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Growing Cities Depend on Ecosystem Services

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by David Ervin, Darrell Brown, Heejun Chang, Veronica Dujon, Elise Granek, Vivek Shandas, and Alan Yeakley

Gerding Edlen

The green building firm Gerding Edlen transformed five blocks of a defunct brewery in Portland, Oregon, into a neighborhood of green housing units and sustainable retail space, with six LEED-certified buildings. The green building industry has been expanding exponentially and now comprises one-quarter of new construction activity and one-third of new nonresidential building.

In Brief

Many studies have documented the growing fragility of a majority of the globe's ecosystems. Policymakers and resource managers often frame such ecosystem challenges as primarily about protecting natural systems in rural areas. However, that conception misses a key part of the story: the rapid growth of urbanizing areas. Home to more than 50 percent of the world's human population for the first time in modern history, urbanizing regions concentrate pressure on ecosystem services, which are necessary to sustain healthy urban living conditions and vibrant commerce. This dramatic urbanization presents both challenges and opportunities for novel ecosystem services management. A transdisciplinary framework is needed to discover innovative solutions to these wicked problems because they involve complex linkages between natural and human systems that transcend any single discipline. The framework should integrate natural and social sciences with stakeholders' intimate knowledge of ecosystem services and urban systems. Here we describe such a framework for training scientists and managers and present four novel cases that illustrate ecosystem management solutions for urbanizing areas.

Policymakers and resource managers often frame ecosystem services management challenges as a matter of protecting natural areas outside of cities. Assuring good stewardship of nature's services in rural areas is indeed crucial but is only part of the solution. Over 50 percent of the world's human population now resides in urban areas, a figure projected to grow to 66 percent by 2050, with huge impacts in developing countries. *The New York Times* reported in 2007 that, "from now to 2030, the world will need to build the equivalent of a city of one million people in developing countries every five days."[1]

This unprecedented demographic shift concentrates pressure on ecosystem services in and around urbanizing regions. Such higher-density development presents challenges and opportunities for management of the ecosystem services that sustain healthy living environments and vibrant commerce. For example, growing cities concentrate large amounts of water pollution and other wastes, but that centralization may result in lower treatment costs than if the damages accumulated in rural areas with vulnerable natural ecosystems. Understanding the dynamics and feedback effects of these systems that span human and natural components is paramount. In this article we suggest a transdisciplinary approach to effectively manage ecosystems that support urbanizing areas.[2–5]

Our framework posits that ecological functioning declines across a continuum from natural ecosystems, such as wilderness areas; to intermediate services, such as urban green spaces; to built replacement services, such as wastewater treatment plants (see Figure 1).[6] Natural ecosystems provide important services if left largely unaffected by human development; these services often are uncounted by markets and in policy decisions.[7] Intermediate and replacement services require modifications of formerly natural ecosystems with diminished ecological value. While several studies have examined ecosystem services in natural environments, few have examined to what degree those services in nonhuman-dominated landscapes are needed to complement or substitute for those lost from human-dominated environments, such as urbanizing areas. To do so, the social and economic dimensions of ecosystem services values should be integrated with ecological values as discussed below.

Ecosystem Fundamentals

Ecological systems deliver a variety of ecosystem services to human society, including provisioning (e.g., timber), supporting (e.g., soil formation), regulating (e.g., water filtration), and cultural (e.g., recreation) services.[8] For example, a natural soil formed over centuries has the ability to adsorb air- and waterborne contaminants, reduce rainfall acidity, moderate the impact of high-intensity storms on streams, and act as a fertile substrate for plants that provide animal habitat as well as food and fiber for human populations. Human impacts on ecosystems include harvesting biological populations (e.g., logging, fishing) and converting landscapes through alterations of substrate (e.g., paving, trawling).[9] Human impacts can exceed most natural disturbances in magnitude, especially when ecosystem surfaces are altered to the extent that natural successional and recovery processes are no longer possible, resulting in a loss of system resilience. Agricultural or aquacultural conversions of landscapes often result in substitution of ecosystem services, where one service is enhanced (e.g., provisioning gains in crops or fisheries) at the expense of other ecosystem services (e.g., losses of supporting soil formation or of buffering coastal habitats) (see Box 1 for a freshwater case). Urbanization conversions of landscapes often result in outright losses of ecosystem services (see Box 2).

