An invitation to ecological economics

Paul R. Armsworth and Joan E. Roughgarden

The emerging interdisciplinary field of ecological economics should be a recognized research priority. Only through a combination of sound ecology and good economics can we hope to manage our exploitation of the biosphere in a manner that is both sustainable and efficient. This article is an invitation to ecologists to use economic tools and to participate in ecological economic debate. To this end, we review basic ecological economic concepts and discuss how the field has arisen, what benefits it offers, and what challenges it must overcome.

A small, but active, subset of ecologists and economists has stimulated growth of the interdisciplinary field of ecological economics[1]. However, we suspect that many academics from these disciplines have not yet participated in ecological economic debate because they have concerns about the appropriateness of this collaboration. We believe that such concerns are misplaced and that significant advances can be made with the wide participation of both ecologists and economists. Furthermore, we believe that the potential benefits of ecological economics warrant it becoming a recognized research priority. The aim of this article is to persuade ecologists not already active in this field to devote research effort to the subject and to provide them with the tools needed to begin.

What is ecological economics?

To define ecological economics, we must first mention other subjects as reference points. Economics is the study of the allocation and use of scarce resources to meet human needs. NORMATIVE ECONOMICS (see Glossary) provides a systematic framework for societal decision making that is based on the preferences of enfranchized individuals. In theory at least, this framework is independent of ideology and is amoral, although particular applications of it might not be.

Within economics, several subdisciplines specialize in decisions about particular goods and services. Environmental economics considers environmental COMMONS, mainly clean air and water, solid waste, public lands and related goods[2,3]. Natural resource economics examines the extraction of exhaustible and renewable resources[3–5], such as mineral deposits, timber and fisheries.

It is difficult to delineate exactly where ecological economics departs from environmental and natural resource economics. Ecological economics is perhaps best thought of as a new perspective, rather than as an entirely new discipline[6]. Ecological economists often emphasize different issues than do environmental and natural resource economists. In particular, they tend to generalize the concept of a resource from a few target species to a larger set of ecological systems than has often been considered in policy-studies, and to generalize from a specific good or service to the multitude of benefits that society derives from natural systems[7].

Natural resource economics focuses on extractive primary industries and tends to consider only a few species. However, human impacts on ecosystems extend far beyond these few well-studied cases[8]. Thus, a new theory is required that examines our dependence on a larger set of ecological systems, and future resource management must proceed on a scale that is at least commensurate with our impact on the environment.

Ecological economics considers the full range of services that society derives from nature. Ecosystems provide many benefits that are nonextractive, and environmental economists have developed methods for valuing such services, even when they are not traded in conventional markets (Box 1). The inclusion of NONEXTRACTIVE SERVICES substantially alters the outcomes of economic analyses[9–11] (Box 2).

The most important issue here is not what academic label we choose to wear. Rather, it is the common commitment throughout environmental, natural resource and ecological economics to analyze the interactions between ecological systems and human production and consumptive activities.

A research priority

We offer four reasons why ecologists might want to devote research effort to ecological economics: (1) ecosystems could be undervalued and overexploited if ecological and economic systems are not tightly coupled; (2) future ecological studies and conservation efforts will be incomplete if they do not consider economic forces; (3) ecological economics provides a valuable interface that allows ecological knowledge to be integrated into policy making; and (4) the subject warrants ecologists' attention because there is a demand from economists for the information that it will provide.

Risk of overexploitation

One common theme in ecological economics is that a deficiency in market-based systems is responsible for overexploitation of the biosphere. Correcting such a problem should be an imperative for both ecologists and economists. Markets provide powerful tools for regulating resource exploitation, but only perform well in certain circumstances[2]. When a resource is undervalued, or when some individuals impose involuntary costs (EXTERNALITIES) on other individuals, then a MARKET FAILURE has occurred. Ecologists can help prevent such failures by identifying different services provided by ecosystems and the role that species play in their provision. We can then attempt to value the contributions of species and account for costs associated with lost services more completely.

