances, values may only be characterized as high, medium, or low, for example, or scored along a scale from 0 to 10 (Dee et al. 1973, Treweek 1999). These characterizations can be made through expert judgment or through individual or community valuation procedures.

Services-based management requires joint consideration of services and values. In the case of high degrees of quantification, where a service change is measurable as ΔS and the average value per unit of that service as V in the range of change in services, $V \times \Delta S$ is the value of the service change. When service changes are large and when values per unit of service vary over the range of service change—which is likely as a service becomes more scarce or critical and there are no easily available substitutes for the service—care must be taken to account for the changes in marginal values over the range of service changes. Additional criteria, such as concerns about equity, can be incorporated by giving greater weight to those services whose changes are of greatest equity concern. The uncertainties as to the magnitudes of values and service changes should be reflected by using ranges. When management options result in time-dated service changes, evaluations will have to incorporate the time-dated path of these changes. An eclectic approach would be to represent the time path of valuations. This would be highly informative, but unwieldy. One option is to establish discounted, or present value, measures of the stream of service values. There is controversy over what discount rates to use, especially for impacts accruing during or after a long period of time, and even over whether to discount (Hanley and Spash 1993, Portney and Weyant 1999). Practical rules suggest that for intragenerational impacts of less than 30 to 40 years, where impacts can be meaningfully converted into monetary values, it is appropriate to use either rates based on the opportunity costs of capital (which may be reflected by rates of return on private or public investments) or rates of social time preference (which may be reflected by interest rates on nontaxable government bonds). There is greater controversy over discounting across generations and over very long periods of time, as would be applicable for issues such as climate change or biodiversity loss. In this case, suggestions range from not discounting at all (counting all generations equally) to using very low discount rates (Weitzman 1998) or rates that become successively lower for impacts at increasingly distant dates (Portney and Weyant 1999). These comments suggest distinguishing between service impacts that may be relatively short-lived and those that have much longer time impacts, and discounting those differently.

When a high degree of measurability is unattainable (because of inherent immeasurability or because the costs of estimation would be excessive relative to the significance of the management issue), lower degrees of measurability may be useful. An elementary service and valuation procedure would rate service changes as (Max..0..–Min) depending on the magnitude of service change relative to the status quo. Valuations of services could be rated (0, 1, 2, and so on) depending on the relative values of those services. This would allow an evaluation, $V \times \Delta S$, reflecting the change in service and its value (Dee et al. 1973). Although this evaluation can be aggregated across the different services to provide a comparison of management options, such an aggregation is less meaningful when the underlying measurements are rankings rather than ratio or interval measures, as the scores for services and values can be scaled in ways that change the relative ratings of management options. Aggregated individual service valuations are also problematic where ecological and economic interconnections are so complex as to require ecological–economic modeling.

The decision process can use the characterizations of service changes, their valuations, and an aggregation rule to highlight superior management options. However, the disaggregated information, such as the full matrices of service changes illustrated in the LTER case studies below and the per-unit measure of service values or social significance of services, can be important input for management decisions and public dialogue. An alternative to the aggregated $V \times \Delta S$ method involves dialogue, discussion, and decisionmaking based on disaggregated information and democratic process; examples include citizen juries and planning cells (Howarth and Wilson 2006).