Effective ecosystem services management depends on how well humans work in concert with how ecosystems naturally function. Ecosystems require continuous inputs of energy via photosynthesis in plants and naturally occurring material inputs such as nitrogen and calcium. Also, ecosystems naturally experience change, known as succession, spanning from recently disturbed areas (i.e., early succession) to mature areas (i.e., late succession, characterized, for example, by old-growth forests). A key question in management is how much of the original natural functioning and resultant services provided by an ecosystem are maintained or at least substituted (see Figure 1). As the case studies indicate (see Boxes 1–4), preserving a net positive balance requires a careful assessment of ecological function along with consideration of social and economic factors. A critical challenge in effective ecosystem services management, particularly in urban areas, is a better synthesis of socioecological relationships and a more transdisciplinary approach, as discussed in the next section.[10]

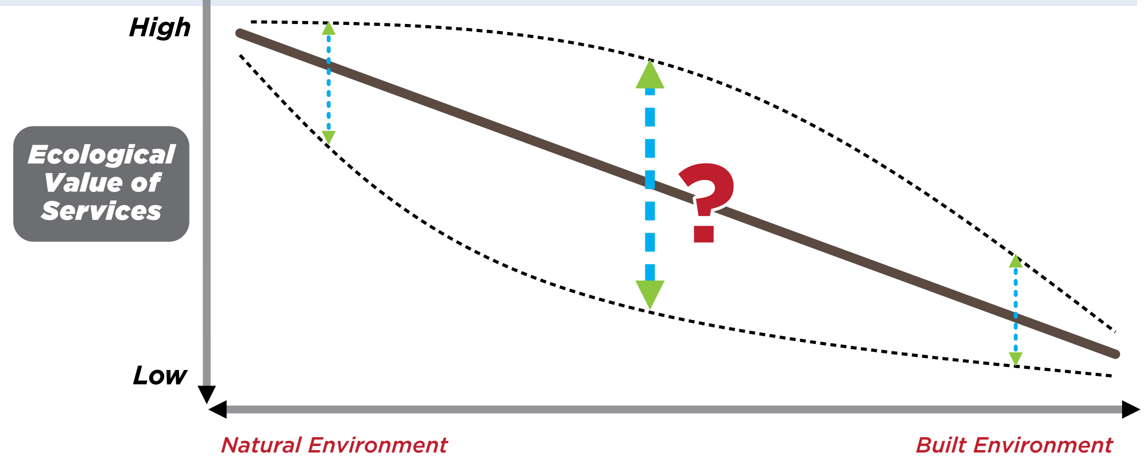
Key Concepts

- **Over 50 percent of the world's human population resides in urban areas, a proportion projected to grow substantially by 2050, concentrating pressures on the ecosystems supporting these urbanizing regions.**
- **Deep problems created by urbanization pressures on ecosystems and the services they provide demand solutions that integrate knowledge and tools spanning fields such as ecological science, urban studies, sociology, business, public policy, and economics.**
- **Exemplary cases involving urban stormwater, wetlands, stream temperature, and green buildings demonstrate successful collaborations between nonprofit, public/government, and private organizations.**
- **Such collaboration brings relevant stakeholders into the processes of problem definition, solution design, and implementation.**
- **New, innovative educational models are needed to train future scientists and managers in integrative problem-based scholarship in order to discover and implement solutions for critical ecosystem management challenges.**

Social Systems

Human communities influence—and are influenced by—the ecosystems of which they are a part and on which they depend. Given the complex and dynamic relationships between society and ecological systems, decisions about how to manage the portfolio of ecosystem services invariably reflect politically and socially negotiated outcomes. The dynamic of these negotiations has important implications for the equitable and socially sustainable provision of ecosystem services needed to support urbanizing regions.

Individual Services	*Natural Ecosystem Sources*	*Intermediate (Natural/Built) Sources*	*Built Replacement Sources*
CARBON SEQUESTRATION /CLIMATE MODIFICATION	National/state forests	Urban parks Greenways	Green roofs Air conditioning
FISHERIES PRODUCTION	Rivers	Reservoirs	Hatcheries
RECREATION	Wilderness area activities	Green spaces	Indoor facilities
WATER PROVISION AND PURIFICATION	Lakes, streams, watersheds, wetlands	Restored wetlands and streams	Wastewater treatment Artificial wetlands



The authors and Richard Morin/*Solutions*

Figure 1: This conceptual model depicts how ecological value declines over three source categories of ecosystem services, from natural ecosystems to intermediate (natural/built) sources to built replacement structures. Examples of sources in each category are given for four ecosystem services. Dashed lines illustrate potential variation around the hypothesized (solid line) gradient in ecological value. This variation is due to the specific context under study and scientific uncertainty about how the ecosystems function.

