Table of Contents

Developing a Scientific Basis for Managing Earth's Life Support Systems

Gretchen C. Daily

Stanford University

ABSTRACT

Here, I review the motivation and science behind efforts to characterize and manage ecosystems as capital assets. I then describe some recent work to evaluate the potential for sustaining biodiversity and ecosystem services in human−dominated landscapes.

KEY WORDS:biodiversity conservation, countryside biogeography, ecological economics, Ecosystem Services Framework, global change, interdisciplinary collaboration.

Published: October 27, 1999

INTRODUCTION

It is by now well known in the environmental science community that human transformations of the biosphere are unprecedented in scale, dramatically altering important characteristics of the atmosphere, the oceans, and terrestrial systems. It is also clear to this community that the rates and directions of these changes are not sustainable, and that many pose serious threats to human well−being.

The level to which people outside the environmental science community are informed of these circumstances varies tremendously, however. Thus, some segments of the private sector, the government, and the general public are deeply concerned, whereas others remain skeptical even of the existence of serious environmental problems. Similarly, some countries have adopted bold policy changes to address certain issues, but the prospects of others doing so remain very dim. In sum, a few problems, such as certain forms of tropospheric air pollution and stratospheric ozone depletion, are being addressed very effectively (all things considered), yet many are hardly being addressed at all.

Indeed, a chronicler of human activities from outer space would likely conclude that next to nothing was being done to arrest or reverse fundamental aspects of environmental degradation. Since the early 1970s, an impressive array of global and regional agreements has been negotiated to protect ecosystem assets. They target wetlands (the Ramsar Convention 1971); forests (e.g., the Tropical Forest Action Plan 1985, the International Tropical Timber Agreement 1990, the Rio Forest Principles 1992, and the Intergovernmental Panel on Forests 1995); marine resources (e.g., the Law of the Sea 1994, the Straddling Fish Stocks and Highly Migratory Fish Stocks Treaty 1995); biodiversity (the Convention on Biological Diversity 1992); and exceptionally valued natural sites (the World Heritage Convention 1972). On the whole, however, these agreements are weak and ineffective, variously lacking in participation, resources, and institutional mechanisms needed to bring about the protection they are designed to achieve. Thus, most trends continue to go in the wrong direction, many at accelerating rates.

It is not surprising that effective action on such complex problems has not been generated overnight. On the other hand, one wonders whether the human cultural evolution required to solve these problems will occur at the required pace. Many ongoing changes are essentially irreversible on a time scale of interest to society. As Peter Vitousek puts it, we are the first generation with tools to understand changes in the Earth's system caused by human activity, and the last with the opportunity to influence the course of many of these changes.

Clearly, neither science nor scientists will be able to solve all of these problems. But there are at least three key areas to which science and scientists, as individuals and collectively, must contribute. The first is in the establishment of standard metrics and systematic monitoring of the magnitude and rates of change of human impacts on ecosystems. Such information is not sufficient, but it is usually necessary to induce policy action. In a number of discussions, I have found my economist colleagues appalled at how little systematic monitoring there is in ecology. After the great stock market crash in 1929, macroeconomists initiated close monitoring of a few statistics (e.g., unemployment rate, GNP, etc.); they have argued about the utility and interpretation of these statistics ever since, but at least they have something to argue about! Certainly, the ecological metrics that we might choose today will not be perfect and will not suit all needs, but they will amount to something. The second is to use these metrics in projecting future courses of change in the structure and functioning of ecosystems. The third is to translate such possible trajectories into meaningful social terms, concerning basic economic, health, and other aspects of human well−being.

My work is oriented around developing the scientific basis for, and public support of, institutions and policies needed to sustain Earth's life support systems. Many different individuals and approaches are needed to address these problems. Here, I offer a personal overview of some important areas warranting further attention. I first present a general conceptual framework, the Ecosystem Services Framework, which I find helpful in structuring work in this complex area. Second, I describe a metric of ecosystem change that requires development: the capacity of human−dominated lands to support biodiversity, a research area that I call "countryside biogeography." Finally, I briefly describe the great need (and some progress that has been made) to foster communication and interaction between scientists and other key sectors of society.

Before going any further, I should state here that my views have been influenced by many people; most of the ideas presented here are derived from the insights of others (who are fully cited in other publications!). Before getting into any of this, I would like to begin with a story.

