REVIEWS IN ADVANCE

The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services

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Abstract

Ecosystem services, the benefits that people obtain from ecosystems, are a powerful lens through which to understand human relationships with the environment and to design environmental policy. The explicit inclusion of beneficiaries makes values intrinsic to ecosystem services; whether or not those values are monetized, the ecosystem services framework provides a way to assess trade-offs among alternative scenarios of resource use and land- and seascape change. We provide an overview of the ecosystem functions responsible for producing terrestrial hydrologic services and use this context to lay out a blueprint for a more general ecosystem service assessment. Other ecosystem services are addressed in our discussion of scale and trade-offs. We review valuation and policy tools useful for ecosystem service protection and provide several examples of land management using these tools. Throughout, we highlight avenues for research to advance the ecosystem services framework as an operational basis for policy decisions.

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INTRODUCTION

Ecosystem services are the benefits people obtain from ecosystems (1). Throughout human history, people have understood that their well-being is related to the functioning of ecosystems around them. Intensifying human impacts on ecosystems worldwide—and on the supply of services they provide—have accentuated the need to move beyond simple recognition of human dependence on the environment and create more sustainable interactions (2). The term "ecosystem services" emerged in the early 1980s to describe a framework for structuring and synthesizing biophysical understanding of ecosystem processes in terms of human well-being (3).

Ecosystem services: the benefits people obtain from ecosystems

MA: Millennium Ecosystem Assessment

Understanding ecosystems from the perspective of humans as beneficiaries has tremendous potential for protecting ecosystems and the services they provide. The ecosystem services framework links conservation and development by relating environmental health to human health, security, and material goods necessary for well-being (4). Coverage in the popular press, as well as attention from diverse leaders in academia, government, and the private sector in communities worldwide, illustrates the broad appeal of the ecosystem services conceptual framework (5).

Tremendous progress has been made toward characterizing ecosystem services in both the natural and social sciences. The Millennium Ecosystem Assessment (MA), the formal international effort to elevate awareness and understanding of societal dependence on ecosystems and currently the benchmark for ecosystem services research, illustrated the wide-ranging importance of ecosystem services. It simultaneously underscored the many remaining research needs (6). In order for ecosystem services to move from a conceptual to an operational framework for decision making, much natural, social, economic, and policy science remains to be done.

Here, we review key fronts on which progress has been made and suggest what is needed in the near- and long-term to make the framework useful, credible, and widely applicable in decision making. This review focuses on terrestrial freshwater hydrologic services, synthesizing discussion from many forums about ecosystem effects on freshwater. Ecosystems provide hydrologic services in tandem with a variety of other essential services, including air quality, carbon dioxide sequestration, and soil generation. These services are often interrelated in dynamic and complex ways; understanding their functioning and relationships requires approaches spanning diverse fields of inquiry. For simplicity and appropriate depth of coverage, we focus on hydrologic services, using them as the point of entry to a more general discussion of trade-offs, valuation, and policy. Although intimately linked to freshwater services, we also limit our discussion of marine services.

Following an overview of the history of ecosystem services, we review the biophysical production of hydrologic services. In presenting a structure for defining and assessing hydrologic services, we aim to provide a blueprint for evaluating other services. We then go on to report the current state of knowledge about the beneficiaries, valuation, and policy for a wider range of services. In closing, we lay out an agenda for future ecosystem services research.

EVOLUTION OF THE ECOSYSTEM SERVICES CONCEPT

Ecosystem service is a new name for an old idea. Plato, and likely many before him, worried about the environment's capacity to provide sufficient resources for a growing population (7). In many cases, these worries were expressed as ecosystems degraded; they chronicle a failure of ecosystem service delivery. Recognizing their reliance on natural systems, people have long attempted to divorce themselves from the vagaries of this dependence. Part of the promise of modernism was that technology could provide services more efficiently and more reliably than natural systems could (8). Although it may be possible to augment or replace some ecosystem services—often at great cost, on a limited scale, or in constrained locations—the reliance of technology on functioning ecosystems often goes unrecognized. Water filtration plants, for example, may be necessary to keep drinking water at mandated standards, but these plants operate most efficiently in tandem with environmental filtration (9).

The services people receive from ecosystems are many and varied; understanding, studying, and making policy on the basis of this broad array of services requires that these services be organized conceptually in a coherent way. The conditions and processes underlying ecosystem service production are so tightly interlinked that any classification is inherently somewhat arbitrary. The MA has suggested dividing services into four categories, illustrated in **Figure 1**, which we have adopted. 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 and provide benefits such as pollination of crops, water damage mitigation, and climate stabilization. Third, *cultural services* make the world a place in which people want to live; they include recreation as well as aesthetic, intellectual, and spiritual inspiration. Fourth, *supporting services* are the underlying ecosystem processes that produce the direct services described above, including the preservation of options (1).

In an effort to increase the tractability of the ecosystem services concept, some have proposed that ecosystem accounting should include only the final products of ecosystem processes, things that are directly enjoyed by humans, not the processes themselves (10). We use the MA's system to emphasize that supporting services are fundamentally intermediate, not end products. Recognizing supporting services is essential to managing and maintaining the delivery of ecosystem end products. Further, end products are variable. Some supporting services, including pollination and nutrient sequestration, have market institutions built around them as end products, although many consider them intermediate services.

The ecosystem services framework makes explicit the complex feedbacks and trade-offs among services and human beneficiaries. Production of one service may come at the expense of another, just as consumption of resources by some people and activities may come at the expense of consumption by others, elsewhere and in the future. These

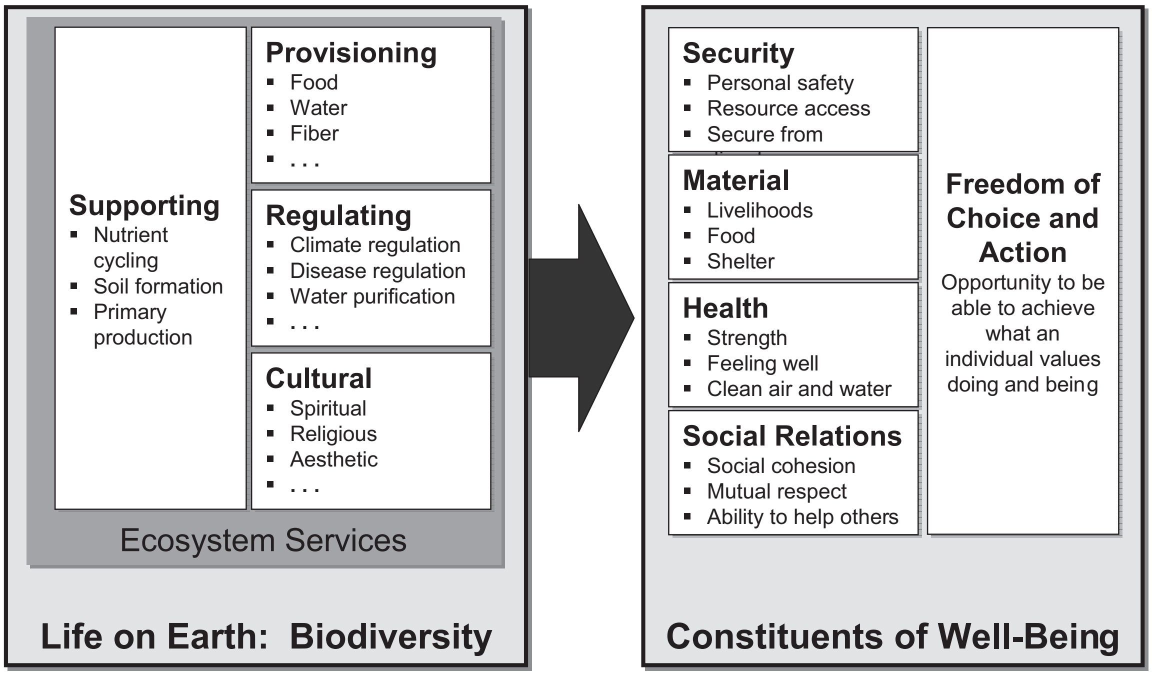

Figure 1

Millennium Ecosystem Assessment classification scheme. Ecosystem services can be divided into four categories. Supporting services create the conditions that allow provisioning, regulating, and cultural services to be delivered. Each type of service affects human well-being in a variety of ways. From (1) *Ecosystems and Human Well-Being: Our Human Planet* by the Millennium Ecosystem Assessment. Copyright © 2005 by the author. Reproduced by permission of Island Press, Washington, D.C.

trade-offs are fraught with practical and ethical considerations beyond the domain of physical and natural science. Integrative science, however, can inform decision making, using tools such as valuation and scenario analysis (11, 12).