The complexity of ecosystem dynamics makes the evaluation and implementation of management alternatives based on ecosystem services more difficult. The services production-possibilities frontier, representing the maximum feasible set of services from various management options, is a useful concept for investigating service trade-offs between management options, but may require modeling (Guo et al. 2000, Costanza et al. 2002, Costanza and Voinov 2003, Nalle et al. 2004). Nonlinearities, irreversibilities, and uncertainties need to be taken into account in the evaluation of management alternatives (Limburg et al. 2002), and some evaluation methods are particularly appropriate and informative to management when these conditions are present. For example, consider the nutrient services of a forest or wetland patch, which removes or reduces nutrient loading into a lake. If the nutrient status of the lake is characterized by thresholds, uncertainties, and irreversibilities (Carpenter et al. 1999, Scheffer et al. 2001), two categories of services can be ascribed to the patch: primary and precautionary. The primary service is a reduction in nutrient loadings and eutrophication in a relatively deterministic manner within some range of loadings. However, increased loadings make it increasingly likely that the lake will undergo ecosystem state changes, the remediation of which may be long and costly. In this case, the precautionary value of the patch is that it provides value associated with avoiding this greater probability of state change. The expected value of approaching this point of state change is the increase in probability of the state change multiplied by the associated remediation costs avoided and lake services lost during the time period of remediation. Probability-based, or expected value, measures of services may not be adequate when the values of losses and gains in services are asymmetric, which may be the case for critical services, the loss of which may be devastating. In such cases, losses would have to be value weighted more heavily than gains. For example, the loss of 1000 ha of wetlands adjacent to New Orleans may be of far greater social concern in storm protection than the benefits from a gain of the same magnitude. Precautionary values are likely to require expert judgment of dynamics and probabilities, coupled with direct evaluations of the services lost or gained as a result of state changes.

The precautionary value is based on an understanding of the biogeophysical dynamics of the ecosystem as well as the stochastic behavior of the system. A more difficult case is when probabilities are not clearly known but the states are; for example, we know that removal of the forest patch increases the likelihood of a change in ecosystem state, but do not know this probability or where the state change could occur. Valuation of the forest patch services relative to these state change conditions is problematic in this case, but management may be based on a precautionary principle, avoiding the range where state changes are likely unless the costs of doing so are unacceptably high.

Case studies: Long Term Ecological Research sites

Three case studies from LTER sites illustrate the potential application of an ecosystem services approach to address management issues. While illustrating the analytical format for a services approach, these cases reflect only rudimentary evaluations of changes in service levels, with no attempts made to place rigorously derived values on those services, a necessary exercise for full value assessment and choice. The LTER program historically has not focused on the paradigms of services or valuation, but the examples included here suggest that an approach based on ecosystem services could be valuable for addressing environmental issues in these large, complex sites.

Coastal ecosystem: Plum Island Ecosystem. The Plum Island Ecosystem (PIE) LTER is focused in the estuary and watersheds of Plum Island Sound, located on the northeastern Massachusetts coast. Three watersheds, totaling 585 square kilometers (km^2), make up the estuarine drainage basin; the estuary itself is roughly 60 km^2. This LTER investigates the effects of climate change, sea-level rise, and land-use change on the trophic structure and productivity of the Plum Island Sound estuary. Population increases are changing the timing and magnitude of water, nutrient, and sediment delivery to the coastal zone. Export of water for human consumption and of sewage for disposal outside the watershed results in portions of the river drying up during low-rainfall summers. River damming and long-term abandonment of agricultural land have decreased sediment export to the coastal zone, while population growth is increasing the estuarine nutrient load. Sea-level rise and diminishing sediment inputs threaten the sustainability of intertidal wetlands. Together, these changes are likely to cause eutrophication and intertidal wetland loss.

A key management issue at PIE is how to reduce estuarine eutrophication and increase the maintenance of wetlands while providing adequate water supplies for a growing human population. Management for water supply and quality is likely to further decrease sediment inputs to the coastal zone. The major management concerns are providing drinking water while maintaining adequate river flow, preserving open space, and maintaining a productive estuarine clam fishery. These objectives represent social trade-offs.

We demonstrate the services-based approach by comparing the effects of two management alternatives on the delivery of specific ecosystem services:

- Business as usual: Continue suburbanization, including sewerage. This approach would increase water withdrawals and further degrade wildlife. Increased nutrient runoff could overly enrich the estuarine ecosystem, threatening the vitality of a productive clam fishery. Wetland land loss would continue.

- Replumb sewer and stormwater systems: Continue suburbanization, but with adequate river flow to ensure a healthy river ecology. Replumbing stormwater systems could reduce nutrient runoff, but wetland loss would continue and perhaps worsen as a result of decreased sediment recharge. Replumbing the sewer system would immediately reduce undesirable cross-boundary flows, as sewage export of water currently accounts for 42% of total cross-boundary flow.