The design and implementation of institutional arrangements are critical for successful ecosystem management and delivery of related services. Studies have documented the effectiveness of formal and informal institutional arrangements for common-property resources in areas such as forestry, fisheries, and irrigation.[11,12] For example, participatory management of the Maine lobster fishery is a success story, showing how local fishers can self-regulate their activities for the long-term survival of the fishery and their livelihoods.[13]

Interest in and capacity to make decisions that support ecosystem services are often closely correlated with the socioeconomic profile of a community (education, income, race/ethnicity).[14–16] In addition, citizens in urban areas whose livelihoods are not directly dependent on resource extraction (e.g., logging, farming) are generally more accepting of adjustments that conserve resources and preserve green spaces. Densely populated areas with substantial built environments, though, pose socio-political challenges for the delivery of ecosystem services (e.g., clean air). Relatively wealthy and well-educated citizens tend to value a broad range of ecosystem services, from the tangible (i.e., with easily assigned monetary values) to intangible (e.g., a beautiful landscape). Less economically and educationally advantaged citizens, in contrast, tend to be less able to pursue sustainable uses of ecosystems, but this is not always the case.[17,18] Adverse environmental and health impacts from poor access to ecosystem services can trigger deep concerns for environmental justice.

While advances in scientific understanding can provide the groundwork for effective policy design and implementation, social, economic, and cultural contexts determine the process and pace of institutional change. For example, citizen concern for protecting productive farmland from urban sprawl led to the creation of urban growth

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Box 1: Restoring a Natural Ecosystem

Clean Water Services (CWS), a public water resources utility in a rapidly urbanizing region within metropolitan Portland, Oregon, operates four wastewater treatment facilities, releasing treated effluent into streams within the Tualatin River watershed.[1] The effluent from the treatment plants enters the river at temperatures high enough to impair resident fish species downstream. The environmental quality authority, the Oregon Department of Environmental Quality (DEQ), requires that CWS reduce the temperature of its discharges. CWS's permits to discharge into the river depend on its ability to meet the proscribed temperature reductions. The utility's service population and the regional economy served by CWS are projected to grow dramatically in the next 20 years, with consequent growth in demands on CWS to treat wastewater. This growth, not surprisingly, adds to the need to find ways to combat increasing water temperatures in the river.

As CWS managers were deciding how to achieve the necessary temperature reductions, they were also confronted with environmental issues of preserving/restoring endangered and threatened salmon habitat and meeting Oregon's land-use requirements. The complexity of dealing with these interacting issues prompted management to consider the water temperature issue from a systems perspective. Instead of simply trying to find ways to mechanically cool the effluent as it entered the river—the traditional method of addressing this problem—CWS personnel considered the real goal of the regulations: to create water conditions that meet the needs of fish and humans downstream from the treatment plants. With this in mind, CWS staff considered their options. To comply with temperature requirements, CWS could construct a new concrete and metal cooling facility, or it could restore the ecosystem above the two treatment plants and use naturally occurring regulating ecosystem services. This latter option entailed planting shade trees, shrubs, and native grasses along the banks of the river for natural cooling downstream. Either option would provide the cooling necessary to meet the needs of the fish and the requirements of DEQ, enabling CWS to obtain the permits needed to operate its wastewater treatment facilities.

In analyzing these two feasible options, the utility examined costs and benefits through both a financial and an environmental lens. The capital cost of building the required cooling plant for the expected demand exceeded U.S.$60 million, with annual operating costs of over U.S.$2 million. The present value total cost of the cooling plant computed to at least U.S.$70 million. There was a clear environmental cost as well, from the carbon footprint of building and operating the plant. The benefits from the cooling plant would be effective cooling of the effluent, resulting in acceptable review by the governing authorities and a relatively risk-free issuance of a permit to practice. There were no other environmental benefits identified.

The cost of planting native shrubs and trees along approximately 35 miles of upstream riverbank, plus the annual payments to landowners for conservation easements to guarantee that the plantings would not be damaged by agricultural use, was estimated at a present value of about U.S.$5 million. For businesses such as CWS, the risk of losing permits creates considerable concern, which translates into a real, but intangible, cost. In this case, CWS worked with the governing authorities to demonstrate that improving the ecosystem above the treatment plants would be effective. The utility convinced the authorities that the plantings and management of the upstream lands would provide the required shading to the river, cooling it sufficiently, in a measurable manner, and thus would meet the permitting requirements. The resulting plantings and additional ecosystem improvements have in fact resulted in a variety of additional ecosystem services benefits that continue to accrue.[2] More than 1.6 million native trees and shrubs were planted between 2004 and 2008, generating total thermal credits of 295 million kilocalories per day.