The MA synthesizes and analyzes the current conceptual theory and knowledge underpinning the ecosystem services framework. The next step is to make the framework practical, straightforward, transparent, and credible enough to be useful to decision makers. Current knowledge about ecosystem service production has often been generated in fields not directly concerned with ecosystem services. Evaluating this knowledge and generating new research that can inform management and policy decisions about ecosystems and their services requires

- Information on service provision and value at policy-relevant scales
- Formal methods for incorporating cultural values in a meaningful way
- Practical know-how in the process of institutional design and implementation
- Compelling models of success

In **Figure 2**, we have compiled a list of policy-relevant questions that are applicable to every class of ecosystem service. Although our answers to these questions are necessarily presented linearly, there is no natural order in which they should be asked and answered, as every question is informed by each of the others. We address the questions for hydrologic services, illustrating one way existing research can be assimilated, new research conducted, and all research presented in formats useful to decision makers.

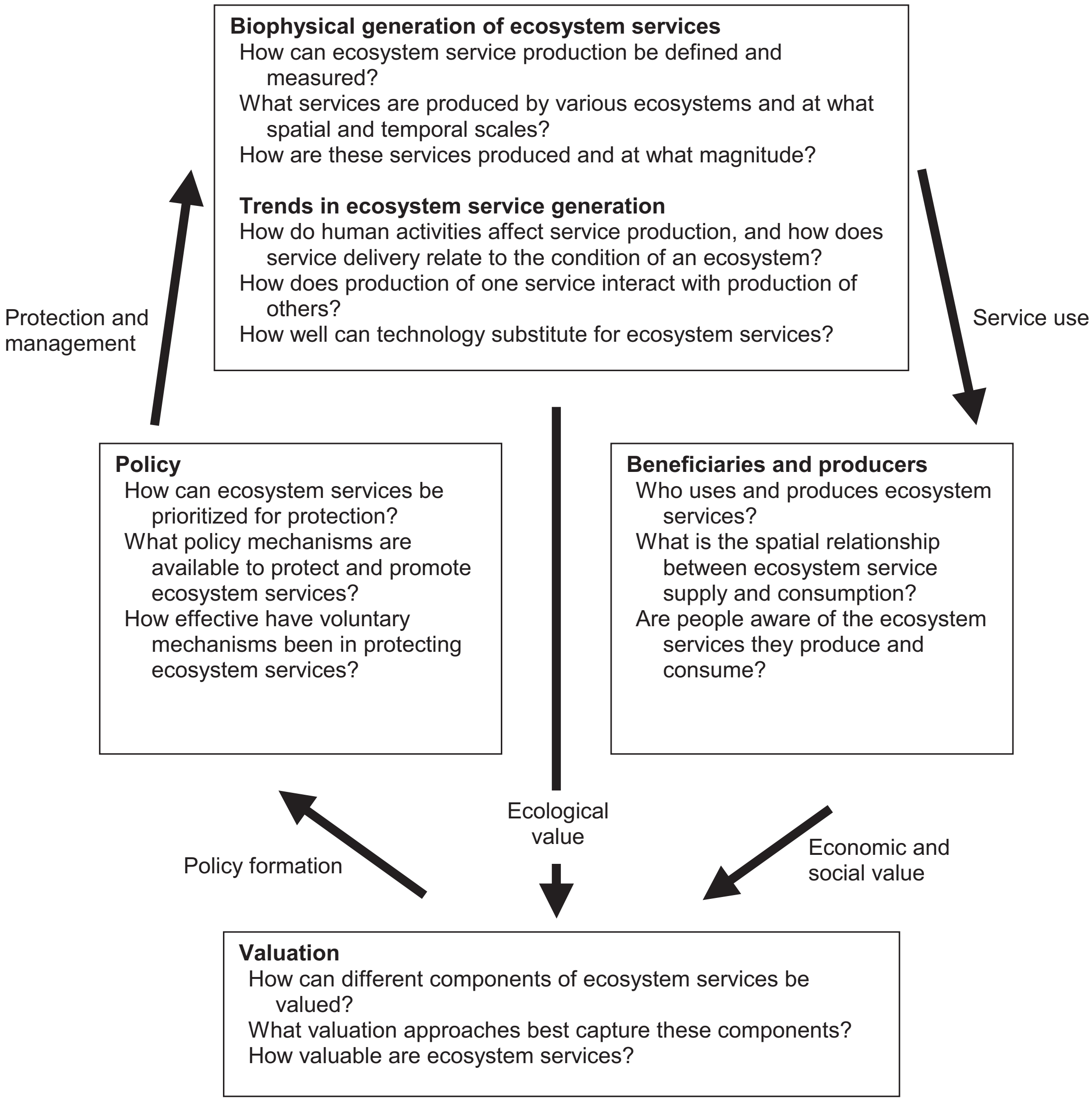

Figure 2

Policy-relevant questions for understanding, assessing, and managing ecosystem services. Each box represents a category of information central to policy decisions. The boxes are connected as shown. Here we emphasize the biophysical generation of services over their social, economic, and institutional dimensions; the other dimensions (boxes) in the figure are at least as complex and important.

BIOPHYSICAL GENERATION OF HYDROLOGIC SERVICES

Reviews prior to this one have defined ecosystem services, provided examples, and illustrated their scope (13–15). The MA is the broadest review to date, synthesizing scientific, governmental, private, and local knowledge of ecosystem services worldwide (1). It effectively documents the importance of ecosystem services for human well-being and

Ecohydrologic process: a process described by both ecologic and hydrologic functions

focuses on projections for future ecosystem service demand and delivery. Although a few particular cases and services are well studied, these reviews underscore how little is known about the way most ecosystem services are generated. We limit this review to hydrologic services in order to focus in greater depth; we begin our discussion by defining and describing the range of hydrologic services. The upper box in **Figure 2** is a condensed list of the questions we address in our synthesis of their production.

Introduction to Hydrologic Services

What are hydrologic ecosystem services? From the supply of water for household use to the mitigation of flood damages, people rely on ecosystems to provide many water-related services. Hydrologic services encompass the benefits to people produced by terrestrial ecosystem effects on freshwater. Because they are a diverse group, it is useful to organize hydrologic services into five broad categories: improvement of extractive water supply, improvement of in-stream water supply, water damage mitigation, provision of water-related cultural services, and water-associated supporting services.

Water supply is a provisioning service describing ecosystem modification of water used for extractive and in situ purposes. Extractive water uses include municipal, agricultural, commercial, industrial, and thermoelectric power use. In situ uses include hydropower generation, water recreation, and transportation, as well as freshwater fish production. Globally, freshwater withdrawals have been estimated at 35% of accessible runoff and in-stream uses estimated at about 19% of runoff, though these diversions are not distributed uniformly worldwide (16, 17). Water damage mitigation is a regulating service; it includes ecosystem mitigation of flood damage, of sedimentation of water bodies, of saltwater intrusion into groundwater, and of dryland salinization. Cultural hydrologic services include spiritual uses, aesthetic appreciation, and tourism. The water-related supporting services of terrestrial ecosystems are wide-ranging and include the provision of water for plant growth and to create habitat for aquatic organisms.

Each of these hydrologic services is defined by attributes of quantity, quality, location, and timing of flow. Most formally, users of diverted water supplies traditionally lay claim to a specified volume of water of an expected quality in a certain form and at a certain time; legal agreements and payment schemes are in place to organize this division. Beneficiaries of flood damage mitigation or of spiritual engagement are likely to have less formal but similarly important requirements. The relationship of services to hydrologic attributes and ecohydrologic processes is illustrated in **Figure 3**.

Trade-offs are inherent in the supply of hydrologic services. Under various scenarios of quantity, quality, location, and timing of flow, some services will be improved at the expense of others. The magnitude of each attribute is not value laden, only descriptive. Value is assessed in the context of the service defined by the attribute. For example, an increase in water quantity is a dispassionate description of a change in volume; this increase might be beneficial in the context of diverted water supply and detrimental in the context of flood damage.

Hydrologic attributes are directly impacted by ecosystems as water moves through a landscape. By affecting each attribute, ecosystem processes improve or degrade the supply of hydrologic services. Within an ecosystem, different ecohydrologic processes may have competing effects on the same attribute or have simultaneously positive and negative effects on different attributes of a particular service. For example, a forest might increase infiltration while decreasing total water volume. Focusing on the way ecosystems affect hydrologic attributes, the center column of **Figure 3**, efficiently translates traditional hydrologic science into an ecosystem services context useful to decision makers.