Paul R. Armsworth*
Joan E. Roughgarden
Dept of Biological Sciences, Stanford University, Stanford, CA 94305, USA.
*e-mail: armsworth@stanford.edu

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Box 1. Types of service and valuation

Measurements of the total value of a good are less relevant than measurements of its MARGINAL VALUE[a,b] (see Box Glossary). For example, an estimate of the total value of all old growth forests is less useful than an estimate of what people would be willing to sacrifice to prevent losing one more acre, and how that would change if these forests became increasingly rare[c]. One would need to consider all services that such an acre of forest provides and, in Table I, we indicate some of these services and techniques that one might use to value them.

Table I. Valuing different services

Type of Exploitation	Good/Service	Valuation Method
Extractive	Timber	Market price
Nonextractive and CONSUMPTIVE	Carbon sequestration Watershed services Prevention of soil erosion Tourism and recreation	Hedonic pricing Avoided cost Avoided cost Travel-cost methods
Nonextractive and NONCONSUMPTIVE	Existence	Contingent valuation

There are different methods that can be used to value environmental goods and services[d,e]; we provide only brief definitions.

- *Hedonic pricing* infers a value for goods that are not traded directly in markets from prices of related goods that are traded.
- *Avoided cost* methods estimate the value of a service from the cost of replacing it. For soil erosion, this could be the cost of building retaining walls. Heal[b] discusses limitations of avoided cost methods.
- *Travel-cost* methods for evaluating recreational benefits from a site consider park entry fees as well as implicit costs, such as the cost and time of travelling there.
- *Contingent valuation* techniques rely on surveys regarding hypothetical situations and not on any actual sacrifices that individuals make. Some economists have concerns about their reliability for this reason.

References

a Daily, G.C. *et al.* (2000) The value of nature and the nature of value. *Science* 289, 395–396

b Heal, G. (2000) Valuing ecosystem services. *Ecosystems* 3, 24–30

c Bulte, E. and van Kooten, G.C. (2000) Economic science, endangered species and biodiversity loss. *Conserv. Biol.* 14, 113–119

d Pearce, D.W. (1993) *Economic Values and the Natural World*, Massachusetts Institute of Technology Press

e Smith, V.K. (1993) Nonmarket valuation of environmental resources: an interpretive appraisal. *Land Econ*. 69, 1–26

Box Glossary

Marginal value: the value of an incrementally small increase or decrease in the amount of a good or service provided.

Consumptive services: services that are valued because they are consumed or used by individuals, such as harvesting or tourism values.

Nonconsumptive services: services that are valued by individuals who are isolated from their provision and never anticipate partaking of them. For example, if an individual derives satisfaction just from the knowledge that some place exists, even when he or she never intends to visit it, then that would be nonconsumptive.

Ubiquity of economic forces

Anthropogenic impacts driven by economic forces permeate every ecosystem[8], and ecologists can no longer ignore these forces if their work is to remain relevant to real problems. Conservation efforts will fail if they do not address the socioeconomic context of conservation problems, because the degradation of natural resources and the threat of extinction for many species is a consequence of socioeconomic circumstances that motivate human actions[12].

Policy making and ecological economics

Ecological economics provides a normative interface for presenting ecological results in terms that are directly relevant to management, and can help ensure that ecological knowledge is used. Ecological results are rarely presented in this form and are typically descriptive. For example, ecology might tell us that creating larger reserves or reducing poaching within existing reserves would increase the probability that an endangered population grows. However, with economic tools, we could inform a manager with a budget constraint what would be the optimal level of investment in each strategy.