LESSONS FROM THE SOUTH PACIFIC

At a global scale, our present situation is unprecedented; at the microscale, however, human populations have confronted many of today's pressing issues before. The tiny, remote islands in the South Pacific, in particular, are well−replicated microcosms, many with nicely preserved records of how human interactions with the environment played out. Their human histories shared very similar initial conditions, with small groups of people of similar cultural origins (from Polynesia) colonizing the islands, introducing to each island the same basic agricultural practices. Yet, what happened from there varied tremendously.

The most perversely intriguing outcome occurred on Easter Island. The original inhabitants, who colonized it 1500 years ago, apparently lived well. Their meat came from porpoises, hunted from ocean−worthy canoes that they fashioned from giant palm trees. Before long, however, the forest was cleared, inducing soil erosion and drying of streams, along with an abrupt halt to the hunting and cooking of porpoise meat (both the canoes and fuel wood were derived from the forest). People next wiped out coastal marine and avian food resources (every species of native land bird became extinct), then resorted to eating rats, and finally turned on one another. The population, thought to have numbered between 7000 and perhaps as many as 20,000 at its peak, comprised only about 2000 people when the island was discovered by a Dutch explorer in 1722. A taunt that survived the population bottleneck was "The flesh of your mother is sticking in my teeth."

Easter Island was not a completely isolated case. Remains on other islands, such as Mangareva and Mangaia, suggest a similar fate for their inhabitants: unchecked population growth, destruction of natural resources, social terror, and cannibalism. Meanwhile, Polynesian societies on other islands also underwent an initial period of environmental degradation, but then, in stark contrast, developed sustainable economies that have persisted to today in relative peace and comfort.

What caused the divergence in environmental and social trajectories? Anthropologist Patrick Kirch (1997) attributes it to "conscious choices," documented in oral history and archeological remains. These choices would not have been easy, nor would their enforcement have been pleasant. They involved eliminating culturally prized pigs from the agricultural production system and imposing rigid population control measures, such as celibacy, abortion, infanticide, and even expulsion of some of the population. Interestingly, these may have been influenced by island size. Evidence is scanty, but it suggests that populations on the tiniest of islands were more likely to persist. All of the islands are small. In fact, Tikopia, a relative success story in both ecological and social terms, is only about 1.7 mi^2 (4.4 km^2) in land area. Kirch proposes that in conditions where everyone was more closely related and where everyone knew everyone else's face, cooperation was more likely; conversely, the slightly bigger islands (Easter is 64 mi^2 or 166 km^2) were just enough larger to have made the population prone to dividing into "them" and "us." (Kirch 1997).

Two issues stand out as relevant to present global circumstances. First, scientific understanding of human interactions with the environment is necessary, but insufficient, to prevent irreversible destruction of life support systems. We, presumably like the islanders cutting down the last trees on Easter Island, know more than enough scientifically to recognize trouble and start moving in the right direction. We face tremendous scientific uncertainties: no one has ever run remotely as massive an experiment on any planet before. Reducing these uncertainties would pay off greatly in designing effective policies. Clearly, however, most of the action is on the social side. Second, human beings evolved as a small−group animal. Our future prospects seem to depend on whether we can foster enough of a small−group feel to forge cooperatively the economic, legal, and other social institutions needed to bring human impacts into balance with what the biosphere can sustain. The task is tremendous, and the huge size of our "island" population may prove a distinct social disadvantage. Again, the action is on the social side. This is why initiatives on the part of scientists to foster substantive communication on environmental issues with leaders in the social sciences, business, and government are so important.

THE ECOSYSTEM SERVICES FRAMEWORK

When human activities approach or exceed the environment's capacity to sustain them, growth in those activities is rarely brought to an immediate, grinding halt. Rather, the people so engaged suddenly find themselves confronted with a set of trade−offs in the allocation of resources to competing uses and users. These trade−offs are becoming increasingly vexing and difficult to resolve, from both ethical and practical perspectives. They involve our most important ideals (such as ensuring a prosperous future for our children), our oldest tensions (such as between individual and societal interests), and sometimes our bloodiest tendencies.