In addition to the significant cost savings of restoring a native ecosystem rather than constructing a mechanized fix to the wastewater temperature problem, the restored ecosystem provides services such as salmon habitat, upland scrub habitat, carbon sequestration, increased biodiversity, and recreation opportunities. Although functioning markets for many of these services are currently embryonic or nonexistent, the market mechanisms and protocols are being created and piloted by the utility and affiliated organizations. The critical roles of these overlooked and neglected ecosystem services will exert more influence on public and private management decisions as we improve our capacity to value them via markets or by other means.[3]

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boundaries for Oregon metropolitan areas in 1973, a unique phenomenon in the United States.[19] These growth boundaries have substantially affected how Oregon urban areas accommodate density, livability, transportation, housing, and green spaces. These impacts influence the quantity and quality of ecosystem services that support the state's urban areas.[20]

Urban Systems

Evaluating the relationships between biophysical systems and social processes is central to understanding how urban systems affect and rely on ecosystem services. While discourse on urbanization continues to emphasize the problematic nature of human-dominated landscapes, evidence increasingly suggests that urban landscapes may be "hot spots" for global environmental solutions.[21] Research has begun to document the effect of urban designs on ecosystems and their services. Scientific studies of urban ecosystem services are reaching novel understandings of coupled human and natural systems, including the role of landscape features in providing the provisioning, supporting, regulating, and cultural services in human-dominated landscapes. In studying interactions between ecosystem functioning and services, researchers consider many factors that work simultaneously at multiple scales.[22] For example, research on urban buildings suggests that green roofs provide replacement services (see Box 4), including stormwater management, air-temperature moderation, and urban-habitat provision.[23] At regional scales, research suggests that canopied vegetation in public streets, open spaces, and private lands can improve urban air quality, regulate microclimates, reduce noise pollution, and improve stormwater management.[24,25]

Clean Water Services

Clean Water Services' Rock Creek Advanced Wastewater Treatment Facility in Hillsboro, Oregon. When ordered to reduce the temperature of its treatment plants' discharges into the Tualatin River, the water utility chose instead to restore the ecosystem upstream. This decision cut costs, cooled the river, and improved overall ecological health.

In addition, while studies suggest that green spaces can enhance the physical and psychological well-being of urban citizens,[26–28] other studies provide evidence that urban landscape features have direct economic and health benefits for residents. For example, recent research suggests that the presence of urban vegetation can have direct and positive impacts on the property value of single-family residences,[29] birth outcomes,[30] and crime.[27] Additionally, efforts to improve stormwater management in urban areas are also delivering cultural ecosystem services through improvement in property values and neighborhood aesthetics (see Box 3). Urban systems in and of themselves rarely provide the ecosystem functioning and services found in natural or less disturbed landscapes; therefore, applying ecosystem services concepts to urban areas requires careful attention to the role of natural areas as supporting systems for these human-dominated landscapes.[19] Although some ecosystem processes such as water availability and purification may depend on areas outside urban centers, other processes such as soil formation and temperature regulation may occur at localized urban scales (e.g., neighborhood level). In addition, replacement services in urban areas often overlook ecosystem function in favor of structural or aesthetic aspects. For example, while restoration to improve stormwater management in urban areas may assume that constructed infiltration facilities will substitute for their non-urban counterparts, such systems may be much reduced in their ability to process nutrients or support wildlife.

Business-Sector Roles

The business sector relies on the panoply of ecosystem services yet also dramatically affects the ability of ecosystems to provide these services. Given the size and influence of the business sector in urbanized and urbanizing regions, any understanding of ecosystem services management must integrate an understanding of how the business sector and ecosystem services relate.

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Box 2: A Wetland or a Storage Tank?

Progressive businesses, using ecosystem services values to inform their decision making, often have opportunities to enhance more than their bottom line. Cook Composites and Polymers (CCP), working in partnership with the U.S. Business Council for Sustainable Development (USBCSD) and The Ohio State University's Center for Resilience (CfR), looked at an ecosystem services framework when confronted with replacing its stormwater management system at a manufacturing facility in Houston.

As CCP contemplated replacement of an aging water management system, the company realized that, instead of simply replacing a set of pipes and tanks, what it was really doing was replacing a set of functions—on-site flood control and water treatment. Considering the problem as one of accessing a set of processes that generate ecosystem services allowed the company to broaden the scope of its decision-making process to consider a variety of possible alternatives. The problem it faced was controlling water flows and treating water, not rebuilding a legacy structure of pipes and tanks.

With this new framing, CCP saw an opportunity to move beyond controlling water runoff issues, and it identified project objectives that transcended the obvious ones of water treatment and control:

1. financial—to minimize the overall cost of the project;
2. environmental—to improve the ecology of the Houston metropolitan area;
3. social—to enhance the well-being of the neighborhood;
4. reputational—to demonstrate CCP's commitment to community values;
5. internal—to build morale and productivity.