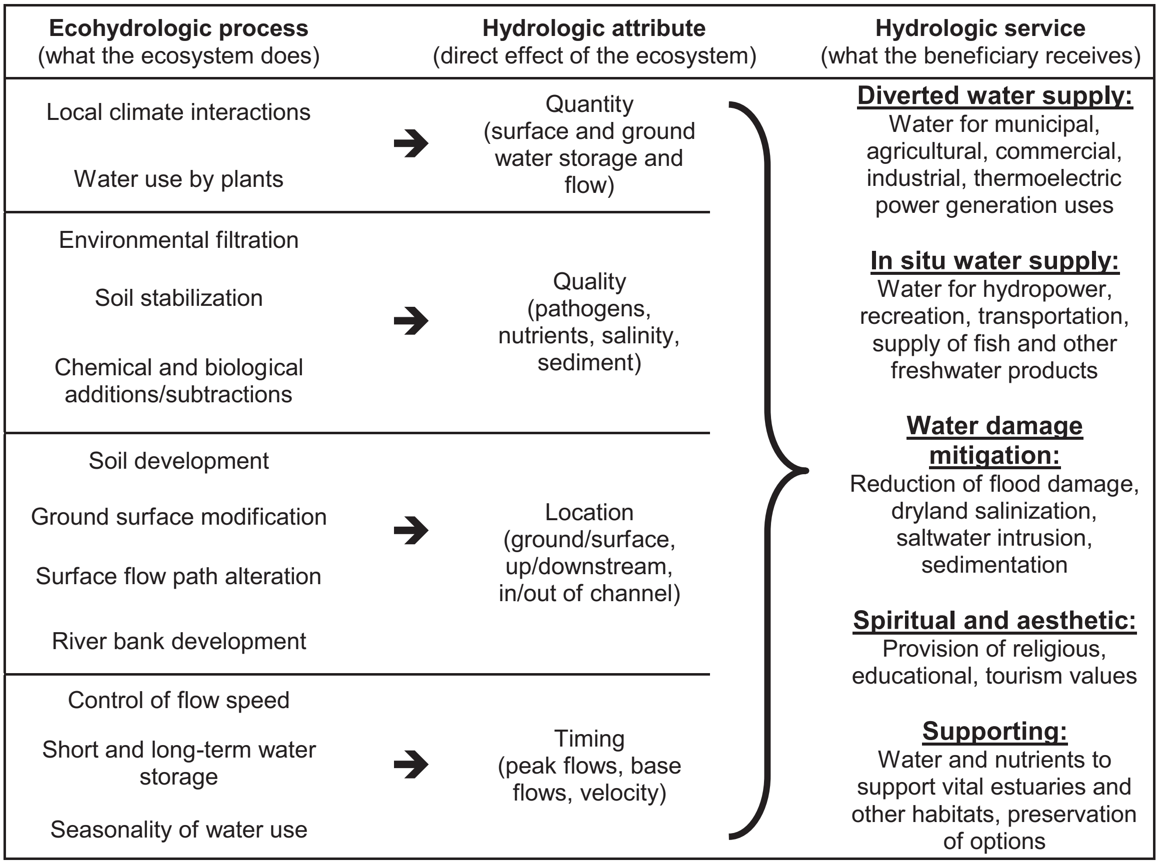

Figure 3

Relationship of hydrologic ecosystem processes to hydrologic services. Each service has attributes of quantity, quality, location, and timing of flow. Municipal water supply, for example, requires not just an adequate quantity of water, but also that it be of acceptable quality and in the right place at the right time. A number of ecosystem processes affect each attribute.

Because ecosystem effects on macroclimate often occur at spatial and temporal scales inconsistent with the scale of landscape hydrologic response to a given climate regime, we do not include the effects of vegetation on macroclimate in our discussion of hydrologic services (18). For information on this topic, see References 19–23.

Which ecosystems provide hydrologic services, and at what scale? Any ecosystem in a watershed will affect the attributes of the water that passes through it. Thus, all ecosystems provide hydrologic services, although to differing degrees (24). Vegetation is often the driving force in ecosystem effects on water, but all elements of an ecosystem, from microbes to megafauna, can and do affect hydrologic service provision.

Hydrologic services are regional services; downstream users experience the effects of ecosystems throughout their watershed. Because the effects are spread over space, the impact of land cover may be diffused in larger watersheds. In Texas, shrub removal provided dramatic water savings in riparian regions when measured at the stand scale, but water savings at the landscape scale were muted or nonexistent (25). In many cases, ecosystem

Peak flow: the maximum volume flow rate passing a given location during a given period of time; attributable to direct runoff due to a storm event

Evapotranspiration: the combined processes of direct evaporation and transpiration by plants that transfers water to the atmosphere

effects on sediment yield and flooding are measurable only in small catchments and for small rainfall events. In Oregon, deforestation caused increased peak flows in watersheds under 100 hectares and for storm flow events with less than two-year return intervals but not in larger basins or for more intense storms (26). Ecosystem effects may either decrease or increase with basin size depending on the extent and location of different ecosystems within the basin and on the frequency, duration, and intensity of climatic events (27). Extrapolations of local and short-term effects of hydrologic services to larger scales may therefore be flawed. Moreover, many aspects of hydrologic response are dominated by extreme but infrequent events. The ability of ecosystems to mediate hydrologic response to these extreme events is unclear yet potentially important and likely not linearly related to the delivery of water services in average years.

The bulk of research about ecosystem effects on water supply and water hazard mitigation comes from studies done in temperate ecosystems, although hydrologic response varies dramatically with climate, geography, and ecosystem type. In the tropics, for example, variations in soil type and rainfall patterns result in ranges of natural sedimentation from less than 1 up to 65 tons per hectare per year (28). Because of this, researchers increasingly seek to evaluate hydrologic response in tropical and arid ecosystems in addition to studying temperate climates (29).

How should hydrologic services be measured? Ecosystem services can be assessed at different stages of production by measuring generation of ecosystem processes, by quantifying the magnitude of attributes or intermediate service levels, or by assessing the amount of final service benefit. At each stage, it is possible to identify multiple baselines and indicators. Although ideal metrics will likely vary with context, institutionalizing uniform measures facilitates comparisons among services and between places.

Each beneficiary of a hydrologic service is likely to describe a different ideal set of attribute levels—a fisherman wants riffles, whereas a rafter wants white water—but both can agree that the quantity, quality, location, and timing of flow enable their pursuits. In lieu of assessing every combination of attributes individually, we focus on the attributes of hydrologic services in the following discussion.

Unlike a provisioning service such as timber, which is produced only in forested ecosystems, water will move through and be altered by any ecosystem. The importance of an ecosystem to water provision and regulation is revealed only by considering the benefits a modified or replacement ecosystem would provide. Some of the processes by which ecosystems affect hydrologic attributes, discussed below, are illustrated in **Figure 4*a***.

Water Quantity

Quantity is the first attribute of a water service many people consider; it constitutes the amount of water available for drinking or agriculture or describes the volume of flood waters. For services such as water supply, an increase in quantity is beneficial; in flood mitigation, decreasing quantity is beneficial.

Although an ecosystem itself does not create water, it does modify the amount of water moving through the landscape. Users may be concerned with the volume of water stored in or discharged from a watershed, either above or below ground. In all cases, mass is conserved, and the volume of available water can be calculated with a water budget model, **Figure 5**.

Each variable in the water balance in **Figure 5** is potentially measurable. Because mass is conserved, any one variable can be calculated if the others are known. Measurement of precipitation is a well-developed field of study. Studies assessing individual plants, as well as models and direct measures of evapotranspiration, provide data about the volume of water that is lost directly to the atmosphere