At the local level, allocation of land or water to competing activities often involves a zero sum game. This is apparent in the widespread loss of water and land from native habitat to farms and, increasingly, to urban and industrial purposes. On what basis should such allocations be decided? How can individual preferences for alternative allocations be aggregated fairly? How can the costs and benefits of alternative schemes be distributed fairly? And how can future generations, the parties with the most at stake, be represented at the bargaining table? At the international level, these questions are writ large. Consider efforts to allocate among nations permits to produce chlorofluorocarbons, to harvest certain marine fish stocks, or to use the global carbon dioxide sink. How these questions are decided will profoundly influence the willingness of nations and individual actors to make and comply with agreements.

Many of the trade−offs facing us today arise in novel circumstances, without precedent or institutional framework to provide guidance for their wise and peaceful resolution. Society is poorly equipped to handle them. Throughout most of human history, environmental impacts were local and reversible, but they are now increasingly regional or global and irreversible on a time scale of interest to society. Many people do not have to wait for resource constraints to take on crisis proportions: they face such crises every day, with poor prospects for escape.

Trade and innovation make possible escape from local resource constraints, and often thereby forestall the appearance of such trade−offs. When trade−offs do appear, they are usually not as stark as was suggested in some early writings. Nonetheless, the approach of natural limits is becoming ever more apparent at the global scale: humanity has heavily transformed about 40−50% of the ice−free land surface, has co−opted about 50% of accessible, renewable fresh water, has fully expoited or overexploited about 65% of marine fisheries, has increased the carbon dioxide concentration in the atmosphere by about 30%, has increased the rate of fixation of atmospheric nitrogen by > 100% over natural terrestrial sources, and has driven about 25% of bird species to extinction (Vitousek et al. 1997). Moreover, escape from local resource constraints is, by definition, temporary in a world in which population and per capita consumption are growing. The projected rapid global increase in demand for food, fresh water, energy, and other resources over the next few decades implies a world much closer to, and more places in excess of, such limits (Daily et al. 1998).

In collaboration with others, I am developing a conceptual framework for helping to resolve these trade−offs (Daily 1997). The framework recognizes natural ecosystems and their biodiversity as capital assets that, if properly managed, will yield a stream of life−support goods and services over time. Society derives a wide array of important benefits from biodiversity and the ecosystems in which it exists. As outlined in Table 1, these ecosystem services include the production of goods, regeneration processes, stabilizing processes, life−fulfilling functions, and conservation of options. Ecosystem services are essential to human existence and operate on such a grand scale, and in such intricate and little−explored ways, that most could not be replaced by technology. Yet, escalating impacts of human activities on natural ecosystems imperil their delivery.

Table 1. A classification of ecosystem services with illustrative examples.

Ecosystem service
Production of goods
Food
Terrestrial animal and plant products
Forage
Seafood
Spice

Pharmaceuticals
Medicinal products
Precursors to synthetic pharmaceuticals
Durable materials
Natural fiber
Timber
Energy
Biomass fuels
Low−sediment water for hydropower
Industrial products
Waxes, oils, fragrances, dyes, latex, rubber, etc.
Precursors to many synthetic products
Genetic resources
Intermediate goods that enhance the production of other goods
Regeneration processes
Cycling and filtration processes
Detoxification and decomposition of wastes
Generation and renewal of soil fertility
Purification of air
Purification of water
Translocation processes
Dispersal of seeds necessary for revegetation
Pollination of crops and natural vegetation
Stabilizing processes
Coastal and river channel stability
Compensation of one species for another under varying conditions
Control of the majority of potential pest species
Moderation of weather extremes (such as of temperature and wind)
Partial stabilization of climate
Regulation of hydrological cycle (mitigation of floods and droughts)
Life−fulfilling functions
Aesthetic beauty
Cultural, intellectual, and spiritual inspiration
Existence value
Scientific discovery
Serenity

Preservation of options
Maintenance of the ecological components and systems needed for future Supply of these goods and services and others awaiting discovery

---

Relative to physical, human, or financial capital, renewable natural capital (embodied in ecosystems) is poorly understood, typically undervalued, scarcely monitored, and, in many important cases, is undergoing rapid depletion. Until now, there has been little incentive to measure or manage natural capital: it has been treated as essentially inexhaustible.

The Ecosystem Services Framework offers a fresh paradigm for resolving trade−offs. Although the concept of ecosystem services is certainly not new (Plato pondered their loss to careless land management, and he was doubtless not the first) it is relatively new in the context of today's environmental issues. Moreover, a growing number of recent policy decisions to protect ecosystem services has made the concept much more operational.