Two alternatives appeared capable of meeting CCP's most immediate needs of stormwater control and treatment. The first, building new sets of pipes and storage tanks, would essentially update the current technology employed for handling storm- and wastewater. The second, building a wetland in the area currently occupied by the existing facility, would create a drastically different business and natural environment. This latter alternative was also drastically different philosophically from the standard operating procedures of CCP and the industry. It would fundamentally create "intermediate" replacement services for ecosystems that no longer existed. CCP management makes decisions about physical infrastructure like pipes and tanks all the time, with clear tried-and-true models for analyzing costs and benefits. Analyzing the costs and benefits of building an ecosystem to provide similar functions, however, required a new mindset and new tools.

To analyze the business decision of choosing between either pipes and tanks or a wetland for water treatment and stormwater management, CCP used a traditional financial model to assess the costs and benefits of pipes and tanks. The benefits of the pipes/tanks were that they eliminated the cost of stormwater discharge. The costs included the tanks, pumps, and pipes from the initial installation; regular maintenance; and stormwater treatment. Ancillary benefits, to meet nonfinancial objectives, did not accrue to this alternative.

To analyze the wetland alternative, CCP engaged with the USBCSD and CfR to test some ecosystem services evaluation tools. These tools provided monetized values for a set of services and identified additional services that met CCP's objectives but were not monetized. The wetland option created both financial and ecosystem services benefits in excess of those accruing to the pipe/tank alternative. CCP used an ecological life-cycle assessment tool to identify these benefits, including the following:

1. enhanced flood prevention, resulting in less stress on the local utility;
2. reduced water usage;
3. reduced nonrenewable energy consumption;
4. reduced greenhouse gas emissions.

While the above benefits provide real value to the company and broader society, in the business context the actual financial impacts of each alternative must be identified and included. Businesses that are not profitable do not survive, and the possible good they produce will be eliminated if they are financially insolvent. So CCP went about analyzing the relative net costs of the two alternatives.

Building the wetland initially cost more than the installation of the pipe/tank alternative. Two major factors were then added to the initial cost: the continuing costs of maintenance and repairs to the water systems and the differential benefits of the two alternatives. On both of these factors the wetland proved to be more financially beneficial to CCP. From an additional cost perspective, the pipe/tank alternative needed periodic maintenance, replacement of components over time, and annual water treatment costs. The wetland, after its initial creation, required minimal care, because it would regenerate itself as a natural system. Likewise, the wetland alternative resulted in benefits that had some real and quantifiable financial impacts that did not result from the pipe/tank alternative. The wetland was estimated to sequester over 3,000 metric tons of CO_2 equivalent of greenhouse gas over 20 years, with potential value under a carbon market system, and would engineer estimated water savings of 1.2 billion gallons over the same 20-year period.[1] CCP computed cost savings and potential benefits due to reduced flood regulation, improved water quality and the resultant reduction in stormwater discharge costs, and carbon emission reductions. Other benefits of the wetland, such as increased biodiversity and improved employee morale, were identified but not quantified.

CCP's analysis ultimately determined that the cost reductions and other benefits due to ecosystem services made the wetland alternative preferable to the pipe/tank alternative. Over a 20-year period, the present value of the wetland alternative was almost 20 percent more positive for CCP than the pipe/tank alternative, an estimated savings of approximately U.S.$200,000. A realistic analysis of the additional opportunities provided by using natural processes to supply needed functions not only revealed social and environmental benefits but also significant savings for CCP. CCP made a sound business decision that reduced overall costs, while creating a range of additional benefits for the natural and social environment. CCP's process of using thoughtful management and collaborative tools to build intermediate and replacement services may well provide a useful model for other businesses looking to improve their ability to address risks and opportunities afforded by ecosystem services. S

Acknowledgments
This case is adapted from information provided by Kieran Sikdar of the U.S. Business Council for Sustainable Development.

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All businesses rely on ecosystem services. Even businesses without obvious inputs from ecosystems, such as financial services, rely on ecosystems for clean air, potable water, and disease control. Similarly, every business affects ecosystem services through its operations—consuming water, emitting exhaust, and occupying space. Most ecosystem services are consumed and degraded outside traditional market systems and are degraded without direct cost to those who are causing the damages (i.e., the effects are externalized). These externalities of business activities have traditionally been ignored unless they were illegal.[31]

Environmental degradation causes direct and indirect impacts on all firms in the long run. As the impacts become more obvious and imminent, smart businesses begin to see ecosystem services as vectors of risks and opportunities. Risks may range from losing market share to more rigorous financing requirements to increasing costs for inputs. Opportunities might include influencing policies to protect ecosystem services on which a business depends, creating products to reduce impacts on ecosystem services, or creating markets to sell the benefits of ecosystem services. Businesses make decisions by identifying and evaluating the risks and opportunities inherent in accepting or initiating actions. Including the risks and opportunities generated through ecosystem services results in valuations that provide better guidance about which alternatives to pursue.