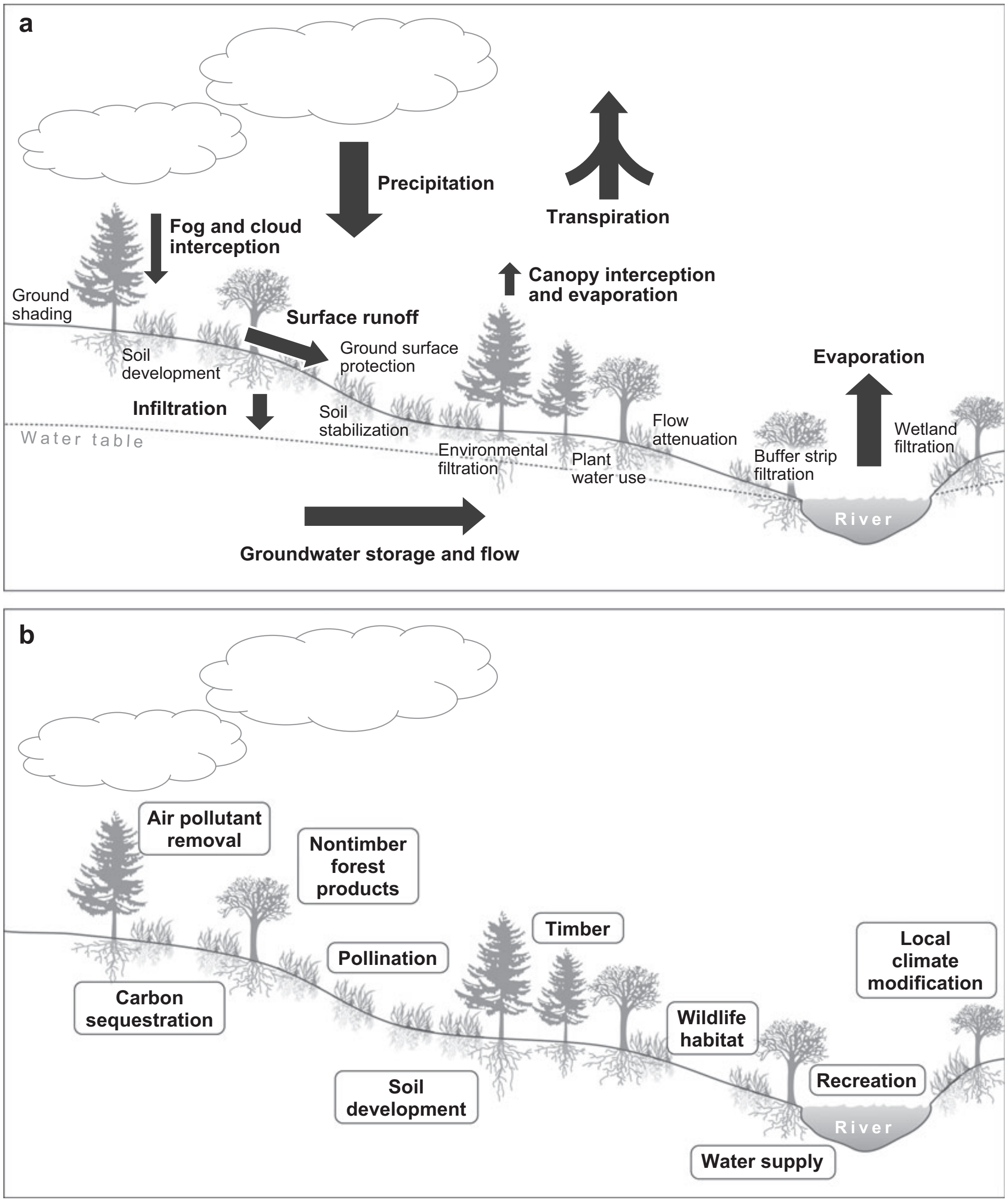

Figure 4

Water cycle-ecosystem interactions. (*a*) At the watershed scale, ecosystems affect water through local climate interactions, water use by plants, ground surface modification, and water quality modification, processes that are detailed in the text. Arrows indicate fluxes of water. The hydrologic cycle is driven by energy from the sun. Water vapor evaporated from oceans or surface water bodies forms clouds and falls as rain, fog, or snow onto Earth's land and oceans. On land, water infiltrates into groundwater or flows over the surface. Both ground and surface water eventually discharge into the oceans. Evaporation from surface water and oceans to the atmosphere completes the cycle. (*b*) In addition to hydrologic services, a watershed produces a variety of other services; examples of these are shown in the figure.

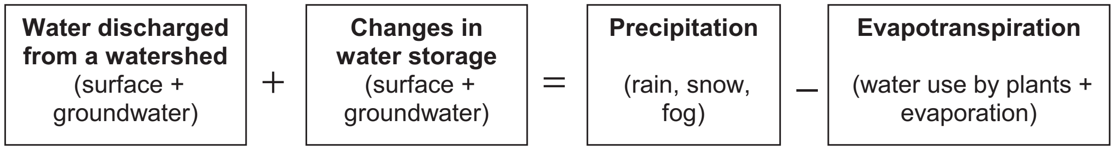

Figure 5

Within a specified time interval, the surface and groundwater that flow out of a watershed, plus any changes in surface or groundwater storage, are equal to the amount of water entering the watershed as rain, fog, or snow minus the volume returned to the atmosphere through water use by plants or by direct evaporation of surface water and soil moisture.

(30). To separate regional-scale ecosystem effects on water quantity from climatic and geographic effects, researchers evaluate changes in surface flow and groundwater storage after natural or human-induced alterations to land cover. The quantity of water delivered from a watershed is conventionally measured only as surface water output and reported as mean annual watershed yield. Ecosystems, however, affect the available quantity of both surface and groundwater.

How are changes in water quantity produced, and how extensive are these ecosystem effects? Through the use, transport, and reapportioning of water, ecosystems can have profound effects on the volume of water ultimately available to downstream users. Local climate interactions can either increase or decrease available water, but the principal effect of ecosystems is to reduce available quantity through direct use of water by plants.

The spatial extent of ecosystems worldwide in which local climate interactions dominate is limited, although the effects can be significant in those areas. Fog or rain that is intercepted by a vegetated canopy can drip to the ground or evaporate directly from leaf surfaces. In foggy and cloudy climates such as the coastal redwood forests of California, where tall vegetation provides an intercepting surface onto which water droplets can precipitate, an average of 34% of stored water originates as fog; treeless sites have fog input of only 17% (31, 32). Vegetation also intercepts snowfall (33), and sublimation from the canopy can reduce average snow accumulation by up to 15% in forested catchments compared to open catchments (34). However, canopy shading simultaneously reduces midseason melt as well as reducing bare soil evaporation, so at the end of the snow season, maximum accumulation may be equivalent in forested and open areas (35). In some places, such microclimatic effects may be large enough to offset water quantity gains from deforestation, and these effects should be considered in land management decisions.

Most ecosystems reduce available water volume because vegetation consumes water through transpiration: Plants effectively trade water for biomass, thereby providing services such as timber, crops, and fruit (36). A synthesis of the limits and controls of forest water use predicts that trees will generally use more water than shorter vegetation because of their height and rooting depth (37). Vegetation that is aerodynamically rough has increased gas exchange and thus transfers water to the atmosphere more efficiently than short, smooth vegetation. When water is not limiting, tall vegetation, e.g., trees, will therefore use water at higher rates. Vegetation with greater rooting depths has greater access to soil moisture. In environments where water is limiting, deeply rooted plants, i.e., trees and riparian vegetation that successfully tap into a scarce water source, will reduce available water volume (38).

The hydrologic effects of forests have at times been the subject of public debate; in general, however, the total volume of surface and groundwater available from forested watersheds is lower than that from grass- or shrub-dominated watersheds (39). Comparative research on changes in groundwater availability given land cover change is scarce, but analysis of surface flow in hundreds of paired catchment experiments has shown an average of 45% reduction in stream flow when grasslands are converted to forest (40–42). Actual changes in surface flow are closely linked to the total volume of water available (43). The effects of vegetation structure given seasonal changes in water availability are apparent in the Amazon, where evapotranspiration from pasture can be as much as 24% lower than evapotranspiration from forest (44). In water-scarce environments, vegetation with lower water requirements is likely to provide greater water supply benefits than those provided by a higher water-use ecosystem. In parts of Australia where rising water tables have brought saline water into contact with crop roots, plants that lower the water table by transpiring large volumes of water can provide valuable damage mitigation benefits.

Climate, soils, and slope, as well as vegetation type, age, and management practice, play governing roles in water use, so regionally specific assessments are highly recommended (45). Young and invasive plants generally have disproportionately large impacts on water quantity because vigorously growing vegetation tends to use more water than mature vegetation (46, 47). Water savings from woody vegetation removal may thus be offset by the water use of replacement vegetation (48). In arid areas, adaptations such as dry-season senescence of native vegetation may limit its water use, whereas an introduced species that lacked these traits would consume water over longer periods during the year (49). Native ecosystems may therefore provide greater water supply benefits than replacement ecosystems characterized by alien species.

Water Quality

Water quality is a measure of the chemicals, pathogens, nutrients, salts, and sediments in surface and groundwater. The importance of water quality to drinking supply is apparent; quality is an important attribute of all other hydrologic services as well, including cultural services, e.g., recreation, and supporting services, e.g., provision of water and nutrients to estuaries.

Terrestrial ecosystems can add and remove a variety of contaminants to flows above and below ground. By altering ecosystems, it is possible to measure associated changes in the quality of a water body. Metrics for assessing ecosystem effects on contaminants of concern include changes in annual average concentration, changes in total maximum daily load, and relative and absolute changes in concentration. Changes in response to extreme rainfall events and changes in the range of responses to rainfall events are also useful indicators (50). Ecosystem effects on water quality can vary seasonally and even daily, and contaminants may move through a watershed over the course of many years, so effective assessments of ecosystem effects on water quality will occur over an extended time period (51). Because monitoring studies are typically not sufficiently long, models such as sediment and nutrient budgets are often used to assess ecosystem effects on water quality.