Demand for ecological information

Ecologists should participate in ecological economics, because economists want the information that they can provide. Two factors have led some economists to seek collaborations with ecologists. First, there is an awareness that physical limits could encroach on economic growth and that the depreciation of NATURAL CAPITAL should be factored into societal welfare indices, such as GNP (Refs 4,11,13). Indeed, achieving economic growth would involve conservation of natural resources if we enlarged our concept of economic growth to incorporate natural capital. Second, people's preferences for environmental goods and services are changing. In a landmark essay, Krutilla[14] suggested that a shift in emphasis in environmental and natural resource economics was required because nonextractive services were being valued more highly relative to EXTRACTIVE SERVICES. The growth of ecotourism, debates over the amount of open space in land-use planning proposals, and other indicators, suggest that this shift in preferences continues today.

How does one do ecological economics?

Most economic analyses start from an initial distribution of property rights. Typically, property rights over a resource evolve as it becomes increasingly scarce. However, the assignment of property rights can provide a tool for adjusting the distribution of wealth, if this is felt appropriate. Instances where property rights are not clearly defined often result in ecosystems being overexploited.

The first stage in an analysis is to identify alternative outcomes that can be achieved with some set of actions. Ecologists can contribute by suggesting alternatives that otherwise might be neglected. Then one attempts to infer the preferences of individuals for possible outcomes, noting that these tend to be situational. For example, would people prefer larger

Box 2. An illustrative model

We illustrate points in the text with a simple model. Suppose the growth of some population is described by Eqn 1:

$$\frac{dN}{dt}=F(N)-H \qquad [1]$$

where N is population size, and growth function $F(N)$ is such that $F'(0)>0$, $F''<0$ and $F(K)=0$ for some $K>0$. Here, H represents the harvesting rate, which is controlled by the regulatory authority, and equilibrium stock sizes $\hat{N}\in[0,K]$ represent achievable outcomes. Let P be the net price of a harvested unit, and $Q(N)$ be the revenue from nonextractive services. For brevity, we assume P is not density dependent, but it is straightforward to relax this assumption. Let ρ be the discount rate so that the present value of US$ x at t future time is US$ x exp($-\rho t$).

Suppose our objective is to maximize the total present value, V, to society from all revenues from the resource by time T. Three contributions need consideration. The net revenue accumulated through time from extractive and nonextractive industries is given by Eqn 2:

$$\int_0^T (PH+Q)\,e^{-\rho t}\,dt \qquad [2]$$

The value of leftover stock at time T is $P\hat{N}$ exp($-\rho T$). Lastly, revenue that could have been obtained by harvesting the entire stock initially and reinvesting elsewhere, $P\hat{N}$, is included as an upfront cost. Thus, our objective is to maximize V, as stated in Eqn 3:

$$V=\int_0^T (PH+Q)\,e^{-\rho t}\,dt-P\hat{N}\,(1-e^{-\rho T}) \qquad [3]$$

A maximization condition specified by Eqn 4 is arrived at by substituting the equilibrium condition, $F=H$, into Eqn 3 and taking the integral.

$$0=\frac{dV}{d\hat{N}}=\frac{d}{d\hat{N}}\left(\frac{PF+Q}{\rho}-P\hat{N}\right)(1-e^{-\rho T}) \qquad [4]$$
$$\Rightarrow \rho=F'+\frac{Q'}{P}$$

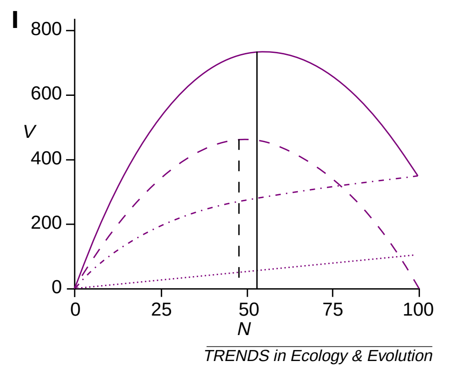

Figure I illustrates this maximization. The dashed and dot-dash curves respectively represent the discounted present value of the revenues from harvesting and nonextractive services summed over 50 years. The solid curve represents the sum of these two quantities, as stated in Eqn 2, and the dotted line represents the upfront cost of the investment less the value of leftover stock. The solid vertical line indicates the optimal target stock size (where the difference between the outer curve and the dotted line is greatest), and the dashed vertical line shows the equivalent target when only considering extractive industries. It is optimal to leave a larger portion of the stock unharvested when nonextractive services are included and it can be optimal not to harvest at all if these services are sufficiently valuable. To produce the figure, we set $F(N)=rN(1-N/K)$ where parameters $[r,K]=[1,100]$ and $Q(N)=qKN/(K+aN)$ where parameters $[P,q,\rho,a]=[1,0.75,0.05,3]$.