Businesses are beginning to create business-specific metrics for valuing ecosystem services. The World Business Council for Sustainable Development and its collaborators developed a corporate ecosystem services review tool to assess ecosystem services values for individual businesses, including consideration of risks and opportunities.[32,33] A small set of companies are "road testing" the tool. These initial tests provide hope that the economic, social, and ecological values of ecosystem services will become an increasingly important part of business decisions (see Box 2).

Integrated Valuation

Establishing comprehensive values for the full portfolio of ecosystem services that support urbanizing regions is essential to assess tradeoffs between natural, intermediate, and replacement services and between present and future uses. The values should incorporate all stakeholders' benefits from the ecosystem services and an equitable distribution of access and wealth in society. In practice, values used to make decisions about managing services rarely meet these conditions due to partial accounting, incomplete information, and inequitable social conditions. For example, private decisions about the green buildings described in Box 4 generally neglect the full measure of off-site benefits, such as urban heat island effects. Further, due to the public good characteristics of many services, values

Clean Water Services

To cool the Tualatin River naturally, Clean Water Services planted shade trees, shrubs, and native grasses along 35 miles of upstream riverbank.

are not expressed in markets but must be estimated through surveys or inferred by observing effects in related markets. For example, as noted earlier, researchers are estimating the value of urban green spaces by estimating effects on the prices of nearby houses. While they capture an important component, such approaches fall short of an integrated valuation that encompasses all of the ecological, social, and economic costs and benefits of ecosystem services. Evidence shows that "undervalued" services will be neglected, leading to underinvestment and degradation.[34]

Most studies of ecosystem services valuation[35–37] focus principally on economic effects and stop short of a comprehensive valuation. An integrated valuation framework informed by our transdisciplinary approach (described below) would move beyond standard monetary measures to include qualitative and quantitative nonmonetary effects across various social groups and public values[38] as well as ecological effects that cannot be monetized, such as risk of system irreversibility. This integrated valuation approach would thus combine the ecological, social, and economic dimensions of ecosystem services values.

Lessons Learned

The confluence of urbanization pressures and ecological degradation creates linked ecological, social, and economic problems involving complex feedback loops and spatial and temporal diversity. These problems are so complex that any attempted solution leads to new issues because of uncertain and unknown feedback effects, where even the best apparent option will expose further issues requiring attention. Such nonlinear problems require starkly different approaches than those devised by individual scientists working within their disciplinary confines.

Successful management of ecosystem services that support urbanizing regions first requires an explicit focus on problem solving. Implementing this problem-based approach necessitates that transdisciplinary teams work in close collaboration with stakeholders who possess knowledge

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Box 3: Urban Stormwater Management Can Provide Ecosystem Services

Traditional approaches to managing urban stormwater emphasize a rapid redirection of water into underground pipes and away from development. Recent innovations suggest alternative approaches that may reduce cost while improving ecosystem functioning and services in urban areas. Many urban areas in the United States are pursuing strategies for replacing degraded pipes and combined sewer systems with aboveground stormwater facilities, also known as sustainable stormwater systems or rain gardens, that capture and absorb rainfall.

The ecosystem services provided by these facilities can be divided into three general categories: pollution removal, water infiltration, and aesthetics. Urban stormwater runoff contains pollutants, which can affect the quality of surface water, seepage water, and groundwater. Heavy metals—such as lead, zinc, copper, and cadmium—along with polycyclic aromatic hydrocarbons, mineral oil hydrocarbons, and readily soluble salts in runoff are regarded as hazardous to water quality.[1] Recent evidence from a synthesis of 300 studies on pollutant removal suggests that, when carefully designed, these stormwater facilities can improve water quality through direct pollutant removal.[2] Infiltration studies of urban stormwater facilities existed over 30 years ago,[3] but recent years have seen a proliferation of studies on infiltration. The U.S. Environmental Protection Agency conducted an extensive study of stormwater systems and concluded that green infrastructure projects can improve infiltration at localized scales, such as neighborhoods, while reducing flooding frequency across watersheds.[4] In addition to improved pollutant removal, infiltration, and aesthetics, emerging evidence suggests that such facilities also provide other ecosystem services, such as carbon sequestration, habitat provision, and air-quality improvement.[5]

