Ecology in Times of Scarcity

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In an energy-scarce future, ecosystem services will become more important in supporting the human economy. The primary role of ecology will be the sustainable management of ecosystems. Energy scarcity will affect ecology in a number of ways. Ecology will become more expensive, which will be justified by its help in solving societal problems, especially in maintaining ecosystem services. Applied research on highly productive ecosystems, including agroecosystems, will dominate ecology. Ecology may become less collegial and more competitive. Biodiversity preservation will be closely tied to preservation of productive ecosystems and provision of high ecosystem services. Restoration and management of rich natural ecosystems will be as important as protection of existing wild areas. Energy-intensive micromanagement of ecosystems will become less feasible. Ecotechnology and, more specifically, ecological engineering and self-design are appropriate bases for sustainable ecosystem management. We use the Mississippi River basin as a case study for ecology in times of scarcity.

Keywords: Mississippi River basin, ecosystem management, sustainability, peak oil, energy scarcity

The functioning of natural ecosystems and the health of the human economy have been intrinsically linked since our species evolved. Human society has depended on solar-based ecosystems for all of its existence. With the development of the industrial revolution, massive increases in fossil-fuel use spurred dramatic growth of the human population and the economy (Hall et al. 2003, LeClerc and Hall 2007) and widespread environmental degradation (MEA 2005). Although natural ecosystem services are still absolutely necessary for human existence (Costanza et al. 1997, De Groot et al. 2002), fossil-fuel use has distanced most humans from direct contact with nature and obscured the important role of the natural world.

Over the past several decades, it has become increasingly clear that the trajectory of rapid growth of the past two to three centuries—what many refer to as progress—cannot continue much longer, and that we are on the threshold, or tipping point, of a new age (Odum and Odum 2001, Wackernagel et al. 2002, Meadows et al. 2004). This situation stems primarily from the growing scarcity of the cheap energy that fueled the industrial and modern agricultural revolutions and the degradation of ecosystems and their services (Hall et al. 2003, Heinberg 2003).

In this article, we address these issues by first discussing the role of the biosphere and the increasing industrial use of energy in the human economy. We then review several lines of evidence for a coming transition, focusing especially on oil because of its central role in the industrial economy. We conclude by discussing how these trends will affect the science of ecology and, more important, what roles ecologists will need to play in the coming societal transition. Our thesis is that major forces in coming decades will drastically affect both the science of ecology and the role of ecology and natural systems in society. These forces include energy scarcity, climate change, resource depletion, and continued population growth. The most important roles for ecologists in this time of transition are to quantify connections between the biosphere and society and to help define sustainable future paths as natural energy flows again assume a greater importance. We define ecology broadly as the study of the functioning of the biosphere, and ecologists as those who seek to understand this functioning.

The importance of natural ecosystems to the human economy

In the preindustrial world, solar-powered ecosystems supported the human economy (figure 1). This was recognized by the earliest formal school of economics, the French physiocrats, who focused on land as the source of all wealth. Practically all materials used in preindustrial societies—including food, fiber, and fuel, as well as ecosystem services such as climate regulation, clean freshwater, fertile soils, wildlife, and assimilation of wastes—were dependent on solar-driven natural systems and agroecosystems. There was low use of nonrenewable materials, such as metals and clay. For millennia, energy flow in the human economy was a small part of that

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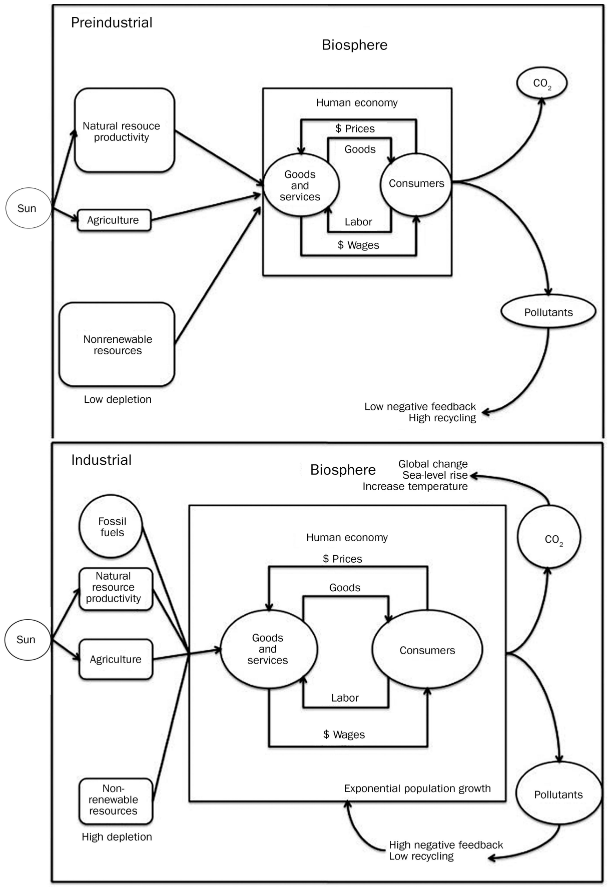

Figure 1. The economic system and the biosphere. The economic system is a subset of the biosphere and is absolutely dependent for its functioning on biosphere sources and sinks. The economic system has grown dramatically over the last two centuries. An important role of ecologists is to develop an understanding of how to sustainably manage the biosphere to maintain its support for the economic system.

of the overall biosphere. There was low generation of pollutants and a high degree of recycling, and humans had little impact on global energy and material cycles. Early primitive farmers may have affected the climate through changes in land use (Muir 2008), but this did not have an impact on greenhouse gases. Until about three centuries ago, the regenerative and assimilative capacities of the ecosphere supported a human society that lived sustainably on Earth.