The PIE services matrix in table 3 shows some of the effects of the two management approaches on the ecosystem services of watershed uplands, streams and rivers, and the estuary. The suite of services reflects a wide range of uncertainty and measurability. Disturbance regulation can be quantified probabilistically and measured as area or depth of flooding. Nutrient services can be measured as reduced nutrient loadings or concentrations. The qualitative measures represented in the third through eighth columns of table 3 suggest that both management options will result in greater storm surges and water-level variations, but less so for the uplands and rivers under the replumbing option. Water supply services, while continuing to decline under both management options, are moderated with the replumbing option. Cultural and historic services, such as clam harvesting festivals, would be improved under the replumbing option.

Services may be interrelated, making the valuation of service changes more difficult. For example, nutrient regulation can affect the availability of water supply. It would be double counting to consider both the water supply impacts of nutrient regulation and the enhancements in water supply, unless there are water supply effects independent of nutrient regulation. Also, the food services of clam harvesting intersect with the cultural and historic services. With this caveat in mind, several of the services in the matrix illustrate how evaluations can be made:

- Disturbance regulation: Flood and storm protection can be valued by hydrologic modeling to reflect the moderating effect of wetlands on storm surges and the resulting cost savings (avoided costs) in property damage to coastal structures.

- Water supply: Water supply service values can be evaluated using replacement costs for alternative supply sources, assuming that water supply is valued at least as highly as its replacement costs, or by treatment cost savings (avoided costs). The market price of water plus any subsidy costs can also be used as a valuation measure.

- Soil retention: Soil retention has value insofar as it enhances the health of wetland ecosystems, which themselves have values that may be transferred to the PIE context. Soil retention in upland systems may be related to agricultural productivities and evaluated as increased farm incomes (*production approach*).

- Nutrient regulation: Nutrient regulation reduces estuarine eutrophication, and thus enhances fisheries. Commercial fishery catch can be valued using market techniques (production approach; Bell 1989, Barbier 2003). Recreation catch values would require nonmarket methods, such as *travel cost* or contingent valuation (Bergstrom et al. 1990), possibly using other studies transferred to the PIE context. Aesthetic values could be measured by connecting property values to water quality conditions (*hedonic pricing*) or by contingent valuation (Leggett and Bockstael 2000, Poor et al. 2001).

Table 3. Ecosystem services matrix for the Plum Island Ecosystem, off the coast of northeastern Massachusetts.

Ecosystem service	Ecosystem function	Anticipated change in service level from current condition(ΔS): –3 to +3						Value weights (V): 0–3	Value of service changes per hectare (V × ΔS)	
		Business as usual			Replumbing					
		Upland	River	Estuary	Upland	River	Estuary		Business as usual	Replumbing
Gas regulation	Carbon dioxide and methane emissions change as land use and land cover changes.	–1	0	0	–1	0	0	1	–1	–1
Disturbance regulation	Presence (and extent) of river wetlands and floodplains, reservoirs, and coastal wetlands decreases storm surges and water-level variations.	–2	–2	–2	–1	–1	–3	3	–18	–15
Water regulation	Land cover plays a role in regulating runoff and groundwater discharge.	–2	–2	0	–1	–1	0	3	–12	–6
Soil retention	Retention of soil reduces sedimentation in wetlands, reservoirs, and coastal marshes.	–1	–2	1	0	0	–1	3	–6	–3
Nutrient regulation	Urbanization increases nutrient runoff and loading, leading to coastal eutrophication. Denitrification removes nitrogen from system.	–2	–1	–2	–2	–2	–3	3	–15	–21
Water supply	Water supply is affected by groundwater extractions or replenishment, diversions, and reservoirs.	–2	–2	0	–1	–1	0	2	–8	–4
Food production	Riverine and estuarine systems produce finfish and shellfish.	N/A	–2	–2	N/A	1	–1	1	–4	0
Genetic resources	The ecosystem provides habitat for the endangered piping plover.	0	0	–1	0	1	–1	1	–1	0
Recreation	Land-use change and river drying decrease recreation, while eutrophication decreases ecotourism, hunting, and fishing.	–2	–2	–2	–2	1	–3	2	–12	–8
Aesthetics	Aesthetically pleasing ecosystem functions include open space and clean water and air.	–2	–2	–2	–2	1	–3	2	–12	–8
Spiritual and historic	River drying, fish kills, and clam harvest all have spiritual or historic implications.	–1	–2	–2	–1	1	–1	1	–5	–1
Total score									–94	–67