How are changes in water quality produced, and how extensive are the effects of ecosystems on water quality? Ecosystems with intact groundcover and root systems are generally very effective at improving water quality. Vegetation, microbes, and soils remove pollutants from overland flow and from groundwater by physically trapping water and sediments, by adhering to contaminants, by reducing water speed to enhance infiltration, by biochemical transformation of nutrients and contaminants, by absorbing water and nutrients from the root zone, by stabilizing eroding banks, and by diluting contaminated water (52). The effects of environmental filtration are potentially very large. One model indicated that converting less than 10% of the Mississippi Basin to wetlands and riparian

Base flow: reliable year-round streamflow, which is sustained by groundwater, not attributable to direct runoff

forest would reduce 10% to 40% of the nitrogen currently creating the hypoxic zone in the Gulf of Mexico (53).

When water moves unimpeded through an ecosystem, there is no opportunity for environmental filtration; thus, ecosystems with characteristics that prevent gully formation or channelization are more likely to improve water quality (54, 55). Roads can also create a direct connection through an ecosystem to a water body. This means that, even in mild rainfall events, road surfaces can route sediment and other impurities to rivers.

Any heterogeneous strip of vegetation that forms a barrier to sediments or removes contaminants from the water stream can be considered a buffer, regardless of its position within a watershed. In semiarid landscapes, patches of vegetation block runoff and sediment transport (56). Streamside ecosystems can also act as buffers, creating time and space for filtration processes to occur. In addition, they can help maintain stream configurations and temperatures that enhance in-stream processing of pollutants (57). Although reviews show substantial variation in the effectiveness of buffers, especially at a landscape scale, it is likely that these vegetated strips can reduce local nitrate concentrations from cropland runoff by 5% to 30% per meter width of buffer (58, 59). Buffer ecosystems can thus potentially reduce water treatment costs for downstream users.

Phyto- and bioremediation efforts take advantage of the uptake and transformation of contaminants by certain plant roots and the microbial communities they support (60, 61). The macrophytes and microbes that promote denitrification and other biochemical processes that improve water quality are particularly abundant in wetlands, which are so reliable at removing suspended solids, phosphorus, and nitrogen from wastewater that they are regularly integrated into treatment plants (62, 63).

Forests and other mature ecosystems generally improve water quality in a catchment. Root systems stabilize soils (64), and vegetative cover affects the force and size of raindrops hitting the ground (65, 66). When this vegetation is removed, such as by logging or applying herbicide, bare soils are exposed to surface raindrop splash, runoff, and wind, which can increase erosion substantially. Nutrients and other impurities built up in ecosystems through decomposition, fertilizer application, or atmospheric deposition can become available for entrainment in water above and below ground (67, 68). Watershed protection plans are premised on the ability of certain kinds of land cover to either improve water quality through filtration or maintain it through limited addition of contaminants to the water stream.

Location of Delivery

Water is useful only when users have access to it, e.g., in downstream diversion ditches or in wells far from a surface water source, and it is harmful only when it ends up in the wrong place, inundating crops or homes. Ecosystems affect the location of water above and below ground as well as its distribution within a watershed (69). Perhaps the most important effect of ecosystems on water location is on the partitioning of precipitation into surface and groundwater. Assessing the percentage of precipitation that becomes groundwater, or the number of days that surface flow is greater than base flow, may be more informative than measuring bulk recharge. Ecosystems also affect the flow of water into and out of streams, lakes, and underground storage; use water; and add and remove contaminants at specific locations in a watershed. Identifying the location of ecosystem effects on water is a key part of quantity, quality, and timing measurements.

How do ecosystems affect the location of water and to what extent? Infiltration is the process by which surface water becomes groundwater. By using water, plants create unsaturated space in the soil into which precipitation can infiltrate. In certain geologic settings, the depth of water storage space in the soil is the primary control on runoff (70). Land uses such as logging and grazing reduce infiltration by compacting soils, and management choices, particularly road building, can reduce infiltration and increase runoff substantially (71). Reducing infiltration increases stream yield at the expense of groundwater storage and discharge.

In addition to infiltration capacity, vegetation can increase recharge and reduce runoff by increasing the rate at which water moves into the subsurface. Roots, worms, and insects help develop macropores in soil that allow preferential flow of water to the water table, beyond the reach of roots, increasing groundwater recharge. Flora and fauna found in forests may be more effective at soil development than the flora and fauna found in other ecosystems (72). In places with low rainfall, vegetation can trap water and enhance infiltration (73). Plants can also redistribute water within the soil profile by hydraulic lift (74). When groundwater storage is important, ecosystems that promote infiltration can be instrumental in improving supply.

Ecosystem effects on the land surface also play a key role in infiltration. Leafy vegetation intercepts rain droplets and, by softening their impact, protects the ground surface from forming an impermeable seal. Leaf litter and roots reduce flow speed, providing greater opportunity for infiltration (75). Although studies are inconclusive, in certain dryland ecosystems, even bare looking patches support biological soil crusts that appear to increase infiltration (76).

Vegetation can also direct water flow, affecting the location of water within a streambed. Riparian vegetation, for example, can impede water moving from a river into a floodplain and slow its movement back into the main channel (77). Replacing dense streamside vegetation with low grasses might therefore reduce flood damage downstream by allowing floodwaters to move into the floodplain.

Timing of Delivery

The attribute of timing describes when water is available. Precipitation is not spread evenly over the course of the year in many parts of the world, and sudden influxes can render much of the mean annual runoff from a catchment unusable or even a hazard. Low flows and flood peaks affect users and are not adequately described by average or annual water volumes. Timing also encompasses the predictability of flows. Anticipating and managing the supply of hydrologic services requires information about the duration, seasonality, and predictability of absolute and relative changes in flood peaks and low flows (78). Information about seasonal variation in water use and the time required for a new hydrologic regime to be established in the wake of land-use alterations may also prove useful.

How do ecosystems regulate timing, and to what extent? Flood peaks are produced by surface water moving quickly into streams, reflecting short-term ecosystem response to rainfall. Base flow is produced by groundwater discharge, so it reflects long-term ecosystem effects on groundwater availability. The same ecosystem processes affect both, but often in different ways.

Water use by plants decreases both flood peaks and low flows, a phenomenon that is exacerbated in high-water-use ecosystems such as forests (79). Plant water use is usually not uniform through the year; seasonal effects are influenced by root depth, seasonal growth patterns, and local climate interactions, e.g., snowmelt (80, 81). In most cases, absolute changes in stream flow are greatest in the wet season, and relative changes are more pronounced in the dry season (78). Effects depend on whether rainfall is synchronized with the growing season: In two Australian catchments characterized by dormant-season rainfall, afforestation reduced wet-season flows by only 50%, whereas dry-season flows were reduced by up to 100% (82). In this water-scarce area, shrub and grass ecosystems provided greater summertime water supply benefits than the replacement tree-dominated ecosystem.

Hydroperiod: the characteristic seasonal fluctuations of wet and dry conditions

Ecosystems such as upland forests and riparian buffers promote the transfer of surface water to groundwater by infiltration, which reduces flood peaks while increasing base flow, generally increasing the predictability of water availability (83). One key supporting service provided by certain ecosystems may be in maintaining an area's hydroperiod, the characteristic seasonal fluctuations of wet and dry conditions. A predictable hydroperiod allows for the continued supply of services such as habitat provision for native fish valued by fishermen and migratory birds enjoyed by bird-watchers.

Water use and infiltration processes may be overwhelmed by the effect of ecosystems on the path that water follows as it moves into a water body. Vegetation mediates flow paths by channeling water into ruts and ditches or physically reducing the speed of overland and subsurface flow (84). In Oregon, forest harvesting increased peak flow by an average of 50% owing to a combination of changes in water balance and flow routing (85). Riparian vegetation can play an important role by reducing direct routing to water bodies as well as by promoting infiltration (86). Floodplain wetlands also reduce flooding by absorbing and slowing floodwaters. Headwater wetlands are more unpredictable; although wetland vegetation impedes flow, the saturated subsurface has no available pore space to absorb water and therefore quickens surface flow (87). Overall, downstream flood risk is likely to be reduced by maintenance of intact forests and upland wetlands.

Trends in Hydrologic Service Delivery

How do human activities affect service production, and how has service production changed? Humans are altering ecosystems and thereby affecting many of the hydrologic production processes described above (88). For example, agriculture can introduce pollutants into a water stream that forests do not, trees introduced into grasslands can reduce water yield, and timber harvest can reduce infiltration and speed water flow. According to the World Resources Institute, in 1998 fewer than 20% of the world's major watersheds had more than 10% of their area protected (89). As the world's watersheds are increasingly developed, the mix of services that they provide is likely to change, potentially quite dramatically.