One of the best known cases is New York City's efforts to restore natural water purification services in lieu of constructing a more expensive water filtration plant. This amounts to an investment in natural capital rather than physical capital, on economic grounds (Chichilnisky and Heal 1998). Could this model be extended to other places and to other services? In other places, water quality is certainly a growing concern: the United Nations Environment Programme reports that most diseases in the developing world are caused by contaminated water, and that 50% of people in developing countries suffer from one or more water−related diseases. An estimated 10−15% of the U.S. population consumes water from systems that violate U.S. Environmental Protection Agency (EPA) contaminant standards. The U.S. EPA forecasts having to spend U.S.$140 billion over the next 20 years to maintain drinking water quality at minimum required standards. To evaluate the potential for extending the NYC model, Walter Reid posed the question, how much land could be protected with an economic justification, using water quality as a major goal? A first−order approximation suggests that the area would be significant: 10% of U.S. land area and 14% of global land area under current population sizes (Reid, *in press*).

In the New York City case, a complex of existing and new financial and legal mechanisms are permitting (officials hope) the capture of ecosystem service values for a win−win−win outcome: New York City taxpayers will receive clean water at the lowest cost; stewards of the watershed in the Catskill Mountains, about100 miles (160 km) away, will be compensated for the purification services that they provide to the City; and those concerned with other services supplied by the Catskills ecosystem (e.g., aesthetic benefits, flood control) will see these better protected under the umbrella of water purification.

To extend this model to other places and other services, appropriate educational, financial, and legal institutions, tailored to cultural and economic circumstances, will be required. Without these, notice from ecologists and economists that ecosystems are important and valuable assets will do nothing. Promising new institutions for safeguarding ecosystem services have emerged in a wide array of cultures and economies (e.g., Australia, Madagascar, the United States, Vietnam); at a variety of scales, from local to international; and in government, NGO (nongovernmental organization), and private sector contexts (e.g., Castro and Tattenbach 1998). The services safeguarded by these emerging institutions include: pollination; pest control; water supply for drinking, irrigation, and hydropower generation; maintenance of soil fertility; sustainable harvesting of tropical timber; provision of aesthetic beauty; and even decomposition (of orange peels produced by Del Oro, an orange juice company in Costa Rica).

Tremendous payoff could result from further research in the characterization (biophysical and economic) of ecosystem services, and in the development of institutions for their safeguarding (Daily et al., *in review*). A series of basic questions, spanning a wide array of disciplines, begs addressing in this area. Questions emphasizing ecology include:

- Which ecosystems supply what services? What is the scale of delivery, transport, and consumption of the services?
- What are the relationships between the quantity or quality of services and the condition (e.g., relatively pristine vs. heavily modified) or areal extent of the ecosystem supplying them? Where do critical thresholds lie?
- To what extent do the services depend upon biodiversity?
- To what extent, and over what time scale, are the services amenable to repair?
- How interdependent are the services? How does safeguarding or damaging one influence the functioning of others?
- What indicators could be used to accurately and efficiently monitor changes in the supply or quality of ecosystem services?
- How effectively, and at how large a scale, can existing or foreseeable human technology substitute for ecosystem services?
- What are the main sources of uncertainty regarding ecosystem services, and how important are they? How can the uncertainty best be quantified and incorporated into policy?
- How can economic principles and tools best be brought to bear on the management of natural capital?
- Given that the value of ecosystems lies mostly in the future and will always lie mostly in the future, how should future benefits be valued, in economic, cultural, or other terms?
- What financial, legal, and other social institutions are needed to safeguard critical ecosystem services? How can their development be catalyzed?

Although a great deal is known about the functioning of ecosystems and the supply of services in general, abstract terms, there is a paucity of information on particular, local ecosystems and economies. Moreover, although the services are known to be extremely important and to be highly threatened, very little is known about marginal values (the net benefit or cost associated with protecting or destroying the next unit of an ecosystem) or about the nonlinearities in ecosystem responses to human impact. Often this information is not acquired until after it is too late to reverse harm done (e.g., after heavy flooding).