This changed dramatically about two centuries ago with the advent of the industrial revolution, and the change accelerated rapidly in the 20th century (figure 1). The human population grew from two billion in 1800 to almost seven billion in 2000. The use of fossil fuels—first coal, then oil and natural gas—burgeoned, and the great reserves of these fuels began to be drawn down, until almost half of recoverable conventional oil reserves had been used, mostly in recent decades (Campbell and Laherrère 1998, Deffeyes 2001, Meng and Bentley 2008). A new worldview of human society and its place in the natural world arose. This new worldview, neoclassical economics, focused more directly on the immediate human economy as represented by transactions in the marketplace and far less on the natural world than had earlier physiocrats and classical economists such as Adam Smith and David Ricardo. But the value of ecosystem services remained very high even as economics began to value those services less (Costanza et al. 1997, De Groot et al. 2002). These authors and others have valued the world's ecosystem services at trillions of dollars (bee pollination in the United States alone is worth $16 billion annually; Pimentel et al. 1997). The societal disconnect from the natural world was so large that by about 1960 the old production functions that were based on land, labor, and capital were replaced with new ones that did not even consider land—let alone energy, water, or other critical resources (Solow 1956). This new technological and philosophical worldview contrasted sharply with traditional beliefs about the place of humans in the natural world (e.g., Moyers and Campbell 1988).

The evolution of human social organization and energy use

The rapidity of change in the last several centuries becomes evident if we consider time on the scale of human generations. Our species, *Homo sapiens,* is about 200,000 years old. But a humanlike existence is much older, and many of the characteristics we associate with the human lifestyle evolved before *Homo sapiens* became a distinct species. If we consider the human lifestyle to include living in bands of hunter-gatherers and using fire and tools, cognition (meaning, apprehension, perception), social behavior that is not purely instinctive, and walking upright, then humanlike creatures have been in existence for about 1 million to 2 million years, or about 50,000 to 100,000 generations (assuming 20 years per generation). A time span of two million years is enough time for species evolution to occur, and indeed it did. Our distant ancestors went through a series of species before evolving into modern *Homo sapiens.*

And as our species evolved, so did the human lifestyle. Language began about 50,000 years ago (2500 generations), agriculture about 10,000 years ago (500 generations), and civilizations first appeared about 5000 years (250 generations) ago. Most initial civilizations began in resource-rich coastal zones and lower river valleys after the sea level stabilized, partially as a result of the subsidy of abundant resources and energy in these areas (Day et al. 2007a). The industrial revolution and intensive fossil-fuel use began about 200 years (10 generations) and a century (5 generations) ago, respectively. Intensive fossil-fuel use represents only 0.1% of the age of our species, and about 0.01% of the time over which the human lifestyle evolved. The "information age" has existed for only about two generations. But "information age" is a misnomer, as we live in a petroleum age, in which intensive energy use supported the development of most technologies, including information technology. Survival values that developed over human evolution (i.e., 2 million years) had time to make it into our DNA. But the current reigning intellectual and social worldviews, which are only a century or two old, mostly ignore these older values. Our main point is that these views that currently dominate human thinking about growth, our place in the world, and the future are extremely recent and run mostly counter to long-term sustainability. A very important societal role of ecology and ecologists in the 21st century will be to help define the environmental and ecological realities and values that foster sustainability.

Evidence for a coming transition

Humans have used much of Earth's resources, and the resulting environmental impacts are global. There is strong evidence that society is approaching a transition and the patterns of the 20th-century consumption and growth cannot be sustained. The interconnected forces leading to this transition include energy scarcity, human impacts on the biosphere, climate change, and population growth.

Coming energy scarcity

Compelling evidence suggests that the world's conventional oil production has already peaked, and that total oil production (all liquids) will peak within a decade (figure 2), which implies that demand will consistently exceed supply and that energy costs will increase significantly (Campbell and Laherrère 1998, Deffeyes 2001, Hall et. al. 2003, ASPO 2008, Meng and Bentley 2008). Projections of peak world oil production are generally based on the approach developed by M. King Hubbert, who became well known because he predicted in 1956 that US oil production would peak in the early 1970s, and it did. Hubbert also predicted that world oil production would peak early in the 21st century (Hubbert 1962, see also Deffeyes 2001). The Hubbert approach is based on the concept that oil discoveries in an area generally precede peak production by 30 to 40 years. Oil discovery in the United States peaked about 1940, and production about 30 years later. World oil discoveries peaked by 1970 and have been falling since; recent discovery success has been very low, despite increased drilling efforts (Campbell and Laherrère 1998, ASPO 2008), and most estimates since 1965 of ultimately recoverable conventional oil run to about two trillion barrels (Hall et al. 2003). Global production increased exponentially until about 1970, but the rate of increase has declined since. Production is now two to three times the discovery rate, and current production is mostly from reservoirs discovered 30 to 40 years ago. Four hundred or so giant and supergiant oil fields provide roughly 80% of the world's petroleum (Skrebowski 2004). Of these, roughly one-quarter are declining in production at an average rate of at least 4% annually. World oil demand is increasing, especially in China and India. For the past few years, all drilling globally did not find enough oil even to pay for the drilling, which implies that we may be approaching the end of a positive return on energy investment for searching for new oil (e.g., Hall and Cleveland 1981, Hall et al. 2008).