A major contribution of the MA was to document current states and future trends in ecosystem services (90). Because of geographic variability, however, the actual impacts of human activities are often difficult to predict. Models based on generic effects of land cover on water quantity, quality, location, and timing provide the best guesses about changes in service delivery (91). An ideal indicator or suite of indicators of service trends would reflect this heterogeneity, provide information at multiple scales, incorporate uncertainty about levels and stability of delivery, and acknowledge trade-offs (92).

How does service delivery relate to the condition of the ecosystem supplying it? Ecosystems affected by different types and intensities of human activity provide different levels of ecosystem service benefits (93). In general, effects of land-cover change on hydrologic processes are not measurable until at least 20% of a catchment has been converted, although in some places as little as 15% or as much as 50% conversion may be needed to observe these effects (94). Other studies have suggested that for wetlands to have an impact on water quality they must cover 2%–7% of a watershed (95). In all cases, the location of an ecosystem within a watershed will play a determining role in its effects. Understanding how much area—locally, regionally, and globally—is necessary to sustain a particular level of ecosystem service delivery is key to land management decisions.

Service amenability to repair is directly related to the timescales of the ecological processes that provide the services. For water-related services, processes such as soil formation or tree growth are slow in relation to human time frames, making service provision difficult to repair (70). Ecosystem restoration to increase infiltration, for example, is unlikely to be effective in the short term (96). Management and reparability are also functions of whether service production responds to ecosystem change incrementally or catastrophically (97). Wetlands, for example, can transition irreparably to new, stable states that do not deliver beneficial filtration services (98). Invasive species can have negative, neutral, or positive effects on service delivery. In South Africa, invasive plant species have reduced water yield in some ecosystems (99). Many water-quality improvement functions of wetlands, however, are performed equally well by monostands of nonnative species (100).

How does production of one service depend on production of other services? Ecosystem services are highly interdependent at many levels. Understanding the complex trade-offs among them provides information about the ways in which exploiting or damaging one service influences the functioning of others. Provision of water quantity, quality, location, and timing; provision of the resulting hydrologic services; and provision of all types of ecosystem services can be synergistic or competitive. For example, clear-cutting the Hubbard Brook watershed increased annual stream flow while increasing nutrient and sediment concentrations in the runoff (101). In addition to increasing net surface water yield and decreasing water quality, logging a watershed may speed the rate of stream flow, decrease average base flow, increase frequency and size of flood events, and degrade soils. Logging may thereby reduce flood mitigation while increasing water supply. The increase in water quantity may offset an increase in contaminants by diluting them. The timber that was logged in the watershed is another ecosystem commodity; production of this service by plants requires them to use water (102).

Land management decisions often entail trade-offs among services delivered at different temporal and spatial scales, which represents an analysis challenge (103). For example, plantation forestry for local timber or global carbon sequestration has been shown to reduce regional water quantity (104, 105). Negative effects of plantation forestry on other services may be exacerbated by the use of nonnative trees that have high rates of water use or that cannot provide habitat for species that reduce disease transfer (106, 107). There are also potential trade-offs between human use of ecosystem services and healthy ecosystem function (108). As humans divert water for agricultural or municipal use, for example, freshwater systems may no longer be able to support fish and other aquatic species (109).

How well can technology substitute for ecosystem services? Although some ecosystem services are partially or wholly replaceable through technology or substitution, technologies may have lower resilience, cost-effectiveness, suitability, and life span than the ecosystem services they replace. For example, New York City calculated over $6 billion in savings from maintaining forests and agricultural buffers in its watersheds instead of building a filtration plant to ensure water quality (110). Technological replacements may themselves have substantial environmental impacts. Desalination technologies can replace water supplied through ecosystems, but energy requirements make this technology both expensive and a potentially substantial generator of carbon emissions (111).

BENEFICIARIES AND PRODUCERS

Human Consumption and Production of Ecosystem Services

We continue our discussion of ecosystem services by focusing on human users and providers, the middle right box in **Figure 2**.

Who uses and produces ecosystem services? All people, worldwide, are dependent on ecosystem services for their survival and quality of life. Scenario-building exercises connected to the MA indicated that demand for ecosystem services will increase across all scenarios in almost all categories; between 2000 and 2010 alone, global water use is expected to expand by 10% (90). Dependence is not homogeneous, however. Regionally, North Africa and the Middle East use more than the available supply of renewable freshwater, whereas Latin America uses less than 4% of its available supply (112). Finer divisions show that a higher proportion of people in developing than developed countries depend directly on local provisioning services (113, 114). However, comparing demand with local supply of primary productivity shows that affluent countries are often net importers; this means they may be less dependent on local services but consume more ecosystem services overall than less affluent countries (115). These variations in dependence at different scales have important equity implications in the face of changing availability of ecosystem services.

In addition to using services, people worldwide influence the generation of ecosystem services, directly and indirectly, through their activities. Services are produced by ecosystems exhibiting a range of human modification and thus by a variety of stewards, including farmers, ranchers, foresters, and managers of nature preserves.

What is the spatial relationship between ecosystem services supply and consumption? As human population densities increase, there is often a spatial mismatch between the places where humans use ecosystem services and the location of ecosystems that produce them. Because of this, feedbacks to ensure the continued provision of services may not exist (116). Moreover, risk of impairment is greatest in areas where land conversion happens most rapidly, often the same places where people depend most directly on ecosystem services. Some ecosystem services are transportable, whereas others are not. Identification of key ecosystem service source areas would aid in ensuring continued delivery. The subglobal assessments in the MA were one approach to visualizing the connection between ecosystem service supply and demand. New approaches include identifying parcels for conservation by quantifying their provision of highly valued services and their proximity to areas of high service demand (117, 118).

Are people aware of their production and consumption of ecosystem services? Awareness of ecosystem services depends on the type of service, the user, and the spatial scale of its delivery. Provisioning services, such as agriculture, timber products, and fish, are widely recognized and may be more highly valued than other service types (119). Water supply services are generally acknowledged, often to the exclusion of the other hydrologic services provided by a watershed (120). Long-term ecological and social research in Mexico has shown that socioeconomic status, including differentiations as subtle as the land type cultivated by farmers, influences which services are acknowledged and the extent to which they are valued (121). This study also indicated that, although beneficiaries may acknowledge a wide variety of services, they might not be aware of the ecosystem processes that produce them. This is often related to the spatial scale of service delivery; beneficiaries recognize and value services at different scales in different ways (122). Beneficiaries can also incorrectly attribute services to particular ecosystems. Management decisions resulting from misperceptions about a forest's role in regulating water supply, for example, may actually diminish freshwater available to downstream populations (123).

VALUATION

Economic, Ecological, and Social Value of Ecosystem Services

Hydrologic services are just one class of many services that provide tremendous benefits to people. The ecosystem services framework points the way to quantifying those benefits. In so doing, it provides a way for people to assess the impacts and trade-offs of ecosystem change, even when gains and losses accrue to different beneficiaries at disparate spatial and temporal scales. Monetary valuation, although not an end in itself, can be a powerful tool for assessment and policy making because it provides a common metric with which to make comparisons (124). For a review of the history, background, and context of environmental valuation see References 125 and 126. Our overview of ecosystem services valuation is structured as a response to the questions in the lower box in **Figure 2**.

What components of the services should be valued? The value of ecosystems comprises use and nonuse elements. Use values are direct, e.g., the value of water fowl to hunters; indirect, e.g., the value of wetland nutrient sequestration in reducing eutrophication and algal blooms downstream; and option, e.g., the value of ensuring that a resource will be available for future use. Nonuse values are derived from simply knowing an ecosystem exists, either now, a passive use value, or for future generations, a bequest value.

One can consider the value of total service flows from an ecosystem, the value of alterations to an ecosystem, or the distribution of costs and benefits from ecosystem service production. While accounting for the same elements of value, each of these approaches will provide information that is useful in specific policy contexts and that is not likely to be meaningful in others (127).

The value of an ecosystem service is, at least in part, a function of the total production of that service. The marginal value of a service, the amount someone would be willing to pay for one additional liter of water, is not independent of the total value: The value of that additional liter depends on whether it is the first or the hundredth liter available. Some early attempts at worldwide ecosystem valuation have been criticized for aggregating marginal into total economic value (128, 129). The marginal price of an ecosystem depends on the magnitude of the assessed change as well as on the beginning and ending points of that change, but it provides no indicators or corrections for nonlinear ecosystem response to degradation.

The way services are partitioned affects their value. The value of a single service, such as water supply, can be assessed as can the value of an ecosystem in providing a variety of services, such as a forested watershed providing water, timber, and recreation (130). Valuations of single services are the most prevalent; whole ecosystem studies and assessments that integrate across multiple services are more difficult and less common (131).