Further development of case studies addressing these issues would be most helpful. Such work would define the envelope of opportunities and limitations in applying this conceptual framework; it would illuminate how general are the findings from specific localities; and it would serve as a guide to policy development. In the New York City case, for instance, officials are purchasing land and changing agricultural and municipal practices in the hopes of restoring the natural water purification services of the Catskills, all with quite limited scientific information. Careful studies are underway to determine the effectiveness of the measures, but the political window of opportunity for pursuing this approach (as opposed to building a physical filtration plant) may close soon. In this particular case, and generally, success in the policy arena hinges on whether the scientific underpinnings of policies are sound. There exist on the books today many laws that could be used for environmental protection, but whose application awaits better scientific information.

Ecology tends to be a retrospective science. In contrast to fields such as climatology, there is very little tradition of anticipating (ecosystem) responses to future perturbation. Instead, effort is devoted to explaining what happened in the past, and why. Society is essentially flying blind, with little understanding of its dependence, or impacts, on ecosystems. There thus exists an urgent need for careful scientific assessment and scenario−making of the societal consequences of ecosystem change. How might human health and economic prosperity be affected by the loss of 30−50% of Earth's species? By a 2_{o}C rise in Earth's average surface temperature? By a doubling of the rate of nitrogen fixation? By the cooption of > 50% of Earth's accessible, renewable fresh water by the human enterprise? By human domination of half of the ice−free land surface? By a rapid, sequential collapse of the world's major marine fisheries? Most of these circumstances already are with us; others lie just over the horizon. I will now turn to one question embedded in this set in a bit more detail.

COUNTRYSIDE BIOGEOGRAPHY

Food production is arguably humanity's most important activity. It is also the most important proximate cause of biodiversity loss worldwide, involving major direct and indirect impacts, including: (1) conversion of natural habitat to agricultural use; (2) facilitation of biotic invasion through trade (thereby increasing the rate of introduction of species) and through habitat alteration (thereby increasing the susceptibility of native communities to invasion); and (3) application of chemical fertilizers and pesticides. Global demand for food is expected to double over the period 1990−2030. In Asia and Africa, food needs are projected to increase by a factor of 2.3 and 5, respectively, with a sevenfold increase or more in some countries (Daily et al. 1998). It is difficult to forecast how these needs will be met. Whatever course is taken, it is fair to expect that growing human pressures will put biodiversity at great risk.

These circumstances beg the question, What is the capacity of human−dominated landscapes to support biodiversity? This question pertains to the future course of, societal consequences of, and appropriate policy responses to the mass extinction currently underway. It has sweeping implications for strategies to produce food and conserve biodiversity and ecosystem services, but it remains little studied relative to its counterpart, namely, the capacity of remnants of native habitat to support biodiversity.

One reason for this emphasis is undoubtedly the crisis nature of biodiversity loss; given the justified panic to "save" remaining natural habitat, it is taking some time to appreciate the corresponding opportunity, namely, to enhance the hospitability of agricultural landscapes for biodiversity. The emphasis traces to other factors as well, including (1) the prominence of the theory of island biogeography, and of the island paradigm, in conservation biology; (2) the notion that a very small fraction of species is capable of persisting outside of "islands" of natural habitat, i.e., in human−controlled habitats; and (3) the frequent (although often subconscious) projection of disdain for humanity's destruction of natural habitat onto the organisms that profit by it.

The principal way of assessing future patterns of extinction involves applying the theory of island biogeography to terrestrial "islands" of natural habitat. Species−area curves, which relate the number of species in a habitat to its areal extent, permit prediction of changes in species richness with changes in habitat area brought on by habitat "destruction." A widely employed simplifying assumption is that no (or only a negligible few) species will survive outside of the remaining natural habitat; this is indeed justified in cases of land conversion to very intensive agricultural and other uses.

The exent of habitat modification varies tremendously, however. Similarly, the fates of organisms that once made their homes in unbroken expanses of natural habitat range along a broad continuum: at one end is population decline to local (and eventually global) extinction; at the other extreme is expansion into human−controlled landscapes. Although habitat modifications and the habitat affiliations of species are poorly documented (for most habitats and species globally), two things are clear: first, large regions of the world are not presently at the extreme end of intensity of land use; and, second, a substantial fraction of biodiversity occurs, at least for the moment, in many kinds of human−dominated habitats.