Arguably, no municipality in the United States to date has pursued a more aggressive stormwater campaign than Portland, Oregon. Although a few sustainable stormwater projects started in the mid-1990s, in the past five years Portland has seen a proliferation of projects, ranging from small bioswales to large facilities designed to capture water from adjacent development. Due to the large number of rain gardens in the Portland region, researchers are able to evaluate the ecosystem services emerging from these "replacement" facilities. Specifically, as part of a National Science Foundation Urban Long-Term Research Areas Exploratory project, researchers are beginning to see several trends regarding the ecosystem services provided by these facilities. Although the infiltration and pollutant removal dimensions of the project are currently under way, recent evidence from the cultural aspects of the program reveals two significant trends. First, as facilities increase in density and age, homeowners experience an increase in property value.[6] Second, perceptions of neighborhood conditions, including walkability, crime, and aesthetics, improve within one year of the installation of these facilities.[7,8]

These examples of urban stormwater management are not a panacea, nor are they an appropriate solution for all urban areas. Rather, Portland's example suggests a need for systematic characterization of these facilities and continued monitoring. In addition, earlier research on similar retention/detention systems in the Seattle, Washington, metropolitan area found that, without proper maintenance, such facilities were no longer effective and in fact could degrade ecosystems over time.[9] Accordingly, if sustainable stormwater systems are to be a feasible solution, several questions remain: (1) What role does maintenance of such facilities play in providing ecosystem services? (2) Are there critical thresholds that reduce the ability of these systems to provide ecosystem services? (3) How can public and private governance processes help to ensure that stormwater management provides ecosystem services that are sustainable for the long run and meet social equity criteria? While further research is needed to address these (and other) germane questions, examples such as Portland can help illuminate the opportunities for finding solutions to urban stormwater management challenges.

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and values not yet codified in science. Researchers and stakeholders who are part of this process must be open to ideas that are not part of their standard theory and practice and must be willing to compromise. In essence, the collective team wisdom trumps individual knowledge and perspectives.

Novel solutions to ecosystem services science and management for urbanizing regions cannot be discovered by following standard management practices that neglect the full range of ecosystem services provisioning, maintenance, and restoration. Our natural and social systems have far too much diversity for such a standard approach. Rather, our framework and experience suggest that the chances of achieving effective solutions can be maximized by the following actions:

1. Build a transdisciplinary team of researchers and practitioners who hold scientific and experiential knowledge about key aspects but who also are open to learning from others.
2. Decide a priori on a facilitation or mediation approach to resolve deadlocks, should intractable differences emerge between team members.
3. Involve all relevant stakeholders from the outset in defining the problem, developing a spatially-explicit analytical model, and devising implementation strategies.
4. Favor holistic strategies that address the full continuum of services in coupled human-natural systems, not in each system independently, and approaches that vary over space and time.
5. Apply adaptive management that incorporates the dynamics of both natural and human systems and that actively learns from experiments.

Gerding Edlen

Oregon Health and Science University's Center for Health and Healing is one of the largest LEED Platinum projects in the United States. Sunshades on the side of the building double as solar-power generators.

Scientists and managers trained to follow these transdisciplinary tenets will have a high chance of replicating the successful solutions featured in the case studies in this article.

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Box 4: Green Building: Replacement of Ecosystem Services

During the last decade, one of the most dynamic developments in U.S. urban areas has been the explosive growth of green buildings. Even more startling for an industry historically slow to innovate, the green building market was one of the most resilient parts of the shattered construction market during the recent economic recession. Starting from virtually nothing in the late 1990s, the green building industry now comprises one-quarter of new construction activity and one-third of new nonresidential building, up 50 percent in value from 2008 to 2010.[1] These rapid rates of market penetration signal far-reaching impacts because the building sector has a huge environmental footprint—consuming nearly 40 percent of all energy and raw materials, using nearly 14 percent of all potable water, and generating nearly 50 percent of all greenhouse gas emissions in the United States.[2] The remarkable progress in shrinking the building sector's environmental footprint has been the product of a novel tripartite collaboration between business, nonprofit organizations, and government.[3] The resulting market transformation represents a potentially replicable approach to reducing the burgeoning pressure on ecosystem services in urbanizing regions around the globe. The potential appears real, especially as developing countries such as China and India, where much of the world's new construction and environmental impacts are occurring, have joined the trend.

How do green buildings affect the continuum of ecosystem services? In the initial phase, green buildings have mainly served to reduce the demands on regulating and supporting ecosystem services by decreasing the use of water, energy, land, and raw material (through recycling and reuse). In that sense, the structures deliver replacement services. These result in positive impacts on the quantity and quality of natural ecosystem services, such as those provided by river systems. As green building practices evolve, "living" or "regenerative" buildings are testing whether green buildings can go beyond replacement to produce their own power and grow food products (provisioning services); to capture and recycle all of their water from precipitation; and also to provide some biodiversity habitat, mostly via green roof technologies. All of these effects would further decrease the ecosystem services load of green buildings. The development of these next-generation projects is being led again by the collaboration of business, nonprofit, and government organizations. Finally, green building practices are expanding their geographic scale beyond individual buildings to campuses, "ecodistricts," and neighborhood developments.

