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Managing Ecosystem Resources[†]

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We explore some of the special problems faced in the management of environmental resources, paying particular attention to valuation of ecosystem services, externalities, uncertainty, and nonlinearities characteristic of complex adaptive, highly interconnected systems. Through consideration of case studies drawn from the management of lake and mangrove ecosystems, we develop a theoretical perspective in which we analyze the challenges, suggest approaches to their resolution, and endeavor to derive principles that may guide management more generally.

Introduction

Humans are part of nature and must utilize the bounty it provides in order to survive. However, the choices we make regarding how to utilize natural systems have fundamental implications for their maintenance and ultimately for the sustainability of the services they provide humans. We rely on natural systems directly for food, water, oxygen, fiber, fuel, and pharmaceuticals and indirectly for pollination, for the stabilization of climates and coasts, and for an uncountable list of other essential aspects of our quality of life (*1*). We deliberately modify some systems (as in agriculture) and extract resources from others, in all cases affecting a range of services these systems do and might provide.

The exploitation of natural systems, including efforts to modify and manage them, forces us to confront the tradeoffs between real and potential services and the effects upon their resiliency.

Although it is appropriate and relatively straightforward to construct lists of the most important of such services, their valuation—an essential step for making management decisions—poses daunting challenges. Despite some efforts in that direction (*2*), it makes no sense to speak of the total value of ecosystem services on the planet. What does make sense, however, is to attempt to estimate the marginal costs that would be associated with having to replace the services currently provided by a piece of nature. The challenge, nonetheless, is far from easy. Conflicting value systems, intergenerational and intragenerational equity, and the basic principle of maintaining the integrity and resiliency of ecosystem functions pose daunting tasks. Our goal in this paper will be to identify some of the problems and to illustrate them with particular examples that exhibit the essential complexities. Our approach represents a theoretical perspective, illuminated by case studies, rather than an effort to deal with all the practicalities of those case studies.

In principle, efficient management of ecosystems involves the same economic principles as does efficient management of fossil fuels and other capital assets. In practice, however, ecosystems possess several features that make good management particularly problematic. They are, first of all, highly nonlinear complex adaptive systems (*3, 4*), with extensive interconnections among components. Such features lead to the existence of multiple domains of attraction, to elaborate potential path dependency in development, and to the possibility of qualitative shifts in dynamics due to a combination of endogenous and exogenous factors. Periods of drought in grasslands, for example, can lead to patterns of erosion, loss of tree species, and eventual desertification if extended across long enough periods of space and time. Similar major transitions can also occur in aquatic and marine systems due to positive feedbacks, and we will return to some of these examples later. Our conclusions will be that, given the challenge of sustaining services and managing ecosystems in the face of exogenous and endogenous uncertainty, such nonlinearites and unpredictable aspects argue for adaptive management and precautionary principles.

A related feature is that ecosystem development is an idiosyncratic, historically constrained process, making generalization difficult and uncertainty high. Finally, regarding human exploitation, ecological assets in large part represent public goods, and the consequent externalities associated with their use are not usually well accounted for in market mechanisms. In this paper, we will attempt to elucidate these difficulties and suggest ways of mitigating their effects. In so doing, we will draw on two specific examples: mangrove swamps in the tropics and shallow lakes in North America.

Managing a Mangrove Ecosystem

Intelligent management of any system requires quantification of costs and benefits and evaluation of the tradeoffs involved in different courses of action. The most powerful way to do this bookkeeping and projection is through some sort of model, which requires as a first step the construction of a systematic, quantitative catalog of the sources and consumers of ecosystem services. For a given location, one must know which services are used locally (e.g., pollination, pest control, renewal of soil fertility, serenity); which are used globally (e.g., preservation of the genetic library, climate stabilization), and which are exported to other regions (e.g., seafood, timber, flood control, water purification). For the case of a mangrove swamp, some of these are obvious, but some are hidden. In the category of directly consumed goods, the mangroves harbor and sustain fisheries containing not only species that are endemic to the swamp but also others that migrate and are only occasional users. The mangrove trees themselves are used as wood for fuel and for construction. Salt can also be produced in some circumstances.

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The mangroves also provide many indirect services. By providing buffers to the coastline, they offer storm control. By anchoring the soil, they reduce erosion. They recycle nutrients, help in the purification of sewage, and provide habitat for a variety of birds; partly as a consequence, they also can serve as an attraction for tourism. Mangroves also sequester carbon as well as toxic materials. Although this is only a partial list, one can see that the dimension of the output space in such systems can be quite large. In and of itself, that fact is not impossible to overcome—after all, the output space of a typical firm contains a large number of products. However, when it comes to measuring and comparing all these effects, the problems are more serious. The firm knows how to measure its products, and the profit motive provides a natural way of comparing the importance of various items; such ready measures, however, are not easily available for ecosystems.

Despite these remarks, we can formulate a general model for analyzing the impact on well-being from different management strategies. We posit the existence of a social planner who represents society in its preferences for services supplied by the mangrove swamp. The Nobel Prize winning economist Tjalling Koopmans showed in a number of articles that these preferences can be represented as the "social well-being":

$$W = \int_0^{\infty} U(C(t)) e^{-\delta} t \, dt \tag{1}$$

where $C(t)$ is a vector of all the relevant consequences from changes in management strategies. The components may be the catch of fish at time t, the amount of fuelwood collected in the swamp, etc. We are assuming here a sufficient degree of altruism that, for practical purposes, we can consider government policy as seeking to maximize the common ethical principles of humanity. In reality, the results we seek only require Pareto optimality, the discussion in terms of a social planner being solely for convenience in presentation.