The equivalent formula to Eqn 4 for n interacting species is given in Eqn 5:

$$(\rho I-J^T)\,\mathbf{P}=\nabla Q \qquad [5]$$

where $\mathbf{P}$ is a vector, J^T is the transpose of the Jacobian associated with production function, $\mathbf{F}$, and $\nabla=[\partial/\partial N_i]_{i=1}^{n}$.

national parks if this required a decrease in their disposable income, or would they prefer to maintain the *status quo*? When possible, preferences should be inferred from actual choices that people make. From preferences, one attempts to estimate what individuals would be willing to sacrifice to achieve a particular outcome.

The process of inferring preferences and estimating the willingness of individuals to sacrifice to achieve some outcome is termed 'VALUATION' (Box 1). People are often uncomfortable when economists talk of valuing the existence of species. This is a matter of convenient, but imprecise, diction – no intrinsic value of organisms is measured, it is only that people's preferences are expressed. Value in this sense is a human construct and not an attribute of some study organism.

The willingness of individuals to make sacrifices has to be aggregated to arrive at a group preference or objective, and this process raises difficult questions that are discussed in the following section. One then identifies the tools at the disposal of regulators to implement policies (Box 3) and any constraints on which outcomes are feasible, as imposed, for example, by ethical considerations. Once the objective, constraints and implementation tools are identified, a selection of optimization methods is available to find the best management plan[5,15] (Boxes 2 and 4).

The procedure that we have outlined forms the basis of benefit–cost analysis. This is one approach, which is certainly imperfect, and that has advantages and disadvantages[16–21]. A number of other decision systems are commonly used, including cost-effectiveness criteria and multicriteria analyses. Policy makers might choose to ignore the outcome of an analysis for many reasons, but if they do so, they should explain their rationale.

Challenges and controversies

This analytical framework presents many challenges that ecological economists must address. We focus on one of the most significant challenges. It concerns how one constructs group preferences and, specifically, whose choices count.

Any outcome will affect different people in different ways. Someone must decide whose preferences matter when constructing the group

Box 3. Regulation and control

One must identify tools that authorities can use to regulate resource exploitation. We briefly discuss regulation of extractive and nonextractive industries and two enforcement methods.

Various methods are employed to regulate direct effects of extractive industries on target populations[a]. Two of these, which are relevant to the management of fisheries or harvested ungulates, are discussed.

No-take reserve

(some region of habitat is closed to harvesting.)

Advantages

- Only viable enforcement tool in some circumstances, for example, a fishery with many landing sites.
- Protects nontarget species.
- Preserves genetic structure of wild stock for populations with restricted gene flow.

Disadvantages

- Can be overly conservative.
- Can adversely affect particular local communities.

Effort control

(time spent harvesting and efficiency of harvesting equipment are restricted.)

Advantages

- Relatively stable method because total catch declines when the stock is depleted.
- Does not require precise data on stock fluctuations.

Disadvantages

- Total catch levels fluctuate.
- Must be adjusted to counteract technological advances.

Data on detrimental effects of nonextractive industries are lacking, but such effects will exist for some services. Regulations include limiting the size of operations, the types of activities permitted and access to wild populations. Butynski and Kalina[b] and Ewel[c] discuss these issues for gorilla tourism operations and wastewater treatment in natural wetlands respectively.