An important factor affecting consideration of energy use is the energy return on investment (EROI). The EROI is the ratio of the energy that is produced to all the energy used to discover and produce that energy. The EROI of US petroleum declined from roughly 100 to 1 in 1930, to 30 to 1 in 1970, to 11 to 18 to 1 in 2000 (Hall and Cleveland 1981, Cleveland et al. 1984, Cleveland 2005). The EROI and potential supplies of foreseeable liquid alternatives to oil, such as oil shales, tar sand, and most biofuels, are mostly very low, generally less than 5 to 1 (Hall et al. 2008), such that it is very difficult to conceive of any substitute on the scale needed and within the time when oil shortages are likely to affect society dramatically (Hall et al. 2008).

Renewable fuels will clearly play a role in providing energy in the future, but there is simply no mix of renewables that can provide high EROI energy at current levels of use in time to offset the decline in oil discovery and production (Heinberg 2003, Hirsch et al. 2005). The thinking about the potential for renewables to replace ethanol, for example, is sloppy. There is considerable support for corn ethanol production (Shapouri et al. 2004), but all the green plants in the United States capture only about 0.1% of solar energy, or about 32 quads (33.8 exajoules). This includes all agriculture, forests, grasslands, and other ecosystems. The United States now consumes a little more than 100 quads of fossil energy annually (USCB 2007). A US federal government proposal to produce 36 billion gallons of ethanol per year would require 80% of net primary production of the 48 conterminous states (Pimentel et al. 2008), assuming 0.1% efficiency. Thus,

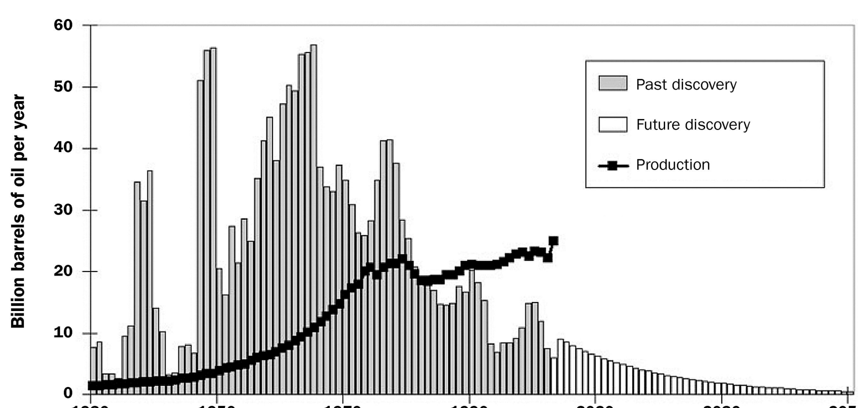

Figure 2. Worldwide oil discovery and consumption from 1930 until the present, and projected future discoveries. Most major discoveries were made before 1980. World consumption is currently four to five barrels for each barrel discovered with most production coming from fields discovered three to four decades ago. Source: Printed with permission from the Association for the Study of Peak Oil (ASPO 2008).

ethanol and other biofuels will never make the United States or Europe oil independent. The 5 billion gallons of ethanol produced last year make up less than 1% of total annual gross US oil use and considerably less than if the net energy of ethanol is considered. It is questionable whether the EROI for ethanol from corn is greater than one. Pimentel and colleagues (2008) estimate that it takes more than 1.4 gallons of fossil-fuel kilocalories to produce 1 gallon of ethanol kilocalories using corn, and 1.7 gallons of fossil energy kilocalories to produce 1 gallon of ethanol kilocalories using cellulose (although some estimates are somewhat higher; Farrell et al. 2006).

Many people hold out the promise that innovative technology will find oil indefinitely into the future (e.g., Lynch 2002). We agree that modern technical innovations can make a difference in the degree to which we find oil in the future. But there is another side of the equation, one that is too often forgotten by those who enthuse over technology. Humans have always been clever, and they have been scouring the earth for oil for a century and a half. The apparent peak in oil production and the declining EROI indicates that in this case at least, depletion is trumping technological advances. The present financial meltdown is a two-edged sword with respect to oil availability. It certainly has and will most likely continue to drive down prices as demand drops, but the crisis will most likely also shut off a great deal of development of existing and potential oil fields, as capital has become very scarce and the low price of oil makes more projects uneconomic. In summary, the evidence suggests that oil will become increasingly scarce and expensive, and no replacement can be supplied at a level that will meet the projected future demand.

Human impact on the biosphere

During the 20th century, for the first time in history, humans began affecting global cycles of material and energy and biodiversity, although "wild" populations on both land and water are heavily affected by the last 10,000 years of human impacts (Pitcher 2001). Humans dominate approximately two-thirds of the land area of Earth (Vitousek et al. 1997) and divert, directly or indirectly, from 40% (Vitousek et al. 1986; but see Haberl et al. 2002) to 50% (Pimentel 2001) of the earth's photosynthate to their own ends. Many fish stocks are overfished and are near collapse (Pauly et al. 1998). Humans increased reactive nitrogen production, much of which becomes biologically available nitrogen, by over an order of magnitude from 1860 to 2000 (15 to 165 teragrams per year; Vitousek et al. 1997, Galloway et al. 2003). Much of this excessive nitrogen eventually is transported as nitrate-nitrogen to rivers and streams, leading to eutrophication and episodic and persistent hypoxia (dissolved oxygen < 2 milligrams per liter) in coastal waters worldwide (Nixon et al. 1996, NRC 2000). An estimated 50,000 species of plants, animals, and microbes have been introduced into the United States since Columbus discovered America. Several of these species, especially our crops and livestock, are valuable introductions. However, many of these invasive species are serious pests, causing an estimated $120 billion in damage and control costs each year (Pimentel et al. 2005). Invasive species also cause an estimated 40% of all species extinctions in the United States (Pimentel et al. 2005). The Millennium Ecosystem Assessment summarized these global impacts (MEA 2005). The ecological footprint of humans has surpassed the carrying capacity of the biosphere (Wackernagel et al. 2002). These forces will interact with energy availability to render further growth more difficult and will also make sustainable management of ecosystems more difficult.