The organisms that can take advantage of countryside (rural and suburban landscapes devoted primarily to human activities) deserve more attention, for a series of reasons. First, it is unlikely that many large, relatively undisturbed tracts of natural habitat will remain in the face of projected growth in the size and environmental impacts of the human population. Second, the conservation potential for many species may rest on preserving or enhancing certain aspects of rural landscapes containing remnants of native habitat, in lieu of protecting large tracts of more or less intact habitat. Third, the supply of important ecosystem system services, such as pest control and pollination, will depend, in many instances, on the biodiversity that occurs locally, in the vicinity of human habitation, i.e., in countryside habitats. Finally, a growing interest in restoration in some regions will require comparing the potential of alternative sites for reestablishing desired community assemblages.

Countryside biogeography is a field aimed at understanding the diversity, abundance, conservation, and restoration of species in rural and other human−dominated landscapes. I am applying a variety of empirical and theoretical approaches to addressing questions in this area, such as:

- Which species traits confer a survival advantage in the face of tropical deforestation and other major habitat alterations?
- How are these traits distributed across taxa? How dramatically, and in what ways, will the current extinction episode shape the future diversity and evolution of life?
- What is the relation between levels of agricultural intensification and biodiversity in countryside landscapes?
- Can simple mathematical theory be developed to predict patterns of persistence of biodiversity in countryside landscapes?
- How accurately can patterns of biodiversity in countryside habitats be predicted on the basis of remotely sensed information (e.g., from satellite images) on land use?
- How effectively can countryside biotas perform ecosystem services?
- What practical measures can be taken to enhance the capacity of countryside habitats to sustain biodiversity and ecosystem services, as well as agricultural activities?

There has not been sufficient work on these issues to anticipate the answers to these questions in most biogeographic or agricultural regions of the world. The work that has been done suggests, however, that many agricultural landscapes do retain substantial biodiversity. My group is presently launching a series of field studies, primarily in Costa Rica, to document the response of various groups of organisms (including birds, mammals, and a variety of insect taxa) to different types and levels of agricultural activity. Using information derived from both satellite images and on−the−ground measures, we are characterizing agricultural intensity in terms of, for instance, the frequency distribution of agricultural plot sizes; the density of crop types; the ratio of plot to hedge−row areas; the spatial configuration and relative coverage of native and human−dominated habitats; and the amounts and types of chemical fertilizer and pesticide applied. The various field studies will illuminate, we hope, how well these measures of intensity predict patterns of biodiversity. We are also synthesizing information in the literature on the habitat associations of species. The findings from these initial undertakings together serve as a basis for theoretical explorations that will, we hope, permit prediction of patterns of biodiversity generally, in other regions of the world and under various scenarios of change in land use.

Illustrative preliminary findings to date are:

1. A significant fraction of the native avifauna of Costa Rica occurs (at least temporarily) in open countryside habitats. The study region of 15 km radius was virtually completely forested in the 1940s and now retains 27% forest cover. Of the 33 families of birds that we censused, 55% occur in forested areas only, showing a significant positive correlation between fragment size and species richness. Another 22% of the species occur in both open habitats and forest, and 23% occur in open habitats only. Based on comparisons with larger forested areas outside the study region, it appears that between 4 and 28 species (1.4 –9.3% of the possible original totals) have gone locally extinct since deforestation began. The avifauna of open areas is similar throughout the study region, as determined by measures of richness, relative abundance, evenness of abundance, and species composition. The fauna of the open countryside does not vary with proximity to extensive forest (Daily et al., *in review*).

2. Large body size and high social status, which are positively correlated, may confer a survival advantage in countryside landscapes, perhaps by allowing greater access to limiting, concentrated food resources. In a guild of fruit−eating tanagers, for example, the larger, dominant species are more abundant in open areas, whereas the smaller, subordinate species are much more restricted to native forest. Analysis of videotapes reveals that, when foraging together at fruiting trees, dominant individuals spend more time actually feeding (as opposed to looking about or sitting away from fruits) than do subordinates (Daily and Ehrlich 1994).

3. A study led by Jennifer Hughes examined with which aspects of countryside habitats birds were most tightly affiliated, among several crop types and remnant semi−natural habitats. Interestingly, the greatest abundance of individuals and of species occurred in fallow pastures and fields (relative to sampling effort). Moreover, two−thirds of all individuals recorded were found in edge habitats that bordered agricultural fields. These findings emphasize the critical role of semi−natural habitats, even when they are relatively limited in extent.