- Genetic resources: These resources, including particular species and biodiversity in general, are among the most difficult services to value economically. Although economists have applied contingent valuation methods to the valuation of endangered species (Loomis and White 1996), concerns have been raised that species-by-species valuations are not valid, or do not reflect the holistic values of associated ecosystems (Kahneman and Knetsch 1992, Cherry et al. 2001). While some studies have considered the medical values of biodiversity (Simpson et al. 1996), it is likely that the primary value of biodiversity may lie in its role of protecting ecosystems from dramatic and irreversible changes—that is, a precautionary value. Unless we know something about the biogeophysical role of biodiversity in affecting the probabilities of change, it is difficult to establish the probability-based precautionary value. At best, we may be able to use expert judgment of this probability as high, medium, or low.

- Recreational benefits: Recreational benefits can be evaluated using methods based on travel cost or contingent valuation. Increased habitat can be translated into increased probabilities of baggings or sightings, which have been used as bases for contingent valuation (Loomis 2002).

- Aesthetics: Aesthetic values of landscape change, such as increased wetland area and open space or reduced eutrophication, can be evaluated using hedonic pricing if there are associated properties that benefit from these conditions (Irwin 2002, Wu et al. 2004). Aesthetic services are also a product of nutrient regulation (noted above), so valuations would have to avoid double counting.

Several of these services can be jointly evaluated using *conjoint analysis,* a survey method that poses scenario choices to respondents, revealing relative valuations of different service components evaluated to determine the socially acceptable trade-offs among them (Farber and Griner 2000, Gregory and Wellman 2001).

Valuations of the social significance of each of the service changes have not been made for this or the other two LTER sites discussed in this paper. However, for a full illustratration of the ecosystem services–based approach, consider a simple valuation procedure in which individuals or a community can rank or rate each service: Suppose the community scores services as being of no, low, medium, or high importance. Also, suppose it is willing to assign values of 0 to 3 to each of those conditions, respectively, as shown in the ninth column of table 3. The product of these value weights (V) and the change in services (ΔS) for uplands, rivers, and estuaries is aggregated in the last two columns for "business as usual" and "replumbing," following the scoring procedures suggested by Expert Choice (*www.expertchoice.com*). The total scores for each of these two management options are –94 for business as usual and –67 for replumbing. This suggests that replumbing, which would allow continued suburbanization but with adequate river flow to ensure a healthy riverine ecosystem, avoids more losses in services than business as usual. It would not be costly to obtain social ratings, rankings, or scores for service significance in LTER communities. The use of a reasonable range of service changes and valuations can improve confidence in management comparisons. Services may change at different rates over time, implying that a simple $V \times \Delta S$ valuation is inadequate, as ΔS and V must be time dated. Discounting of the time-dated changes in service values would be appropriate (Hanley and Spash 1993).

Urban ecosystem: Central Arizona–Phoenix. A major issue of the Central Arizona–Phoenix (CAP) LTER is the scarcity of water resources in a rapidly growing desert city. Water use is a major driver of ecological patterns and processes in this urban ecosystem, and is the single most important controlling factor for primary productivity. Managed Phoenix landscapes can be divided into mesic (highly watered) and xeric (low water use) landscapes, with xeric landscapes more common in newly developed areas (Martin and Stabler 2002, Martin et al. 2004). Water use is not necessarily lower in xeric landscapes, as humans increase water usage in xeriscapes to make desert plants look greener, especially during drought (Martin 2001, Martin et al. 2004). Xeriscapes typically use more native plant species than do mesiscapes (Hope et al. 2003), providing refugium functions for native species such as arthropods and birds (Germaine et al. 1998, McIntyre and Hostetler 2001). On the other hand, mesiscapes tend to be cooler than xeriscapes, providing improved climate regulation services (Brazel et al. 2000).