Global climate change

There is a broad consensus in the scientific community, although not without debate, that human activity is affecting global climate (IPCC 2007). Climate change will significantly affect many of the world's ecosystems, including agroecosystems. Global climate change is predicted to affect temperature; the amount, distribution, and seasonality of rainfall; sea-level rise; and the intensity and frequency of strong storms. The Intergovernmental Panel on Climate Change (IPCC) predicts that global temperatures will rise by 1 to 5 degrees Celsius in the 21st century, directly affecting biota. In general, precipitation is predicted to increase in the intertropical zone (about 10 degrees north and south of the equator) and at high latitudes (above about 45 degrees) and to decrease in intermediate latitudes (IPCC 2007). Eustatic sea-level rise was about 15 centimeters (cm) (1.5 millimeters [mm] per year) during the 20th century, and the IPCC predicts a rise in the 21st century of about 40 cm, although some estimates are more than twice as high (Pfeffer et al. 2008). Recent measurements indicate that sea-level rise is now about 3 mm per year, or 75% of the average rate predicted for this century by the IPCC. Although some of these predictions are uncertain, the precautionary principle suggests that management plans for ecosystems should take climate change into consideration. There is also growing evidence that human activities may have the potential to push components of the earth system past critical states into qualitatively different modes of operation (tipping points), implying large-scale impacts on human and ecological systems (Day et al. 2008, Lenton et al. 2008). For example, as the earth warms, the vast peatland wetlands in North America and Eurasia may dry and oxidize to carbon dioxide and methane, exacerbating the climate-shift problem (Mitsch and Gosselink 2007).

World population

The current world population of 6.7 billion doubled during the last 50 years. Based on its present yearly growth rate of 1.2% per year, world population would double to more than 13 billion within 58 years (PRB 2007). Many countries and large world regions are experiencing rapidly expanding human populations. For example, China's current large population of 1.4 billion is still growing at an annual rate of 0.5%, despite the governmental policy of permitting only one child per couple (PRB 2007). Recognizing its serious overpopulation problem, China has passed legislation that strengthens its one-child-per-couple policy. However, the Chinese population, with its young age structure, will continue to increase for another 50 years even if couples have no more than one child. India, with 1.1 billion people living on approximately one-third of the land of either the United States or China, has a current population growth rate of 1.6%, which translates to a doubling time of 44 years (PRB 2007). Together, the populations of China and India constitute more than one-third of the total world population. However, given the steady per-capita decline of virtually all vital natural resources, especially oil, we believe that these projections of population growth are unlikely to be fulfilled; nonetheless, the pressure on natural resources will be very strong.

Ecology and ecologists in the new world order: What will "the end of cheap oil" mean?

In an energy-scarce future, services from natural ecosystems will assume relatively greater importance in supporting the human economy. What role will ecology and ecologists play in helping society adjust in the 21st century? We believe the primary role will be to help elucidate how to sustainably manage ecosystems without causing their deterioration and destruction. What ecologists, who are involved in protection, ecosystem management, and research, do will be profoundly affected by the coming end of cheap oil, both in how we carry out studies and in what we study. Unfortunately, ecologists are generally not trained or inclined to think about oil or broader societal issues, even though these issues will greatly affect ecology in this century. Below, we list several ways in which ecology will probably be affected in coming decades.

Most scientific research is expensive in terms of dollars and thus in terms of energy. One of the main ways in which ecologists will feel the effects of oil shortages will be as everyone does: by enormous inflation in the cost of doing business—inflation-corrected financial resources will be worth less than current resources. It is common for ecologists to have far-flung research programs, but in the future, research in specific areas will most likely be performed by local scientists. Trips to distant scientific meetings by a professor and several students may become prohibitively expensive. On average, for each dollar spent today, the energy equivalent of about a cup of oil is used (Hall and Day 2009). A trip to a scientific meeting that costs $1500 consumes nearly two barrels of oil. If, over the next decade or so, the cost of oil increases by a factor of 2 or 3, then it is likely that only the professor will go to the meeting. If it increases by a factor of 10, then there will most likely be no meeting, at least in the sense we now think of meetings; electronic conferencing will probably become more common. Likewise, a large project funded by the National Science Foundation (NSF) can cost $1 million and consume the equivalent of about 1100 barrels of oil. In the future, the same amount of research done in the same way will cost significantly more. The implication is that ecologists, and scientists in general, will have to become much more efficient and inventive in their work.