In addition to deciding on a type of regulation, one must also decide how to enforce it[d]. In command and control strategies, the regulatory agency imposes policies on firms. Market-based methods, such as harvesting taxes, involve configuring market forces so that the desired outcome coincides with the self-interest of individuals.

References

a Milner-Gulland, E.J. and Mace, R. (1998) *Conservation of Biological Resources*, Blackwell Science

b Butynski, T.M. and Kalina, J. (1998) Gorilla tourism: a critical look. In *Conservation of Biological Resources* (Milner-Gulland, E.J. and Mace, R., eds), pp. 294–313, Blackwell Science

c Ewel, K.C. (1997) Water quality improvement by wetlands. In *Nature's Services: Societal Dependence on Natural Ecosystems* (Daily, G.C., ed.), pp. 329–344, Island Press

d Kolstad, C.D. (2000) *Environmental Economics*, Oxford University Press

Box 4. Managing fluctuating populations

Natural variability and uncertainty about many ecological and economic factors complicate resource management. Management strategies that are not sensitive to environmental fluctuations or imperfect policy implementation are needed, particularly when authorities have only limited institutional power or when enforcement and monitoring costs are high[a–c]. An optimal target can be found for such situations. The derivation assumes a quasi-stationary distribution of population sizes, instead of assuming the population is in equilibrium[c]. It accounts for implementation errors, and the expected cost of lost revenue due to the non-zero probability of population collapse. We neglect nonextractive services for now. This time we solve Eqn 1:

$$0 = \frac{d\varepsilon[V(\hat{N})]}{d\hat{N}} \qquad [1]$$

where $\varepsilon[V(\hat{N})]$ is the expected present value from harvesting when allowing an effort level corresponding to a mean target stock size $\hat{N}$. Eqn 2 states this more explicitly:

$$\varepsilon[V(\hat{N})] = \varepsilon[B(\hat{N})] - C(\hat{N} \qquad [2]$$

where $\varepsilon[B(\hat{N})]$ is the expected revenue from harvesting plus the expected value of any leftover stock, and $C(\hat{N})$ is the upfront cost of the initial investment.

Fig. I illustrates this maximization problem. The solid curve is $\varepsilon[B(\hat{N})]$ where harvesting revenues have been summed over 50 years and the dotted diagonal line is $C(\hat{N})$ the revenue foregone by not harvesting all of the stock initially. The solid vertical line represents the optimal target. The dynamics are governed by a first order autoregressive process, obtained from linearizing $F(N) = rN(1-N/K)$ about the deterministic harvesting equilibrium. The relevant parameters are $[r,K,P,\rho] = [1,100,1,0.05]$ and the standard deviation of the autoregressive process is 20.

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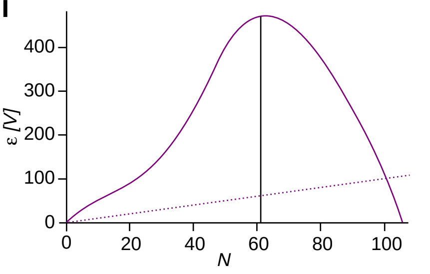

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The optimal target stock size when accounting for extinction risk is higher than the traditional target (from Eqn 4 in Box 2 but with only harvesting revenue, i.e. $Q = 0$). The optimal target is typically to the right of the peak of the production function and may be as high as $2K/3$. If nonextractive services or density dependent net prices were also considered, then the optimal target would be larger still. The models in Boxes 2 and 4 indicate that economic forces need not oppose conservationist arguments.

References

a Lauck, T. *et al.* (1998) Implementing the precautionary principle in fisheries management through marine reserves. *Ecol. Appl.* 8, S72–S78

b Roughgarden, J. and Smith, F. (1996) Why fisheries collapse and what to do about it. *Proc. Natl. Acad. Sci. U. S. A.* 93, 5078–5083

c Roughgarden, J. and Armsworth, P. Ecological economic theory for managing ecosystem services. In *Ecology: Achievement and Challenge* (Press, M.C. *et al.*, eds), Blackwell Science (in press)

objective, and how those preferences should be weighted. This is particularly difficult when effects from a single action are felt over different scales.

