Ecology for a Crowded Planet

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Within the next 50 to 100 years, support and maintenance of an extended human family of 8 to 11 billion people will become difficult at best. Our consumption rates already exceed the supply of many resources crucial to human health, and few places on Earth do not bear the stamp of human impacts (*1*, *2*). Fossil fuel combustion and fertilizer production have doubled the global rate of nitrogen fixation, which has exacerbated ongoing eutrophication while fertilizing remote portions of the planet (*3*). Increases in global commerce have led to the spread of pests and diseases that do great harm because they are divorced from their natural predators and pathogens (*4*).

Studying the few and rapidly shrinking undisturbed ecosystems is important, but now is the time to focus on an ecology for the future. Because our planet will be overpopulated for the foreseeable future and natural resource consumption shows no signs of slowing, human modifications of the environment will only increase. Thus, a research perspective that incorporates human activities as integral components of Earth's ecosystems is needed, as is a focus on a future in which Earth's life support systems are maintained while human needs are met.

Ecological science has been important in improving human life (*5*), and research addressing the sustainability and resilience of socioecological systems has begun (*6*, *7*). Elsewhere, we discuss partnerships and programs that are required (*8*). Here, we recommend a research agenda centered on ecosystem services and the science of ecological restoration and design.

The Science of Ecosystem Services

Natural ecosystems provide great benefits to human societies. Clean drinking water, soil stabilization by plants, buffering of vector-transmitted disease outbreaks, and pollination are ecosystem services that in most cases are irreplaceable, or the technology necessary to replace them is prohibitively expensive. For example, desalination, although often proposed as an alternative to conservation and planned growth in areas with limited fresh water, is more than twice as expensive as most water users are willing to pay (*9*).

Maintenance of ecosystem services will require a considerably better understanding of the natural patterns and processes that sustain them (*10*). Innovative research must be initiated to answer crucial questions. Which ecological services are irreplaceable or too expensive or whose replacement with emerging technology would have undesirable outcomes? What habitats must be protected to ensure that key services are provided? Which agents impoverish ecological services and how can their impacts be mitigated or reversed? How do individual, corporate, and government decisions sustain or degrade ecosystem services? What options can ecologists provide when conservation is not possible?

For some services, substantial knowledge already exists, yet it is neither widely known nor consistently applied. For example, as vegetation is replaced with concrete and rooftops, rainfall that once permeated soils now moves through storm drains or as runoff directly into streams and coastal areas, causing flooding and water pollution. Nevertheless, development typically proceeds without greenways, protected riparian zones, or storm drainage infrastructure necessary for mitigating this degradation. Enhanced public appreciation of ecosystem services would help promote connections between science and management. In many cities in Germany, rooftop gardens and other techniques to decrease the impacts of hard surfaces are gaining broad support.

Without greater public understanding of the links between ecosystems and human welfare, science will be of little use. For example, consensus exists among stakeholders in the Chesapeake Bay watershed in the eastern United States that water quality needs improvement and that restoration of a collapsed fishery, the American oyster, is desirable. Stakeholders value clean water and the oyster fishery for the material, cultural, and spiritual benefits they provide. They are willing to consider upgrading water treatment facilities and replacing native shellfish with a non-native oyster. However, stakeholders need to understand risks associated with introduction of a non-native species, as well as scientific evidence that recovery of shellfish may not be possible without changes in current land-use practices.

Designer ecosystem. In the desert southwest, natural stream flow (**top**) varies but may increase substantially after large summer rainfall events. A common engineering solution has been to convert stream channels to concrete culverts (**middle**). This reduces economic loss from flooding but provides few other ecological, social, or economic benefits. An alternative to concrete is a designer ecosystem, such as Indian Bend Wash in Scottsdale, AZ (**bottom**), in which vegetated pathways and wetlands minimize flood damage, improve water quality, enhance surrounding land values, and create a park-like environment for recreational activities.

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Determining how natural systems provide ecological services entails measuring services and exploring their dynamics at scales that match ecosystem properties. New spatial, analytical, and other quantitative approaches will be needed to understand how ecological responses depend on space and time (*11*). Interdisciplinary frameworks that incorporate multivariate causality, nonlinear feedback, and individual-based decision-making are critical to research that explicitly incorporates humans in ecosystems.

Designed Ecological Solutions

Restoration of ecological systems has already become a booming business; billions of dollars are spent annually to restore polluted waterways and to revegetate lands that have been degraded, fragmented, or paved over (see the figure on page 1251). However, "designing" ecosystems goes beyond restoring a system to a past state, which may or may not be possible. It suggests creating a well-functioning community of organisms that optimizes the ecological services available from coupled natural-human ecosystems.

Designed ecosystems span the range from manipulation of slightly altered systems to ones that are created de novo where other alternatives are not possible. The latter are synthetic systems consciously created to achieve ecological, social, and/or economic goals. For example, in the Netherlands, fresh water deep under coastal dunes has been extracted for drinking by highly populated cities for many years. To alleviate overextraction of this groundwater, artificial lakes were built and filled with river water that was piped into the dune subsoil. Although not free of all environmental problems, such ecological solutions have great potential (*12*).

Such systems are not necessarily based on historical views of ecological structure and function at a given location as is the case for restored ecosystems. Instead, systems may be designed to mitigate unfavorable conditions by means of a blend of technological innovations, coupled with novel mixtures of native species, that favor specific ecosystem functions. Such patently artificial systems may be anathema to many conservationists and ecologists, and we are not recommending them as a substitute for natural systems, but they will be part of a future sustainable world.