Another way that scarcity will affect ecology is that societal priorities are likely to shift. Scientific research is supported because society, in one manner or another, deems it beneficial. In a time of limited resources, society will look much more carefully at how resources, especially public resources, are allocated. More than ever before, we believe science will be justified and supported on the basis of the perception of how it is helping solve societal problems. In coming decades, these problems will increasingly be related to energy and other resource scarcity and the impacts of climate change. Ecologists and ecology will play a critical role because the importance of natural ecosystems to the human economy will become much more obvious. Sustainable and efficient management and use of both natural and managed ecosystems will become key to maintaining human welfare, and a primary role of ecologists will be to help define how to do this. Because much of society is now unaware of the value of natural ecosystems to human welfare, ecologists will also have to help educate the public on this issue. And they will have to do all of this with fewer resources.

Most scientists, including the authors of this article, have encountered the dichotomy between basic and applied science. Basic science has often been considered intellectually superior and more elegant than applied science. And much NSF funding, and other country-specific national funding for biological sciences, has been for basic science. In coming decades, information will be required to preserve the functioning of ecosystems and the services they provide. Applied science will very likely become the dominant form of research, and scientists will have to clearly justify their research in terms of societal good. The dichotomy between basic and applied science is a false one; the important dichotomy is between science that is excellent and that which is less so. In coming decades, society will need the very best science, whether basic or applied, to help solve problems associated with looming resource scarcities.

Most ecological science has been carried out in an open and collegial manner. This could change in a time of energy and resource scarcity. A close colleague from a developing country described the allocation of scarce resources to support scientific research as "the land of the limited good." Because resources to support science are so much more limited in developing countries, competition for these resources is intense. One of the ways this competition works is that groups form to garner resources and to actively exclude other individuals or groups. This balkanization often does not result in the most talented people receiving support or in scientific problems being efficiently addressed, because the success of the group, not necessarily support of the brightest scientists, becomes paramount. Will science in general move from an open and cooperative effort to one characterized by battles over resources and attempts to exclude others? We do not mean that groups of scientists working together are unnecessary for solving the problems we are discussing. To the contrary, groups of bright, creative, collaborative, socially aware scientists will have to come together to solve these problems. Groups are not the problem; the problem is the culture of competition taken to the extreme.

Rich, productive ecosystems with high provision of ecosystem services (Costanza et al. 1997) will be relatively more important in supporting the human economy as fossil fuels become scarcer. These ecosystems include coastal areas with estuaries, reefs, deltas, and intertidal wetlands; rich, alluvial river-valley floodplains and wetlands; productive forests and rain-fed grasslands. These areas are subsidized by high natural energies such as rainfall, rivers, and tides. It is not surprising that the first civilizations and most large cities in the preindustrial world were in areas with rich natural resources, such as the coastal zone or along major rivers (e.g., Day et al. 2007a).

As productive ecosystems, including agroecosystems (e.g., Boody et al. 2005), become more important in supporting the human economy, these areas should receive more attention from ecologists. More food, fuel, and fiber will have to be coaxed from nature while high ecosystem values and services are sustained. But political power is not necessarily concentrated in areas of high ecosystem services. Will politically powerful but highly unsustainable southern California, with its relatively low level of ecosystem services, support the spending of resources in places such as the lower Mississippi floodplain and delta, which are politically weak but have a very high level of ecosystem services? The same argument can be made for resource-rich areas in other countries, such as the Usumacinta and Ebro deltas in Mexico and Spain.

Loss of productivity is important because it is related, at least partially, to ecosystem services. The conversion of natural landscapes to other uses and the degradation of natural landscapes have caused a great loss of ecosystem productivity and related service provision. Both of these processes have affected the natural ecosystems of high productivity, such as river valleys and floodplains, wetlands, and deltas, to a greater extent than they have other areas (Downing et al. 1999). The degradation of productive ecosystems leads both to a reduction in biodiversity and to a loss of ecosystem services. As a result of such changes, environmental impacts include more flooding, loss of biodiversity and natural habitat, poorer water quality, and threats to human health. The conditions in the Mississippi basin described below are symptomatic of such conditions worldwide.

Much conservation effort over the past century has been directed toward preservation of biodiversity and natural habitats in areas such as national parks and wilderness zones. Much less attention, however, has been devoted to the loss of ecosystems with high primary production but low biodiversity, even though many of such ecosystems are intensively used. We believe that in this century, more emphasis will have to be placed on these highly productive systems. There is a growing realization that efforts to protect biodiversity for its own sake have not been particularly successful. In coming decades, biodiversity conservation must be tied to the preservation of productive natural ecosystems, and it must be shown that preserving biodiversity complements the provision of high ecosystem services and helps meet human needs (Kareiva and Marvier 2007).

The Wildlands Project (*www.wildlandsproject.org/cms/page 1090.cfm*), which focuses on conservation of natural areas in North America, is one example of the effort to protect natural areas and biodiversity (figure 3). The goal of the Wildlands Project is to protect and enhance existing wild areas and provide corridors. The project area includes broad swaths of land across northern Canada, down the crest of the Rocky Mountains from Alaska through Central America, along the coastal mountains of the West Coast, and along the Appalachian Mountains from Canada to the southeastern United States. What is most striking is what is not included: all coastal zones are excluded, as well as almost the entire Mississippi River basin.

We realize that the Wildlands Project has specific goals, and we certainly support such efforts. Our concern is that plans of similar magnitude are not in place to protect rich, productive ecosystems with high ecosystem service provision, such as river valleys and coastal areas. One reason that most of the lands of the Wildlands Project are still relatively wild is that they were unsuitable for extensive agriculture. Projects of equal vision and magnitude are needed to restore ecosystems and their services in rich areas that have been intensively used. These include alluvial valleys, coastal zones, tropical forests, and agricultural areas. It is interesting that the Mississippi delta and other comparable areas, which still retain a largely wild character, were excluded by the Wildlands Project.