For example, consider a decision on whether to designate as a reserve a region of marine habitat. Fish stocks are a societal resource, ownership of which is shared by all. However, creation of the reserve will affect fishing communities more than it will people not involved in that industry. Many communities along hundreds of kilometers of coastline might enjoy benefits of the reserve as an exporter of larvae and a buffer against stock collapse. The costs in lost fishing rights in particular waters will be borne by a select few communities. Individuals in these few communities are less likely to respect the reservation status if they feel their interests are not given fair consideration. It is not clear in this situation who should form the enfranchized set or how their preferences should be weighted. Another example where the outcome of an analysis depends on the choice of enfranchized set is given by Kremen *et al.*[22] for tropical deforestation.

Although it is necessary to discuss preferences of the current generation, many ecological economic decisions have irreversible consequences and implications for subsequent generations. How can we account for preferences of future generations, when we have no way of knowing what form these will take[23]? In the marine reserve example, creation of the reserve would increase the probability that fish stocks would persist and be available to future generations. However, not creating the reserve would allow more fish to be caught and resulting revenues to be invested elsewhere, perhaps in some form of capital that subsequent generations will value more highly than fish.

People tend to value having US$100 today more highly than they would having the same amount in ten years' time, and present-day values are given more weight than are future values when comparing revenues at different times. Values are commonly compared in the present, and a DISCOUNT RATE is employed to back-calculate the present-day equivalent of revenues earned in the future. Discounting can be thought of as an inverse process to accumulating interest. This process poses difficulties for ecological economic analyses. Ecological time-scales are often much longer than are customary economic time horizons, and catastrophic losses in the distant future appear as only rather minor costs in the present when employing a constant discount rate. Table 1 displays future values equivalent to US$100 in the present when employing a 5% annual discount rate. Experimental research, however, suggests that discount rates might not be constant and that people might employ decreasing discount rates for decisions with effects that are felt over progressively longer time-scales[11,24].

Table 1. Future value of US$100 today

	Years in future			
	25	50	100	200
Future value (US$)	339	1147	13 150	1 729 300

Thus far, we have assumed the current allocation of wealth is fixed when constructing the enfranchized set. This assumption itself warrants scrutiny, because the current distribution of wealth within and among nations has a high variance. Many economists would maintain that it is not their responsibility to assert what is a fair or equitable allocation of wealth. However, if one takes the present wealth distribution as sacrosanct, then one posits a particular enfranchized set that is weighted by existing income brackets. Furthermore, what people value depends on the wealth distribution. Suppose we wished to infer preferences for an environmental planning decision that would affect each person equally, and we decided to give their preferences equal weighting. Then we could not use price-based estimators of preference without adjusting for the income levels of each individual, because the values they assign will depend on their particular economic circumstances. However, it is not clear how one could make such an adjustment in any systematic way. Of particular concern for ecological economists is that there will be a relationship between preferences for some ecosystem services and an individual's economic circumstances, although it is unknown what form this relationship will take.

Avenues for future research

There is much scope for simply updating the ecology used in natural resource economics. In particular, more attention should be given to population structure and to simple management strategies with low data requirements. Only recently have models been designed that consider the spatial structure of populations[25–28], and we know of few models[29] that account for their genetic structure. Uncertainty and variability pervade ecological systems, and although many analyses assume a sophisticated level of control over these systems, we rarely have the data or institutional authority to implement such management strategies. Analyses are required of simpler robust strategies that have low data demands and need minimal continuous updating (Box 4; Refs 30–33).