The CAP services matrix in table 4 suggests that the mesic and xeric management options will have substantial impacts on disturbance prevention, pollination, refugium, and combined artistic, spiritual, and historic services. The disturbance prevention service is related to fire protection, which can be valued on the basis of probabilities of occurrences and property damages (avoided cost). The supporting pollination services translate into aesthetic and biological regulation services. Landscape plants have commercial value, and their loss could be estimated using replacement cost methods, or the value of such plants could be obtained from hedonic pricing methods if real estate differs in value according the abundance of those plants in the landscape. The supporting habitat services translate into aesthetic and historic values associated with enhanced habitats for species, such as native birds, and could be valued on the basis of contingent valuation or conjoint analysis methods that pose realistic scenarios for valuation. Enhanced habitat values for other taxa, such as arthropods and reptiles, are not likely to be estimable from direct value elicitations, such as contingent valuation or conjoint analysis. Rather, the role of these species in enhancing or protecting things of value to humans will have to be determined, and their values inferred from the indirect impacts of the species on things people value. The spiritual and historic values would have to be determined through direct elicitations of social groups. These values may not be eco-

Table 4. Ecosystem services matrix for Central Arizona–Phoenix.

Ecosystem service	Ecosystem function	Anticipated change in service level from current condition (ΔS): –3 to +3		Value weights (V): 0–3	Value of service changes per hectare (V × ΔS)	
		Mesic	Xeric		Mesic	Xeric
Climate regulation	Moderation of urban heat island	2	–1	2	4	–2
Disturbance prevention	Fire risk	2	–2	3	6	–6
Biological regulation	Greater diversity of native pollinators in xeriscapes	–2	2	2	–4	4
Water regulation	Rate of water runoff	+?	–?	2	?	?
Soil retention	Erodibility	+?	–?	1	?	?
Nutrient regulation	More nitrogen-fixing plants in xeriscapes?	?	?	1	?	?
Water supply	Water for irrigation	–2	0	3	–6	0
Genetic resources	Better habitat in xeriscapes for native birds, arthropods, reptiles, and most likely other taxa	–2	2	2	–4	4
Aesthetic	Large differences in appearance; uncertainty about preferences of residents	?	?	3	?	?
Spiritual and historic	Preservation of Sonoran desert identity	–3	3	2	–6	6
Total score					–10	6

nomic, but may be measurable on some other scale of ranking or importance. There are many uncertainties and unknowns associated with the effects of the two management options on some ecosystem services, as noted in table 4. There is no current research under way at CAP to assess valuations of services, so the value weights shown in table 4 are assigned to illustrate the methodology. The total scores indicate that the combined service value enhancement is larger for the xeric option than for the mesic option.

Agricultural ecosystem: Kellogg Biological Station. The Kellogg Biological Station (KBS) LTER site in southwestern Michigan comprises 1600 ha of cropping systems, successional communities, and small lakes. Surrounding KBS is a diverse, rural to semirural landscape typical of the US Great Lakes and upper Midwest regions. This LTER was established to examine ecological relationships in row-crop agriculture, particularly the question of whether agronomic practices based on ecological interactions can replace chemically intensive practices. Replicated cropping systems were established, representing a broad range of management inputs, including annual row crops, perennial forage, woody biomass crops, and unmanaged successional communities. A broad range of ecosystem, community, and population processes are measured on these plots, including nutrient dynamics, crop yield, plant competition, and insect and microbial community structure.

This design allows researchers to compare ecosystem services across a wide range of agricultural management practices that are options for farmers. Initial efforts to evaluate ecosystem services at the KBS LTER have focused on nutrient retention and management, particularly N and C (Robertson et al. 2000). Nitrogen is a critically limiting nutrient in row-crop agriculture, and intensive agricultural production relies on inorganic forms of N to maintain crop yields (McNeill and Winiwarter 2004). Use of inorganic N as a fertilizer source can increase nitrous oxide (N_2O) fluxes to the atmosphere, contributing to global warming. Increases in

Table 5. Ecosystem services matrix for the Kellogg Biological Station in southwestern Michigan.