We believe that in coming decades the restoration and sustainable management of rich natural ecosystems will be equally as important as the protection of existing wild areas. It will be a different kind of conservation because restored ecosystems will exist in a mosaic of intensively used areas, such as agroecosystems.

Natural resource management sometimes tends to be energy intensive. In the future, such energy-intensive management will become less feasible because energy and resources will be scarce. Ecosystem management will have to include a large element of letting nature take its course, or self-design. The evolving Everglades restoration plan has elements that may not be possible to continue in the future (Sklar et al. 2005), such as pumping vast quantities of water. Future energy costs will limit pumping, and gravity and tides will have to do more of the work of moving water.

Restoration of natural ecosystems within a mosaic of intensively used landscapes will enhance biodiversity, and productivity and diversity may be related for individual systems (Tilman et al. 1997, Flombaum and Sala 2008). The relationship between productivity and biodiversity doesn't seem to be global, however. Ecosystems with high productivity can be highly diverse (tropical rainforests and coral reefs) or have low diversity (salt marshes, mangroves, freshwater marshes in general, sugarcane fields), but it is clear that intelligent restoration of productive natural habitats will often result in enhanced productivity and biodiversity.

Figure 3. Map of megalinkage areas proposed by the Wildlands Project for wildlands conservation planning. No program of comparable scale exists for highly productive natural and managed ecosystems such as coastal zones and the Mississippi alluvial valley and delta. An important role for ecologists in the 21st century is to develop such programs. Source: Printed with permission from the Wildands Project.

A main goal for ecology in coming decades will be to provide information on the restoration of different kinds of habitats. How much area of different habitats should be restored and how should they fit into the landscape? We will not be able to control to a great extent what species will exist in these different habitats; for the most part, we will have to let nature decide. In the next section, we present a conceptual framework for ecology in times of scarcity, and we use the Mississippi basin as an example.

There is, and has been for decades, an antagonism between environmental protection and conservation and much of the business community. It has been argued that environmental protection and conservation hurt the economy. We know now that this is not true, that a good environment is good for the economy (Meyer 1992, Templet 1995). An important role for ecologists in the coming decades will be to show the economic importance, both direct and indirect, of ecosystem services.

From a broader perspective, a major impediment to convincing society that management for ecosystem sustainability is important to the human economy is the dominance of neoclassical economics (NCE). NCE has been extensively criticized from environmental and logical points of view (e.g., Daly 1991, Hall et al. 2001, LeClerc and Hall 2007). We believe that NCE has limited ability to effectively address issues such as climate change or loss of productivity and biodiversity, and is largely disconnected from the biophysical reality upon which economics should be based. Rather than being on the margins of the economic system, sustaining rich ecosystems and biodiversity will become central to the health of the economy. If we don't include ecological considerations in future societal decisions, the current credit crunch and other factors may result in less funding for science and a shift away from sustainable management. The global market may degrade many natural resources and make sustainable management more difficult. Or, to paraphrase Iago in *Othello*, "O, beware, my Lord, of globalization! 'Tis a red-toothed monster, which doth mock the meat it feeds on."

The impending end of cheap oil has enormous implications for many of the things that ecologists do. But most ecologists and economists don't discuss these issues, because over the last few decades of energy abundance, the concept of limits has disappeared from our economic thinking. In addition, because limits are intrinsic to ecology (i.e., Scheiner and Willig 2008), there will certainly be conflicts with NCE's tenets of infinite substitutability and the lack of absolute scarcity.

Conceptual basis for sustainable ecosystem management in a resource-scarce, variable world

The sustainable use of ecosystems by humans involves an understanding of how these ecosystems contribute in the broadest sense to human welfare, and how they work in the broadest and most fundamental way. It also involves an understanding of the critical management requirements for maintaining sustainability in a time of increasing resource scarcity and environmental variability.

In a time of resource scarcity, especially energy, we suggest that ecological engineering (sometimes referred to as ecotechnology), including agroecology, is an appropriate basis for sustainable ecosystem management. Probably one of the most important shifts is for ecology to become more prescriptive and less descriptive, mostly through the growth of the ecological fields of ecological engineering and ecosystem restoration (Kangas 2004, Mitsch and Jørgensen 2004, Palmer et al. 2004). Ecologists have a rich history of describing ecosystems and their functions but are less well trained in solving ecological problems. These new fields relate to solving ecological problems, borrowing approaches from engineering and landscape architecture. There are many active efforts in ecological engineering around the world, defined as "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch and

Jørgensen 2004). The related field of restoration ecology, defined as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER 2004), is a subset of ecological engineering. Ecological engineering combines basic and applied science for the restoration, design, construction, and sustainable use of aquatic and terrestrial ecosystems. Because it uses mainly natural energies, it is very energy efficient. The primary tools are self-designing ecosystems (nature chooses the species from countless possibilities, with humans involved sometimes in species introduction; Mitsch and Jørgensen 2004), and the components are mostly biological species and processes. Ecological engineering is very different from environmental engineering, which is more involved with pollution control, such as conventional sewage treatment and air pollution control. The goals of ecological engineering are (a) the restoration of ecosystems that have been substantially disturbed by humans, and (b) the development of new sustainable ecosystems that have both human and ecological value (Mitsch and Jørgensen 2004).