Although work is needed in conventional natural resource economics, there is a more pressing need to develop the field of ecological economics itself, by generalizing the concepts of a resource and of a service. These generalizations open ecological economics to a much broader range of ecologists than have traditionally interacted with economic ideas, and rapid advancement is possible in many new areas. For example, we anticipate substantial further analyses of the economics of pollination

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Glossary

Commons: (or equivalently a common property resource or public good); a resource that provides services that must be shared by some community of individuals or the public.
Discount rate: used to allow comparisons of benefits and costs experienced at different points in time. It allows conversion of future values into their present-day equivalent.
Externality: occurs when the actions of one individual impose costs or benefits on another individual, who has not agreed to receive those costs or benefits.
Extractive services: services that are provided by extracting some amount of the resource in question.
Market failure: when the market alone does not result in an efficient provision of some good or service. The provision of a service is said to be efficient when it is impossible to make any individual better off without making someone else worse off. Market failures are typically caused by the presence of externalities.
Natural capital: (as opposed to human or manufactured capital) is the stock of society's environmental assets.
Nonextractive services: services that do not involve removing biomass from the ecosystem providing the service, for example, water purification services.
Normative economics: provides recommendations to policy-makers concerning what should happen in some situation and how best to intervene to ensure that it does. By comparison, positive or descriptive economics is the more objective study of what does happen.
Valuation: the process of estimating the willingness of individuals to sacrifice or pay to achieve some goal or outcome.

services[34], and more studies in ecological economic epidemiology that treat the pool of infectious diseases as a commons to be managed[35,36].

Few analyses incorporate nonextractive revenues, but these predict markedly different findings from analyses that only consider extractive industries[9–11]. These analyses have urgent new data requirements, and foremost among these is the need to identify and value the breadth of services that natural systems provide. Several ecologists are currently contributing to this area[7]. Attempts to classify and value ecosystem services and to identify how different ecosystem components contribute to their provision can quickly seem overwhelming. We feel that some benchmark of success for such valuation studies needs to be developed and that those attempts that set modest goals are likely to meet with most success. One issue receiving less attention is whether certain species suffer detrimental effects because of nonextractive services and, if so, what regulation of industries exploiting these services is required (Box 3). Finally, analytical approaches focusing on only a few target species might not be adequate to capture the full value of ecosystems, and a more holistic approach might be needed. Macroecological ideas could provide an excellent foundation for such an approach[33]. This again would be an entirely new area where any amount of research could yield rich returns.

It is difficult to highlight select areas where research will prove beneficial, because so much needs to be done and so much stands to be gained by doing it well. Natural capital is being degraded at an accelerating rate and a combination of sound ecology with good economics will go a long way towards decelerating that degradation.