4. Nocturnality may confer a dispersal, and possibly a survival, advantage in the face of tropical deforestation. Surveys of the diversity of diurnal birds and butterflies and nocturnal beetles and moths in forest patches reveal the classic island biogeographic pattern for birds and butterflies (fewer in smaller patches), but similarly high diversities of moths and beetles among forest patches of all sizes (0.1–225 ha). A possible mechanism explaining this apparent advantage is that, typically, the movement of nocturnal species occurs when conditions of temperature, humidity, and solar radiation are similar between native forest and cleared areas. During the day, the hot, dry, bright conditions in open areas may seriously impede dispersal for many organisms. The nocturnal taxa seem to treat the fragmented countryside as one continuous habitat with patchily distributed resources (Daily and Ehrlich 1996).

5. The foregoing study sheds some light on the potential utility of different taxa as indicators of overall species richness. Namely, the distributions of butterfly and bird species richness are correlated ($r_2 = 0.55$, $P < 0.05$), as are those of nocturnal moths and beetles ($r2 = 0.58$, $P < 0.025$). The diurnal and nocturnal groups are not significantly correlated with one another, however ($r2P$<= 0.05 in three of the four cases).

6. In a follow−up study led by Taylor Ricketts, samples of moth diversity within a large forest tract and four surrounding agricultural habitat types revealed no differences in diversity among agricultural types. Agricultural sites that were distant (>3.5 km) from the forest tract, however, had significantly lower diversity than did near (<1.0 km) sites, which had diversities similar to that of the forest interior. These results suggest that most moth species depend on forest for larval food plants, but their home ranges include substantial areas of countryside (Ricketts et al., *in review*).

7. An ongoing study of nonflying mammals will permit an assessment of the occurrence in open areas of a taxon with less vagility than some of the previously discussed groups. We are documenting the occurrence of mammals in a large tract of forest, in different agricultural habitats near and far from forest, and in countryside habitats with and without tiny (< 2−ha) forest remnants. Results thus far reveal that some species are restricted to forest, but there is an abundance of medium−sized species in

countryside habitats, with higher species richness and abundance in sites that encompass a tiny forest fragment.

(This ongoing work has been possible only with the collaboration and assistance of numerous people, including George Burtness, Yvonne Burtness, Ellyn Bush, Gerardo Ceballos, Scott Daily, Tom Davis, Claire Devine, Paul Ehrlich, John Fay, Jennifer Hughes, Yimer Ilama, Jesús Ilama, Jesús Pacheco, Henrique Pereira, Taylor Ricketts, Arturo Sánchez−Azofeifa, Cagan Sekercioglu, Tom Sisk, Gerardo Suzán, and Jim Zook.)

In summary, these findings, along with those of other researchers, suggest that there is considerable potential for conserving or enhancing biodiversity in countryside habitat. On the basis of this work, we are now trying to develop a theoretical framework for explaining and predicting patterns of biodiversity under alternative courses of land use change. This metric, the capacity of countryside to support biodiversity, could serve as a basis for forecasting important societal consequences of ecosystem change.

PUBLIC OUTREACH

In her 1997 plenary address to the American Association for the Advancement of Science, Teresa Heinz warned that science seems to be going the way of the Medieval Church. Increasingly, the public image of scientists is of an arrogant, self−cloistered elite that discusses in uninterpretable language issues of little or no significance to the daily lives of normal people. One might argue that the demise of the Medieval Church was no tragic loss to society. But public support of the scientific enterprise is dwindling at a time when society could hardly need science more: a sound scientific basis is a critical prerequisite to solving the environmental issues it now faces (Lubchenco 1998).

That public image of scientists is justifiable in many ways. Scientists, as a group, rarely attempt to communicate the excitement and relevance of their work to the public. There is often little short−term, individual incentive to do so and, indeed, "public" scientists often face major professional disincentives.

To draw this essay to a close on a personal note, I am very fortunate to enjoy the support of prominent, well−respected scientists and other individuals who have dedicated much of their career to changing these circumstances. In my early days as a graduate student, their efforts led to a remarkable phenomenon on the Stanford campus: some economists and ecologists started speaking to one another. The interaction intensified and has proven extremely productive, now involving individuals in many other areas including climatology, engineering, law, and anthropology, and offering diverse, but increasingly convergent (and informed!) perspectives on environmental issues. At about the same time, some of these same individuals played key roles in establishing the Beijer International Institute for Ecological Economics of the Royal Swedish Academy of Sciences. Being involved in, and observing the evolution of, these two groups has been very educational for me. I believe that the payoff on such exchanges can be very high, in both intellectual and practical terms.