If done properly, ecological engineering should result in solving environmental problems and resource depletion with a maximum use of natural energy and a reduction in the use of fossil energy. In times of energy shortage, these ecological solutions will be selected.

Ecological engineering and ecosystem restoration are intertwined (Mitsch and Jørgensen 2004). Ecological engineering is an amalgam of several fields dealing with ecosystem restoration and creation. Restoration ecology has many features in common with ecological engineering. In fact, Bradshaw (1997) called ecosystem restoration "ecological engineering of the best kind" because we are putting back ecosystems that used to exist, not creating new combinations of populations or systems.

Self-design and the related concept of self-organization are important properties of created and restored ecosystems (Mitsch and Jørgensen 2004). Self-organization is the property of systems to reorganize themselves in environments that are inherently highly variable and nonhomogeneous. Self-organization is a systems property that applies to ecosystems in which species are continually introduced and deleted, species interactions—for example, predation, mutualism—change in dominance, and the environment itself changes. Organization is derived not from outside forces, but from within the system. Self-design is important in times of scarcity because ecologically engineered ecosystems tend to take care of themselves and are less energy demanding. Self-organization develops flexible networks with a much higher potential for adaptation. Implicit in ecological engineering and self-design is that the functioning of the natural systems should form the basis for sustainable management; working with nature rather than against it is more energy efficient.

Case study: The Mississippi-Ohio-Missouri river basin

The Mississippi-Ohio-Missouri (MOM) river basin is an example of the issues we have been discussing (figure 4; Mitsch et al. 2001, Mitsch and Day 2006). It is a continental-scale system with high ecosystem values that has been severely impacted by human activities, and that will require sustainable management in a time of resource scarcity. The 3.2-million-square-kilometer system is the largest drainage basin in North America, and one of the largest in the world, with a mean discharge of nearly 20,000 cubic meters per second to the Gulf of Mexico. The ecosystems of the basin, which are among the most productive in the United States, include the Mississippi delta, riparian and floodplain systems, eastern deciduous forests, and rain-fed prairies. The MOM river basin also includes one of the most important agricultural areas in the world.

During the 20th century, navigation, flood control, reservoirs, and agriculture profoundly affected the basin. Dams on the Missouri reduced sediment input to the delta, and navigation and flood control activities separated the mainstream channels from most of the riparian floodplain. But the most far-reaching impacts come from agriculture. The agricultural landscape of the Midwest changed from a diverse mixture of uses such as corn, soybeans, hay, pasture, oats, forests, and wetlands to one dominated by soybeans and heavily fertilized corn (Boody et al. 2005). More than 80% of the wetlands in most midwestern states have been drained since presettlement time. An estimated 23 million hectares (ha) of wet farmland, including wetlands, were drained under the US Department of Agriculture's Agricultural Conservation Program between 1940 and 1977, and an estimated 18.6 million ha of land, much of it wetlands, were drained in seven states in the upper Mississippi River basin alone (Mitsch and Gosselink 2007). The combination of these factors led to rapid runoff of fertilizer and the deterioration of water quality throughout the basin, from small streams draining agricultural fields to the hypoxia zone in the Gulf, covering thousands of square kilometers (Mitsch et al. 2001). In the Mississippi delta, isolation of the river from the delta is a primary cause for the dramatic loss of coastal wetlands, which has resulted in an overall reduction in productivity (Day et al. 2007b).

To develop a plan to correct these problems, it is essential to understand river basin functioning. Understanding river ecosystems has evolved from concepts of the river continuum to those of the flood pulse (Schramm and Eggleton 2006, Junk and Bayley 2008) and dynamic habitat interactions (Stanford et al. 2005). Understanding deltas evolved from physical-based models (e.g., Roberts 1997) to the concept that deltas are sustained by a hierarchy of energetic forcings (tides, storms, floods) interacting with biogeochemical processes (Day et al. 2007b). Continued good applied science and adaptive management will be an essential part of basinwide restoration.

Efficient restoration of the MOM basin in a time of resource scarcity will require energy-efficient sustainable management based on ecosystem functioning (e.g., Day et al. 2005, Mitsch and Day 2006). The massive flood-control system in the basin was built and is maintained by cheap energy. Such energy-intensive approaches simply will not work on such a large scale as fossil energy becomes very expensive. An alter-