Ecosystem service	Ecosystem function	Anticipated change in service level from current condition (ΔS): –3 to +3			Value weights (V): 0–3	Value of service changes per hectare (V × ΔS)		
		No till	Low-chemical organic	Pasture and grazing		No till	Low-chemical organic	Pasture and grazing
Gas regulation	Reduced emission of N_2O, CH_4, CO_2	0	0	2	1	0	0	2
Climate regulation	Sequestration of CH_4, CO_2	1	1	2	2	2	2	4
Biological regulation	Habitat for consumers	0	1	2	3	0	3	6
Water regulation	Reduced runoff	2	1	2	3	6	3	6
Soil retention	Reduced soil erosion	2	1	1	3	6	3	3
Nutrient regulation	Reduced leaching of NO_3	1	1	1	2	2	2	2
Food	Agricultural crop yields	0	0	–1	2	0	0	–2
Raw materials	Soil formation	1	1	2	2	2	2	4
Aesthetics	Appearance	0	1	2	1	0	1	2
Total score						18	16	27

CH_4, methane; CO_2, carbon dioxide; N_2O, nitrous oxide; NO_3, nitrate.

two other important greenhouse gases, methane (CH_4) and CO_2, have also been linked to agriculture (Robertson et al. 2000). Incorporation of legume cover crops into row-cropping systems can provide sufficient N to maintain crop yields and may provide additional ecosystem services, such as reduced soil erosion and increased C sequestration (Robertson et al. 2000). Conversion of tilled agricultural lands to pastures to support grazing, particularly on marginal lands, may further enhance C sequestration and enhance food security (Lai 2004).

The KBS services matrix in table 5 reflects the increases and decreases in natural system services from three agricultural management options compared with traditional agricultural management practices. Reduced water runoff can be modeled using hydrologic models, in which stream capacities determine whether rainfall events will increase the likelihood of flooding downstream. Agricultural and structural damage estimates can be made using avoided cost methods. Downstream water management costs necessary to deal with increased runoff (dams, retention ponds, stream widening, etc.) would reflect costs of replacing water regulation services otherwise provided by the agricultural landscape, but only if those options would be taken. Soil retention services have economic values, including increased crop yields and reductions in stream turbidity. Protection from soil loss can be valued using fertilizer cost savings (replacement cost) or income increases to farmers (production) from higher crop yields. Benefits to downstream water users include sediment removal costs avoided and enhancements in recreational fisheries, measured by travel cost or contingent valuation. Changes in pollination support services have implications for biological regulation and crop yields, both of which can be valued using avoided cost or increased-income (production) procedures. An illustration of the value aggregation, using the hypothetical value weights shown in table 5, suggests that the pasture and grazing management option is superior to the other two in optimizing the value of ecosystem services in this landscape.

A study of the economic and ecological implications of different landscape management options for an agricultural watershed in Iowa illustrates the usefulness of a management approach based on ecosystem services, and the types of measurement necessary for such an approach (Coiner et al. 2001). Table 6 summarizes and reorganizes the findings in that study. The levels of soil erosion, nitrate (NO_3) runoff and leaching, and economic returns from land under current agricultural practices and landscape configurations are shown in the second column; for example, the average soil erosion rate is 16.2 metric tons (t) per ha per year over the 5100-ha landscape studied. Changing agricultural use of the landscape to increase agricultural production and profitability increases profits by more than $24 per ha and increases soil retention by 11.8 t per ha, but reduces NO_3 retention by more than 0.7 kilogram per ha. A scenario designed to improve water quality increases soil and NO_3

Table 6. Changes in annual ecosystem services for an agricultural watershed in Iowa, using hypothetical value weights.