With the support of individuals in these groups (in providing training, contacts, and opportunities), I have developed a series of outreach efforts aimed at communicating the findings of my research to a wide array of academics, the business community, policy makers, and the general public. The times certainly seem to be ripening: although there is powerful, entrenched opposition to change, there are also important segments of the private sector and general public who are very serious about doing something and who keenly want to know what that something should be. There appears to be growing demand for ecological understanding to evaluate the merits of alternative courses of action and to identify efficient paths toward reducing deleterious human impacts on the environment.

I have also recently become involved in building exchange between the environmental science community in the United States and those in developing nations, especially in Latin America. The benefits of such exchange are manifold, including improving the science of all parties, enhancing local capacities for environmental management, better directing U.S. foundation and government funds for conservation efforts, and fostering the trust and political cooperation needed to solve regional and global problems.

Clearly, there are many important fronts to which one could contribute. Considering our tentative lessons from the South Pacific, my hope is to help foster productive nuclei of small−group interaction to chart new intellectual territory and to help forge a transition to a sustainable economy.

RESPONSES TO THIS ARTICLE

Responses to this article are invited. If accepted for publication, your response will be hyperlinked to the article. To submit a comment, follow this link. To read comments already accepted, follow this link.

LITERATURE CITED

Castro, R., and F. Tattenbach, editors. 1998. *The Costa Rican experience with market instruments to mitigate climate change and conserve biodiversity.* MINAE and FUNDECOR, San José, Costa Rica.

Chichilnisky, G., and G. Heal.1998. Economic returns from the biosphere. *Nature***391**: 629−630.

Daily, G. C., editor.1997. *Nature's services: Societal dependence on natural ecosystems.* Island Press, Washington, D.C., USA.

Daily, G. C., P. Dasgupta, B. Bolin, P. Crosson, J. du Guerny, P. Ehrlich, C. Folke, A. M. Jansson, B.−O. Jansson, N. Kautsky, A. Kinzig, S. Levin, K.−G. Mäler, P. Pinstrup−Andersen, D. Siniscalco, and B. Walker. 1998. Food production, population growth, and the environment. *Science***281**: 1291−1292.

Daily, G. C., and P. R. Ehrlich. 1994. Influence of social status on individual foraging and community structure in a bird guild. *Oecologia***100**: 153−165.

Daily, G. C., and P. R. Ehrlich. 1996. Nocturnality and species survival. *Proceedings of the National Academy of Sciences (USA)***93**: 11709−11712.

Daily, G. C., P. R. Ehrlich, and G. A. Sánchez−Azofeifa.*In review.* Countryside biogeography: Utilization of human−dominated habitats by the avifauna of southern Costa Rica. (Available from G. C. Daily.)

Daily, G. C., T. Soederqvist, K. Arrow, P. Dasgupta, P. Ehrlich, C. Folke, A.−M. Jansson, B.−O. Jansson, S. Levin, J. Lubchenco, K.−G. Mäler, D. Starrett, D. Tilman, and B. Walker.*In review.* The value of nature and the nature of value. (Available from G. C. Daily.)

Kirch, P. V. 1997. Microcosmic histories: Island perspectives on "global" change. *American Anthropologist***99**: 30−42.

Lubchenco, J. 1998. Entering the century of the environment: A new social contract for science. *Science***279**: 491−497.

Reid, W. V.*In press.* Capturing the value of ecosystem services to protect biodiversity. *In* Processdings of the "Managing Human−Dominated Ecosystems" Conference. Monographs in Systematic Botany, Missouri Botanical Garden.

Ricketts, T. H., G. C. Daily, P. R. Ehrlich, and J. P. Fay. *In review.* Countryside biogeography of moths in a fragmented landscape: biodiversity in native and agricultural habitats. (Available from G. C. Daily.)

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. Human domination of Earth's ecosystems. *Science* **277**: 494−499.

Address of Correspondent:
Gretchen C. Daily
Department of Biological Sciences
371 Serra Mall
Stanford University
Stanford, CA 94305−5020 USA
Phone: (650) 723−3171
gdaily@leland.stanford.edu

Return to Table of Contents for Volume 3, Issue 2

Main Issues How to Submit Subscription Benefits