References

1 Costanza, R. and King, J. (1999) The first decade of *Ecological Economics*. *Ecol. Econ.* 28, 1–9
2 Kolstad, C.D. (2000) *Environmental Economics*, Oxford University Press
3 Kneese, A.V. and Sweeney, J.L. (1985) *Handbook of Natural Resource and Energy Economics* (Vols 1–3), Elsevier Science
4 Dasgupta, P.S. and Heal, G.M. (1979) *Economic Theory and Exhaustible Resources*, Cambridge University Press
5 Clark, C.W. (1990) *Mathematical Bioeconomics: The Optimal Management of Renewable Resources* (2nd edn), Wiley-Interscience
6 Pearce, D. (1998) *Economics and Environment: Essays on Ecological Economics and Sustainable Development*, Edward Elgar
7 Daily, G.C. (1997) *Nature's Services: Societal Dependence on Natural Ecosystems*, Island Press
8 Vitousek, P.M. *et al.* (1997) Human domination of Earth's ecosystems. *Science* 277, 494–499
9 Vousden, N. (1973) Basic theoretical issues of resource depletion. *J. Econ. Theory* 6, 126–143
10 Hartman, R. (1976) The harvesting decision when a standing forest has value. *Econ. Inq.* 14, 52–58
11 Heal, G. (1998) *Valuing the Future: Economic Theory and Sustainability*, Columbia University Press
12 Milner-Gulland, E.J. and Mace, R. (1998) *Conservation of Biological Resources*, Blackwell Science
13 Boulding, K.E. (1966) The economics of the coming Spaceship Earth. In *Environmental Quality in a Growing Economy* (Jarrett, H., ed.), pp. 3–14, Resources for the Future
14 Krutilla, J.V. (1967) Conservation reconsidered. *Am. Econ. Rev.* 47, 777–786
15 Intriligator, M.D. (1971) *Mathematical Optimization and Economic Theory*, Prentice Hall
16 Kelman, S. (1981) Cost-benefit analysis: an ethical critique. *Regulation* 1, 33–40
17 DeLong, R.V. *et al.* (1981) Replies to Steven Kelman. *Regulation* 2, 39–43
18 Arrow, K.J. *et al.* (1996) Is there a role for benefit-cost analysis in environmental, health and safety regulation? *Science* 272, 221–222
19 Gatto, M. and de Leo, G.A. (2000) Pricing biodiversity and ecosystem services: the never-ending story. *BioScience* 50, 347–355
20 Goulder, L.H. and Kennedy, D. (1997) Valuing ecosystem services: philosophical bases and empirical methods. In *Nature's Services: Societal Dependence on Natural Ecosystems* (Daily, G.C., ed.), pp. 23–47, Island Press
21 Ludwig, D. (2000) Limitations of economic valuation of ecosystems. *Ecosystems* 3, 31–35
22 Kremen, C. *et al.* (2000) Economic incentives for rain forest conservation across scales. *Science* 288, 1828–1832
23 Solow, R.M. (2000) Sustainability: an economist's perspective. In *Economics of the Environment: Selected Readings* (4th edn) (Stavins, R.N. ed.), pp. 131–138, W.W. Norton
24 Loewenstein, G. and Prelec, D. (1992) Anomalies in intertemporal choice: evidence and an interpretation. *Q. J. Econ.* 107, 573–597
25 Tuck, G.N. and Possingham, H.P. (1994) Optimal harvesting strategies for a metapopulation. *Bull. Math. Biol.* 56, 107–127
26 Brown, G. and Roughgarden, J. (1997) A metapopulation with private property and common pool. *Ecol. Econ.* 22, 65–71
27 Conrad, J.M. (1999) The bioeconomics of marine sanctuaries. *J. Bioecon.* 1, 205–217
28 Sanchirico, J.N. and Wilen, J.E. (1999) Bioeconomics of spatial exploitation in a patchy environment. *J. Env. Econ. Manage.* 37, 129–150
29 Stokes, T.K. *et al.* (1993) *The Exploitation of Evolving Resources*, Springer-Verlag
30 Weitzman, M.L. Landing fees vs. harvest quotas with uncertain fish stocks. *J. Environ. Econ. Manage.* (in press)
31 Lauck, T. *et al.* (1998) Implementing the precautionary principle in fisheries management through marine reserves. *Ecol. Appl.* 8, S72–S78
32 Roughgarden, J. and Smith, F. (1996) Why fisheries collapse and what to do about it. *Proc. Natl. Acad. Sci. U. S. A.* 93, 5078–5083
33 Roughgarden, J. and Armsworth, P. Ecological economic theory for managing ecosystem services. In *Ecology: Achievement and Challenge* (Press, M.C. *et al.*, eds), Blackwell Science (in press)
34 Southwick, E.E. and Southwick, L. Jr (1992) Estimating the economic value of honey bees (Hymenoptera: Apidae) as agricultural pollinators in the United States. *J. Econ. Entomol.* 85, 621–633
35 Brown, G. and Layton, D.F. (1996) Resistance economics: social cost and the evolution of antibiotic resistance. *Environ. Develop. Econ.* 1, 349–355
36 Philipson, T. (2000) Economic epidemiology and infectious diseases. In *Handbook of Health Economics* (Vol. 1b) (Culyer, A.J. and Newhouse, J.P., eds), pp. 1761–1799, Elsevier Science