For policy and management decisions, the value of service production is often most meaningfully understood in comparison to service production from an alternative land use (132). Tropical forest conservation in certain areas, for example, may provide net hydrologic benefits in comparison to annual cropping or grazing, but not in comparison to agroforestry (133). The choice of comparative land use also affects the economic attractiveness of ecosystem restoration versus conservation or land-use change. Value is also crucially dependant on the scale at which services are assessed. Locally and globally, forest conservation in Madagascar was shown to have higher value than logging, but the opposite was true at the national scale (134).

The way the future is valued can greatly affect how a resource is managed over time and thereby affect the stock of that ecosystem resource at any point in time. In recent years, intertemporal valuation and discounting methodologies have gone beyond traditional, constant-rate exponential discounting, which tends to severely discount future generations in decision making (135, 136). Studies indicate that preferences concerning future utility are best described by a declining discount rate (137, 138); declining-rate discounting models are supported on theoretical grounds as well (139–141). These models weight the near future at a level similar to conventional exponential schemes but give much more value to the mid- to long-term future. These alternative discounting methodologies could be especially important when analyzing resources that are essentially nonrenewable or renewable only on very long timescales.

What valuation approaches best capture these components? A variety of ecosystem products, such as produce, timber, and fish, are commodities valued in the marketplace. Many other services, however, are public goods, that is, nonrival, nonexcludable, and essentially free to any user. Still other services, such as stability, resilience, and reparability, have no easy translation into market value. Because people mostly do not pay for these ecosystem services, and because many people can use them without diminishing their value, there is no direct measure of demand and willingness to pay, presenting difficulties in discerning their value (142). Nonmarket methods for determining value include revealed preference methods such as hedonic pricing and travel cost, stated preference methods such as contingent valuation, and avoided cost or replacement cost methods (143, 144). Although in some cases nonmarket methods are very effective, in other cases monetary valuation of ecosystem services is highly imperfect (145).

Sociocultural value and ecological value are important aspects of overall ecosystem value. Because most ecosystem services are traditionally public goods, equitable access is often an important social value. When people in distant locations are given an opportunity to express their willingness to pay for different ecosystem benefits and trade-offs, however, the values they assign will be weighted not only by their preferences but also by their incomes. Society may not be interested in valuation methods that discount some people's dependence on ecosystem services. New approaches to ecosystem valuation attempt to integrate economic valuation methods, which are based on consumer preferences and the exchange value of services, with ecological valuation methods, which are based on the cost of production, and social values (146, 147). Production function approaches to valuation explicitly incorporate ecosystem processes into economic studies (148). These integrative approaches are more likely to capture the full value of ecosystems in providing services.

How valuable are hydrologic services? Hydrologic services have been recognized for some time, and valuation studies of freshwater-related services have been made since at least 1970 (149, 150). These studies have quantified the value of environmental amenities such as water quality (151, 152). The value of actual ecosystems to the production of these valued amenities is less clear.

Valuation studies of wetlands and riparian buffers often use a proxy related to production of an attribute such as water quality and then value the incremental impact of changes in that attribute (153). In California, farmers were assessed to have a net benefit from vegetated buffer strips; improved water quality and reduction in soil loss outweighed the costs of land taken out of production (154). The spatial relationship of an ecosystem to service beneficiaries affects its value. A study of flood damages related to wetland development in Florida showed wetlands within a floodplain to be very valuable, whereas wetlands outside of flood-prone areas were not (155).

Attempts have been made to value several of the hydrologic services produced by watersheds. Models indicate that in some places the value of increased groundwater recharge under conserved forest is substantial; the net present value of one forested watershed in Hawai'i was calculated to be between \$1.5 and \$2.5 billion (156). Forests are particularly valuable for their effects on the timing of water for in situ and diverted supply. In China, forested watersheds may improve the functionality of existing dams on the Yangtze river by up to US$600,000 per year. One study in Chile calculated that native forest is worth over US$200 per hectare per year because of its effects on drinking water supply (157, 158).

The generic value of hydrologic services is apparent, but the functionality and value of an ecosystem is likely to be highly variable, so site-specific assessment remains important (159).

POLICY

Tools for Ecosystem Service Protection and Management

There is often a vast spatial and economic disconnect between those who control land use and those who benefit from ecosystem services, which limits feedback between land use and service delivery. Policy mechanisms can correct this, conserving the delivery of desired services, but institutional and financial limitations constrain the mechanisms that can actually be put into place. We address the policy questions listed in the middle left box of **Figure 2**.

Which ecosystem services should be prioritized for protection? If service provision is to be maintained, growing pressures on both the supply and demand for ecosystem services, such as land-use changes in watersheds coupled with increasing human demand for water, must be addressed (160). Implications of external drivers, e.g., climate change, must be taken into account as well. In almost all cases, limited resources will require prioritizing certain areas for protection.

There is a wide range of competing criteria for prioritizing ecosystem service provision. The best schemes integrate the needs of users with the biophysical constraints of service production (161). Ecosystems can be protected or managed to maximize the provision of a single service, maximize output of a suite of services, maximize diversity of services, minimize loss of services, or minimize variability in service provision. The susceptibility of ecosystem service delivery to decline in the face of ecosystem change, and ecosystem affinity for management and repair, are further criteria for prioritization.

Policies can attempt to maximize, distribute, or target value among beneficiaries; equity is often a top priority. Diverse user groups are able to tolerate different levels of uncertainty in ecosystem service supply, and they will place a range of value on increased certainty in delivery in addition to valuing the service itself. Agencies involved in the protection of hydrologic ecosystem services in rural watersheds have emphasized the difficulty, as well as the importance, of ascertaining the value of ecosystem services to all stakeholder groups at many different scales (162). When users have conflicting service needs, social patterns, including varying organizational efficiency and political power among groups, are often stronger drivers of outcome than increasing total benefit (163).

Trade-offs in the protection of ecosystems and the production of services are an inevitable consequence of prioritizing the delivery of certain services and promoting specific management schemes. Ideally, policy makers will assess trade-offs to the full range of consumers over the full suite of services provided by an ecosystem (164). Given the challenges in obtaining this social, biophysical, and valuation information, good policy mechanisms will also include uncertainty as a criterion. (165)

What are the available policy mechanisms for protecting ecosystem services? Broadly, the classes of policy mechanisms available to protect ecosystem services are government ownership or control of land, government regulations, government incentive payments, and voluntary payments. Voluntary market-based or negotiated payments are attractive because they potentially allow

PES: payment for ecosystem service

Ecosystem service districts: governmental authorities dedicated to the management and protection of ecosystem services

conservation to occur outside a government-mediated framework and to be financed with nongovernment money (166). These payments are made in the form of voluntary contractual arrangements, transfer payments, marketable permits, tradable development rights, and certification; funding might come from user fees, taxes, or donations. It may be most effective to combine several types of payments or to design voluntary measures to work in tandem with existing nonmarket mechanisms. In each place where voluntary payments for ecosystem services (PESs) are used, policy design must address who pays, how much, to whom, for what, and for how long (167, 168)

Although voluntary approaches to ecosystem services conservation are potentially more easily accepted, effective, and flexible than regulation, they also have unique requirements (169). If beneficiaries are to agree to pay for the delivery of ecosystem services, they must trust that ecosystems are producing the contracted services and that they will continue to do so. This requires an impartial, trustworthy, transparent institutional structure. In addition, understanding baseline production and ongoing monitoring are required, both of which are likely to be expensive and time consuming, creating high transaction costs during design and implementation phases (170).

Markets do not develop spontaneously or predictably, so market design is important to effectiveness and equity. Commodifying ecosystem services can be difficult. Even in the most straightforward cases, a marketable commodity remains a proxy for all the ecosystem processes that provide a service. In many other cases, it is difficult to determine the most effective proxy because, for example, ecosystem goods are intangible or do not have a clearly identifiable clientele. Competition takes time to establish, and start-up and transaction costs can be very high, so efficiency in new markets is usually low. Because ecosystem services are commonly thought of as public goods, preserving their equitable distribution may be an important aspect of conservation schemes. Market mechanisms can affect participants in unexpected ways, so equity issues often influence policy design and level of payment (171).

The scale, as well as the spatial and temporal congruence, of supply and consumption of ecosystem services determines the scale at which policy will be effective (105). If a lower bound exists for the area of an ecosystem necessary to produce a service, markets might need to bundle services at the beneficiary end, provide adjacency bonuses to suppliers, or develop existing institutions into structures such as ecosystem service districts (172). At the same time, the scale at which management decisions are made constrains the ways in which ecosystems can be protected. Landscape-scale assessments of service production and beneficiary needs help investment strategies reinforce one another instead of conflicting or creating perversions in which individual service valuation leads to recommendations for one ecosystem to replace another (173).