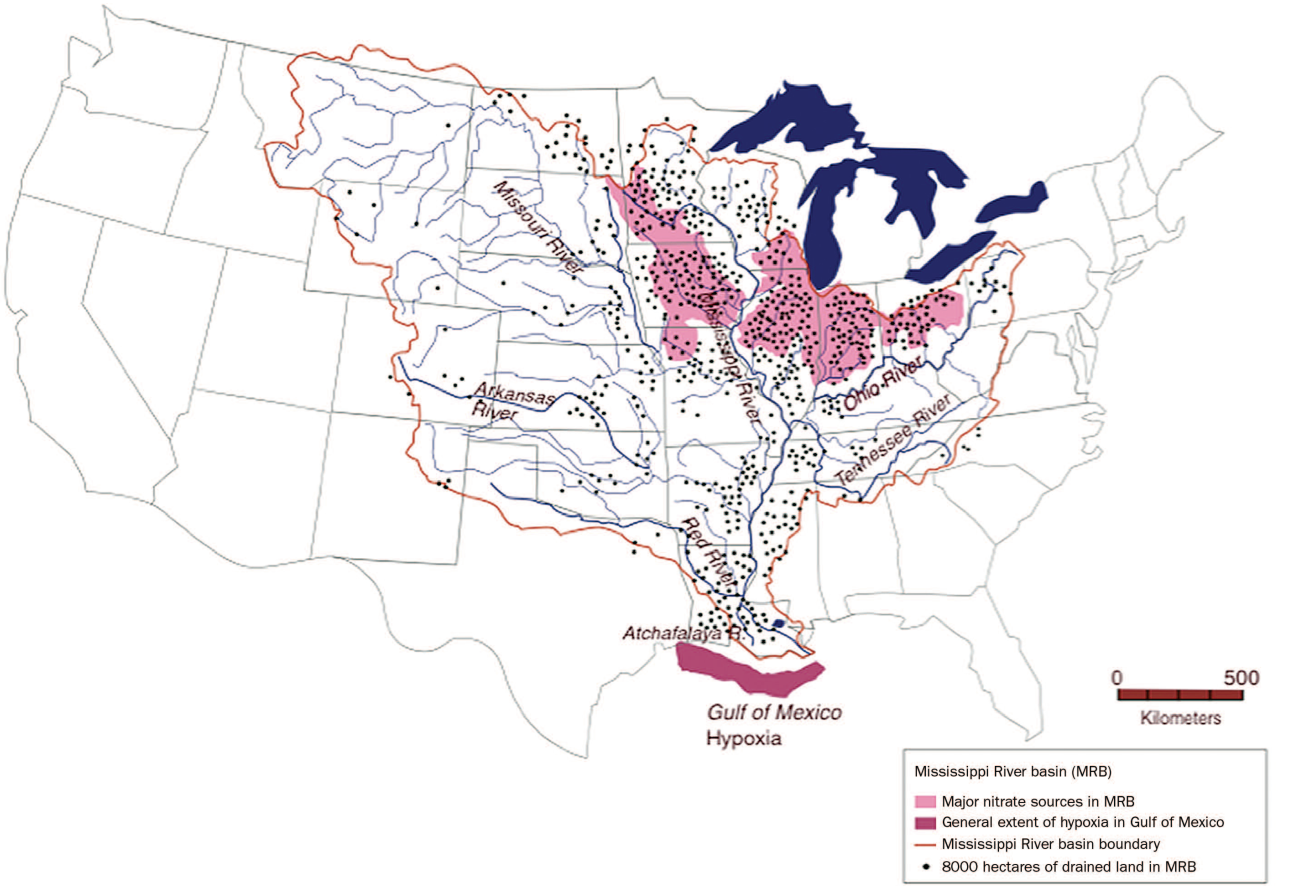

Figure 4. The Mississippi River basin in the United States, showing the location of major nitrogen sources, major hydrological drainage in the basin, and the hypoxic zone in the Gulf of Mexico. Source: Used with permission from Mitsch and colleagues (2001).

native view is to work with nature, using areas such as wetlands to hold water on the landscape and reconnect the river with the floodplain and delta through pulsed introductions of river water. The creation and restoration of millions of hectares of wetlands, about 2% of the agricultural landscape, would reduce nutrient discharge and restore river, deltaic, and wetland habitats (Mitsch et al. 2001, Mitsch and Day 2006, Day et al. 2003, 2007b). Agriculture will most likely return to the diverse crop assemblages of the past, what has been called multifunctional agriculture (Boody et al. 2005). High energy costs will certainly reduce fertilizer use and make maintaining the energy-intensive current flood control system much more difficult. Controlled inundation of the floodplain could reduce flood costs and help replenish soil nutrients. Such ecotechnological approaches will improve water quality, increase biodiversity, reduce flooding, provide wildlife and fisheries habitat, reduce threats to public health, and increase the value of ecosystem services, while maintaining productive agriculture on much of the landscape. These sustainable, energy-efficient approaches will contribute to reducing climate impacts because less energy will be used to maintain the system. For example, wetland assimilation uses much less energy than conventional treatment plants (Ko et al. 2004) and produces less greenhouse gas. Efficient flood control and delta restoration can save enormous amounts of energy. The functioning of ecologically engineered projects is also less sensitive to energy disruption and environmental variability; for example, treatment systems using ponds and wetlands were much less affected by Hurricane Katrina than were conventional treatment plants. This is ecological engineering at a grand scale and it is sustainable in an energy-scarce future; the current system is not. It will require ecologists, engineers, landscape architects, and others working together. If this restoration is not implemented, water quality will continue to deteriorate and habitat will continue to be lost, with an almost complete loss of wetlands in the Mississippi delta.

Summary and conclusions

Humans will have to become more integrated into natural ecosystems in a future affected by climate change, with energy and other resources scarce. Ecologists should generally not attempt to create landscapes that require a high level of maintenance. Rather, the role of ecologists is to gain an understanding of the functioning of natural and managed ecosystems that will allow those ecosystems to be used in energy-efficient and sustainable ways to support the human economy through ecological engineering and ecosystem restoration. In this sense, landscape ecologists and landscape architects and other ecosystem experts have an opportunity to work together in ecosystem management. Ecologists have had the luxury for the last half-century or more of pursuing a wide variety of often rather esoteric pursuits. In a time of increasing resource and energy scarcity, the success of ecology will very likely be linked to the field's ability to help society make the transition to a lower-energy, more sustainable society. This does not mean that basic research is not important, but it does mean that ecologists should think carefully about both the kind of basic research to be pursued and the management implications of this research. Many other societal changes will have to be made in the coming transition, and ecologists should take heed of the role ecology can play to help in that transition.

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