Ecosystem service	Current erosion, runoff, and profit (per hectare)[a]	Change in service level reletive to current landscape (ΔS): Production scenario[a]	Water quality scenario[a]	Biodiversity scenario[a]	Value weights per unit of service (V): Low	High	Value of service changes per hectare ($V \times \Delta S$): Production scenario: Low	Production scenario: High	Water quality scenario: Low	Water quality scenario: High	Biodiversity scenario: Low	Biodiversity scenario: High
Soil retention (+ reflects more retention [less erosion])	16.2 t	+11.8	+13.1	+13.1	$9 per t[b]	$13 per t[b]	$106	$153	$118	$170	$118	$170
Nutrient regulation (+ reflects more retention [less runoff] of NO_3)	15.6 kg	–0.7	+3.3	–2.8	$20.20 per kg[c]	$23.72 per kg[c]	–$14	–$17	$67	$78	–$57	–$66
Food and genetic resources	$361	+$24	–$99	+$39	1	1	+$24	+$24	–$99	–$99	+$39	+$39
Total value							$92	$137	$185	$150	$61	$104

kg, kilograms; NO_3, nitrate; t, metric tons.

a. Coiner et al. 2001.

b. Pimentel et al. 1995. This study estimated on-site and off-site wind and soil erosion costs in the United States of $44 billion per year, with erosion on agricultural lands of 4 billion t per year, an estimated cost of $11 per t; $9 per t and $13 per t bracket this point estimate.

c. Skeen 2005. This article reported an estimated cost of $10.6 million to remove 119 t of nitrates from groundwater using one method, and a cost of $13.6 million to remove 130 t using another method.

retention, but also reduces agricultural profits. A scenario that enhances biodiversity through intercropping and organic farming on some lands increases soil retention and increases profits, but also reduces NO_3 retention (table 6).

The ecological implications of the various scenarios could be translated into economic valuations using studies that relate soil loss to future losses in agricultural productivity (production approach), increased fertilizer costs necessary to replace N (replacement cost), and increased downstream water treatment costs (avoided costs) or recreational fishery losses (contingent valuation). The study does not go this far, however. Other studies can be used to establish economic value weights, as shown in table 6. We use a range of values to reflect uncertainties in measurement for the soil retention and nutrient regulation services. The low and high values of service changes under the three alternative management scenarios are also shown in table 6; for example, the production scenario would save between \$106 and \$153 per ha, compared with current practices, in costs related to soil erosion; however, reduced N and NO_3 retention would increase groundwater remediation costs by \$14 to \$17 per ha. The last row of table 6 shows the net gain in value, compared with current practices, for the three scenarios. Interestingly, practices designed to improve water quality result in the most value-enhancing scenario, even though they lead to reductions in agricultural profits. This example should be taken as merely illustrative, however, especially since the values of NO_3 reduction services were estimated crudely.

Summary

Ecosystem services to humans can sometimes be simply assessed, as in the case of fish harvested from the sea, but in other instances may be indirectly enjoyed in ways that can be complex and difficult to determine. Management based on ecosystem services requires a full understanding of the complex ways in which these services benefit humans. The valuation of ecosystem services is also necessary for the accurate assessment of the trade-offs involved in different management options. Valuation can be expressed in economic terms in many instances, using an expanding set of practical valuation techniques. These valuations should reflect the significance or importance of the ecological service categories, and ideally the valuations of unit changes in the levels of those services across management options. When unit valuations based on ratio or interval scales are not feasible, practical methods of scoring, ranking, or rating can be used in combination with assessments of the changes in service flows. Valuations can be made at individualistic or communal levels.

The LTER studies described in this article illustrate several applications of the services-based method, and some of its limitations. Many of the service changes at these LTER sites can be reasonably quantified, as there is some understanding of the impacts of management options on some services. However, there is little formal understanding of the value weights, or relative significance, of those service changes at LTER sites. As discussed above, reasonable research methods can be used to obtain these valuations at various levels of quantification, and these valuations can be coupled with service-change assessments to evaluate ecosystem management options. Each of the case studies illustrates that the attempt to formalize changes in service flows can be a useful management exercise in its own right, and the coupling of this information with value weights can provide insight into what is gained or lost with management options. We have not addressed management issues per se, but it should be noted that current management institutions may have to be reconfigured to allow the simultaneous consideration of the entire set of services. For example, Heal and colleagues (2001) suggest using "ecosystem services districts" as opposed to traditional institutions, which typically focus on separate, narrow sets of services.

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