One of nation's preeminent green building firms is Gerding Edlen in Portland, Oregon. An early leader, Gerding Edlen has consistently pushed the envelope of green building. These three projects showcase some of their innovations.[4]

1. Brewery Blocks

When Gerding Edlen first viewed the five blocks of a defunct brewery in a neglected area of Portland in 2000, the firm could have easily overlooked the area's potential to become a vibrant neighborhood full of urban sustainability projects, such as green housing units, sustainable retail space, and smart transportation options. Over the next five years, Gerding Edlen constructed a 15-story mixed-use condominium tower and a 242-unit high-rise residential building, significantly increasing housing density and offsetting demands for building and land conversions elsewhere in the metropolitan region. Projectwide sustainability features included energy-efficient appliances, high-efficiency glazing, rainwater harvesting, a chilled water system atop one of the commercial buildings that provides water for air conditioning and heating in all of the Brewery Blocks, and other resource-saving initiatives. Construction activities, including demolition, recycled nearly 94 percent of the waste. The project's holistic approach yielded six LEED-certified buildings (one with a Platinum rating, four Gold, and one Silver), and the principles of preservation and place-making generated many sustainability innovations for urban mixed-use settings, integrating residential, office, and neighborhood communities and including streetcar transportation and shared parking.

2. Oregon Health and Science University

The Center for Health and Healing at the Oregon Health and Science University (OHSU) is one of the largest LEED Platinum projects in the United States and the first medical facility in the world built to this standard. The 16-story, 412,000-square-foot building has eight levels devoted to physician practices, surgery, and imaging and three floors that house a health and wellness center. Four levels are dedicated to education and research activities, including space for a biomedical engineering program. The ground floor houses retail space, including a pharmacy, optical shop, and a café. To obtain LEED's Platinum rating, Gerding Edlen employed a number of innovative sustainability solutions. Sunshades on the side of the building double as solar-power generators, and the building houses the first large-scale, on-site microturbine plant in Oregon, for generating electricity. This helps meet 30 percent of the building's electrical demand and nearly all of its hot water needs, reducing reliance on nonrenewable energy sources. This kind of thinking extended throughout the project, from sourcing local products for construction to recycling more than 90 percent of construction waste. An on-site wastewater treatment plant treats 100 percent of the wastewater, with rainwater and wastewater harvested for toilets and landscaping, all of which reduces potable water use by approximately 56 percent over a similar conventional building and prevents 15,000 gallons a day from reaching the city's overburdened sewer system. Also, the Center for Health and Healing is the first large building in the United States to replace air conditioning with a vastly more efficient system in which chilled water passes through overhead beams and natural convection currents carry cool air down to the occupant zone.

3. Twelve West

Twelve West stands out as one of the first urban buildings in the nation to integrate small-scale wind energy within its 22-story design. Rooftop wind turbines provide enough energy to power the building's elevators. This mixed-use high-rise also makes prominent use of stormwater management, high-efficiency radiant heating and cooling, natural ventilation, and a rich variety of recycled and reclaimed materials. The project incorporates multiple sustainability concepts, including an underfloor air distribution system, passive chilled beams, rainwater recovery, solar collectors for preheating domestic hot water, energy-efficient air handling units, daylight dimming controls, occupancy sensors, and a green roof. The sustainability features incorporated into this building are anticipated to reduce CO_2 emissions by 1,884,000 pounds per year, exceeding the requirements set in the 2030 Climate Challenge issued by Architecture 2030. Simulations predict energy savings of over 45 percent compared to a baseline-code building and a 47 percent reduction in potable water usage. Recovered rain and condensation are used to water the green roof and are used in office toilets. Solar thermal panels heat 24 percent of the hot water used in the building. Low-emissivity glass regulates temperature by allowing 35 percent of visible sunlight to enter the building while reflecting 74 percent of the associated heat. Recycled and sustainable materials were used in finishing the building. Office space and apartments were designed to maximize daylight and indoor air quality (integrating operable windows) to improve comfort.

Important parallels exist between the processes used to design, construct, and operate these green building projects and the approach needed for managing ecosystem services. First, objectives are pursued through interdisciplinary or transdisciplinary approaches. Second, relevant stakeholders are given voice in planning and execution, starting with an inclusive design workshop. Third, the systems under study are viewed as holistic, coupling the human and the natural, rather than as simple combinations of individual components. And finally, green buildings are increasingly being designed to function in ways that mimic biological systems (i.e., using biomimicry principles), which inform the management of ecosystem services as well. S

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