To build the science of ecological design to meet rising needs, researchers must work with agencies, businesses, and other groups that are implementing restoration to help develop guiding principles for answering questions such as: How much intervention is necessary to sustain or restore a site to an acceptable baseline? When are restoration efforts constrained or futile?

Ecological design approaches will need to combine ecological principles with ideas or technology from other disciplines. For example, wastewater engineers and ecologists share strong scientific interests yet rarely enter into dialogue. Engineering process design could benefit from new molecular-based advances in our understanding of nutrient transformations, and ecologists could benefit by using engineered biosystems as research tools (*13*).

There is a particularly urgent need for research to design ecological solutions for problems related to three issues: urbanization, the degradation of fresh water, and the movement of materials between ecosystems. Shortages of clean surface water, overextraction of groundwater, and long-distance transfers of water are increasing at alarming rates (*9*). Research priorities must include an increased understanding of how to restore the natural services provided by waterways, to restore or design ways to naturalize flow in regulated rivers, and to slow the high extinction rates of freshwater species. Upland watershed use is critical in determining coastal water quality and health of coastal fisheries. Yet basic research on how best to restore upland waterways and to design ecological solutions to minimize downstream and coastal impacts has suffered from far too little interaction among natural resource managers, regulatory agencies, and basic researchers.

By 2030, more than half of the world's population will be living in urban areas, most of them near the coast. Urbanization, even in places where it is not the dominant land use, will have major influences on regional and global environments (*14*). Solutions must be designed to mitigate impacts arising from the enhanced flux of people, materials, and energy to and from urban centers and to the coast. Insight into biodiversity and evolutionary processes in cities is needed to restore or augment ecological services. Solutions designed to moderate the dangerous interactive effects of urbanization, climate, and human health are critical. For example, fires and floods have important roles in restoration and maintenance of the natural services upon which humans depend. Yet near areas with large human populations, these natural disturbances can destroy lives and property. Thus, there is a tension between human needs and ecosystem needs that socio-ecological research must address.

Changes in ecological commerce, the movement of living and nonliving materials that influence ecosystems and ecological processes, are not unique to urban areas. Undesirable commerce includes the global spread of infectious diseases and invasive species that stems from increased travel and the deposition of NO_x and SO_2 due to human activities. Examples of desirable commerce include annual migrations and floods that, when halted, cause negative impacts on fisheries, agriculture, and biotic diversity (*15*). We need to identify ecological commerce routes and the impacts that changes in the routes or rate of material exchange will have; to consider the potential to use ecological commerce in designing solutions for environmental problems; and to develop principles that can be used to diminish negative impacts.

Pragmatic Ecological Science

Our future environment will largely consist of human-influenced ecosystems, managed to varying degrees, in which the natural services that humans depend on will be harder and harder to maintain. The role of science in a more sustainable future must involve an improved understanding of how to design ecological solutions, not only through conservation and restoration, but also by purposeful invention of ecological systems to provide vital services. Shifting from a focus primarily on historical, undisturbed ecosystems to a perspective that acknowledges humans as components of ecosystems, together with new research on ecosystem services and ecological design, will lay the groundwork for sustaining the quality and diversity of life on Earth.

References and Notes

1. J. Lubchenco *et al.*, *Ecology* **72**, 371 (1991).
2. A. J. McMichael, C. D. Butler, C. Folke, *Science* **302**, 1919 (2003).
3. P. M. Vitousek *et al.*, *Ecol. Appl.* **7**, 737 (1997).
4. W. F. Font, *Bioscience* **53**, 1061 (2003).
5. Examples of the role of ecological science in solving critical problems are available as supporting material on *Science* Online.
6. Millennium Ecosystem Assessment, *Ecosystems and Human Well-Being* (Island, Washington, DC, 2003).
7. L. H. Gunderson, L. Pritchard, *Resilience and the Behavior of Large-Scale Systems* (Island, Washington, DC, 2002).
8. M. A. Palmer *et al.*, *Ecological Science and Sustainability for a Crowded Planet: 21st Century Vision and Action Plan for the Ecological Society of America* (2004); available at http://esa.org/ecovisions/.
9. P. H. Gleick, *The World's Water, the Biennial Report on Freshwater Resources* (Island, Washington, DC, 2000).
10. G. C. Daily, Ed., *Nature's Services: Societal Dependence on Natural Ecosystems* (Island, Washington, DC, 1997).
11. Understanding how naturally occurring and introduced microorganisms influence marine ecosystems can be enhanced by using mobile sensors that can follow, identify, and investigate the behavior of microbes in situ in real time; see http://deerhound.ats.ucla.edu:7777/portal/page?_pageid=54,48720,54_48721&_dad=portal&_schema=PORTAL.
12. M. L. Martinez, N. Psuty, Eds., *Coastal Dunes: Ecology and Conservation* (Ecological Studies Series, 171. Springer-Verlag 2004).
13. D. W. Graham, V. H. Smith, *Front. Ecol. Environ.* **2**, 199 (2004).
14. M. Alberti *et al.*, *Bioscience* **53**, 1169 (2003).
15. S. R. Palumbi, *Proc. Natl. Acad. Sci. U.S.A.* **100**, 1197 (2003).
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Supporting Online Material

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