Some have argued against payment programs on the grounds that scientific knowledge is still too weak to ensure the production and delivery of services, particularly for hydrologic services, which are characterized by heterogeneous systems, conflicting processes, and high uncertainties (174). The World Bank has advocated structuring payments in such a way that delivery can be monitored after implementation and payments adjusted accordingly (170). The best policies will develop with flexibility and recognize that as the value systems, institutions, and technology that constrain management decisions evolve, policy choices are likely to change.

How effective have voluntary mechanisms been in protecting ecosystem services? A variety of mechanisms, public, private, and hybrid, already exist to protect and promote ecosystem services (162, 175). Approaches to hydrologic service protection include investments by trust funds and direct payments to landowners. In Quito, Ecuador, a trust identifies and invests in measures such as government acquisition of important watersheds, local education, and incentives for improved agricultural practices. In Costa Rica, landowners are paid a flat rate by the government for the services supplied by their land (176). These programs have successfully enrolled many landowners and dispersed a significant amount of money, although there is little assurance that services are actually being produced.

The effectiveness of PES varies depending on the payment mechanism as well as on features such as commodities sold, characteristics of participants, level of competition, geographical extent of trading, level of maturity, and the degree to which markets are embedded in broader institutional contexts. In general, the effectiveness of ecosystem service policy is difficult to evaluate because these policies usually have multiple goals and there are many metrics for success. For hydrologic services, some studies have illustrated a clear economic benefit of watershed protection on the basis of sediment reduction or reliability of water yield, but others have indicated that the integrated effects of forest protection on water quantity, quality, location, and timing on users throughout the watershed may be neutral or negative (177). Models comparing ecofriendly subsidies to direct conservation payments indicated that direct investment in ecosystem protection may be the most cost-effective mechanism for ensuring service provision (178).

The International Institute for Environment and Development, after reviewing almost 300 emerging markets for several different services, found that unintended consequences of markets, particularly related to equity, were troubling. Additionally, they noted that many reports on existing ecosystem service payment schemes tally benefits of service payment programs without accounting for costs or comparing this cost-benefit ratio to that of alternative structures such as regulation (171). In all cases, assessing not only the functioning of markets but comparing them to alternative mechanisms and assessing their effects on ecosystems and people will be very important. Moving forward, transparent accounting of ecosystem services policy will aid in the design of new policies that are both more efficient and more equitable.

ECOSYSTEM SERVICE-BASED LAND MANAGEMENT IN PRACTICE

Existing policy designed to enhance ecosystem service provision is limited and imperfect. The following three cases provide both inspiration and lessons for future attempts.

Extensive flooding on the Yangtze River in 1998 motivated Chinese officials to reduce erosion and improve water retention in upland watersheds by protecting and replanting forests. The Sloping Lands Conversion Program and the Natural Forest Conservation Program are now two of the world's largest ecosystem services-based conservation programs. The Sloping Lands Conversion Program, also known as Grain-to-Green or Farm-to-Forest, compensates farmers with in-kind grain allocations, cash payments, and seedlings to take the most erodible farmland out of production, replacing crops with trees. The Natural Forest Conservation Program protects natural forests and improves management of natural and plantation forests (179). Assessments of these broad-scale programs to reduce erosion and retain water are limited. Evaluation is more often based on achievement of target outputs, such as the number of hectares planted or removed from cultivation, than on the provisioning of services themselves. Existing information indicates that, although program guidelines may be well designed, targeting is often compromised by lack of funding for research, implementation, and systematic monitoring (180, 181). Both programs have multiple objectives, including poverty alleviation and restructuring of local economies, which are not always compatible with erosion mitigation goals (182).

In South Africa, the Working for Water Programme has dual goals of increasing water supply and employment. Launched in 1995, it is aimed primarily at invasive species management and eradication. Recent reports indicate that restored native ecosystems are now releasing on the order of 50 million cubic meters of additional water each year (183). The program also employs more than 20,000 people annually and runs a variety of public education programs (184). Working for Water has perhaps the best basic science, assessment, and monitoring programs of any ecosystem services project in existence. One conclusion of this research has been that significant gaps in understanding still exist, despite substantial spending, illustrating that well-developed ecosystem services projects may be costly (99).

In the United States, the City of Portland's Watershed Management Program is basing some of its land management decisions on ecosystem services. By allowing flood waters from Johnson Creek to move into the floodplain, the city will benefit not only from reduced flood damages, but also from the maintenance and restoration of biodiversity, air quality improvement, water quality improvement, and cultural services provided by the floodplain. Over a 100-year time frame, one study calculated a $30 million benefit to the public (185).

SUMMARY POINTS

1. All people, worldwide, are dependent on ecosystem services for their survival and quality of life. As the size of the human population increases, demand for ecosystem services is projected to increase as well. At the same time, the sustainable production of most services is under threat and, in many places, in decline.
2. Vast geographic, economic, and cultural disconnects between those who control land use and those who benefit from services produced on that land often limit feedback between land use and service delivery. Policy mechanisms are needed to correct this and sustain the delivery of desired services.
3. Understanding and managing ecosystem services requires information about the biophysical nature of services as well as information about their social, economic, and institutional dimensions. Although generalizations are possible, the functionality and value of an ecosystem is likely to be highly variable, so site-specific assessments will always be of great importance.
4. The ecosystem services framework makes explicit the complex feedbacks and tradeoffs among services and human beneficiaries. Services are produced by ecosystems exhibiting a wide range of human modification, from intensively managed farmland to native habitats only lightly touched by humanity. Production of one service may come at the expense of another, just as consumption of resources by some people and activities may come at the expense of consumption by others, elsewhere and in the future.
5. Much knowledge about ecosystem service production exists in fields historically not directly concerned with ecosystem services. Ecosystem services science, policy, and management require synthesis and interpretation of this knowledge.
6. Hydrologic services encompass the benefits to people that are produced by terrestrial ecosystem effects on freshwater. They can be organized into five broad categories: improvement of extractive water supply, improvement of in-stream water supply, water

damage mitigation, provision of water-related cultural services, and maintenance of aquatic habitats that produce services. To translate traditional hydrologic science into an ecosystem services context, it is useful to focus on four key attributes of each service: quantity, quality, location, and timing of flow.

7. Valuation provides a way for people to assess the impacts and trade-offs of ecosystem change and illuminates the accrual of gains and losses to different beneficiaries at disparate spatial and temporal scales. Monetary valuation, although not an end in itself, can be a powerful tool for decision making because it organizes information using a common metric for making comparisons.
8. Voluntary market-based or negotiated payments are attractive because they potentially allow conservation to occur outside a government-mediated framework and to be financed with nongovernment money. Payment schemes must address who pays, how much, to whom, for what, and for how long.

FUTURE ISSUES

Existing research on ecosystem services has been extraordinarily productive up to this time; we hope to have illustrated the outstanding needs for continued and directed research on service production, users, value, and policy. Although effective policy will respond to science, society, and valuation, for ecosystem services protection to be effective, research in those areas must be driven by the needs and constraints of policy.

Information about the magnitude of ecosystem service production is particularly pressing. Even though one can often determine which services an ecosystem produces, the rate or level of service production is typically difficult to quantify, which complicates comparisons with other land-use options. Policy makers need information about the magnitude of natural service variation as well as how service supply will vary in the face of human-induced environmental change.

Location and scale of delivery also represent substantial knowledge gaps. Without information about the places from which people receive services, policy that effectively protects important supply areas will remain elusive. Ecosystem services are inherently spatial, so mapping exercises are likely to be important in the assessment of scale and for understanding the connections between ecosystem service suppliers and users.

Trade-offs in biophysical production need to be directly assessed. It is important to understand whether interactions are synergistic or competitive and which processes dominate at different scales. Ecosystem processes occur at a variety of timescales, so trade-offs may not be immediate. We need biophysical information about how time-lagged services interact and models to assess trade-offs among them. There is limited information on the effective comanagement of services; thus it is unclear to what extent trade-offs and win-wins actually occur.

Institutional questions abound. The scope and limitations of alternative conservation approaches are uncertain, especially in the international context. We do not yet know how management plans and investment strategies conflict with or reinforce one another. Assessments of the effectiveness of the policy mechanisms that are already in place are also necessary. New institutional mechanisms to provide for ecosystem service delivery will be required as well. Particularly on the landscape scale, we need information that will help design conservation and management schemes that are reinforcing.

To effectively conserve and enhance ecosystem services, physical and social science must be expanded and integrated to identify, prioritize, and target ecosystems of concern. This broad area is fertile ground for transformative interdisciplinary work.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

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