All these consequences are aggregated into the utility at time t by the function U. Typically, U is a concave function, reflecting diminishing returns. This implies that the gains from higher than average utilization in some years does not compensate for the losses in less than average years; hence, this implies that, everything else being equal, society is interested in a more equal distribution between different time periods. W is the present value of future flows of utility, discounted at rate $\delta > 0$. Note that this rate is the utility discount rate, which in general is different from the rate at which consumption (or the monetary value of the consequences) is discounted. That the utility discount rate is positive is, according to Koopmans, a mathematical necessity. Otherwise, we would not be able to define preferences for the consequences from now and into the infinite future. Determining the discount rate can be problematical, however, especially given issues of intergenerational equity. The discount rate (which more generally need not be constant as the time horizon expands) is perhaps the most influential parameter governing cost-benefit analysis and management choices, yet its proper choice is extremely difficult.

We can now define the optimal management as a choice of all the control variables that determine the future development of the mangrove swamp, including all the services provided by the swamp, as being a choice that maximizes social welfare. The choice need not be fixed for all time but is a best estimate based on current information. In adaptive approaches, continual updating may be necessary. The social planner thus chooses the use of the mangrove trees, the fishing effort, etc. so as to maximize the present value of the stream of future utilities. To do that, one obviously needs information on the working of the ecological systems and on the utility derived from the services provided by the mangroves. With this in mind, let us now return to the comparison with the multiproduct firm.

There are several reasons why the problem of managing an ecosystem is different in character from that of managing a multiproduct firm. For one thing, the producers in the firm generally have good knowledge of the products that they can (potentially) produce and of the production technology for doing so. By contrast, we are relatively ignorant concerning relationships in ecosystems and are likely to underestimate the list of services they provide. This represents a particular form of uncertainty—what unknown benefits, such as potential pharmaceuticals yet to be identified, lie concealed from our view, awaiting discovery?

A second difficulty with attempting to manage an ecosystem like a multiproduct firm is that, for the firm, the future utilities are given by the forecasted market prices for the goods it is producing; in contrast, for the mangrove, system many of the outputs have a "public" or "common property" feature that makes it difficult to determine the relative value the service conveys or to appropriate that value to the entity doing the managing.

For example, storm protection has this public character. If it is provided, everyone inland automatically gets the benefits. If any particular farm had to contract for such services, it would find that most of the benefits would go to others (free riders); thus, there would be little incentive to participate. Contrast this with wood for fuel, which is similar in character with most of the products we associate with the multiproduct firm. This wood is private, in that the benefits of its use accrue to the person who gets it. Consequently one can contract for it, and the price paid will be a reasonably good measure of the value it has to the person who values it most highly. Fish are a common property resource to the fishermen but take on private goods aspects once caught. Thus, the fish can be contracted for, but the common resource must be managed centrally if we are to avoid overexploitation of the resource. Among the other services identified in the mangrove swamp, soil erosion protection and nutrient recycling have very much the same public character as storm protection. Carbon sequestration is an extreme example where the benefits are not even confined locally but accrue to all of humanity. Indeed, the beneficiaries of conservation actions designed to sequester carbon are in general separated spatially and temporally from the costs of those actions. Determining the values to place on such items, relative say to firewood, is quite difficult but must be done if there is to be any "bottom line" for managers to pursue.

The next step in effective modeling is to understand the dynamic relationships among the various variables of the system. This step is analogous to knowing the production relationships in a multiproduct firm. Some variables of an ecosystem are fixed at a moment of time and can only be changed with the passage of time. These we refer to as the *state* variables of the system. For the mangroves these will include the area of the swamp (A), the biomass of the mangroves (M), the fish stock(s) (Y), and the stock of nutrients in the soil (N). Other variables of the system (flow or control variables) can be changed at a moment of time. In the mangroves, control variables will include the number of person and boat hours devoted to fishing for the various species, the number of fish caught per unit time (h_y), the amount of wood cut for fuel and construction materials (h_m), and the number of boats used for sightseeing.

Once we have identified the relevant variables, we need to characterize the interdependencies among them and, consequently, the ways in which they will evolve over time as functions of choices we make. From a mathematical point of view, the result will typically be a system of differential equations that tell us the rates of change of the state variables at any moment of time as a function of the current state and values of flow variables. In the absence of uncertainty, these equations would determine the transformation of the ecosystem over time.

For the mangroves, we can start to construct the necessary system as follows. To begin, we model the local, near-shore fish population in terms of two functions, the unimpeded growth rate (g_y) and the carrying capacity (C_y). This is a drastic oversimplification, neglecting such complexities as the age structure or size structure of the population; but it is a place to begin. The unimpeded growth rate is in itself a compound function, collapsing the rates of recruitment and mortality into a single variable; furthermore, it will depend on the state variable and extrinsic variables in ways often difficult to quantify. Furthermore, for fish endemic to the mangroves, both of these parameters will depend on the area A of the swamp and stock of nutrients N. Thus, simplistically, the dynamics of the fish population are assumed to change according to a logistic relation of the form

$$dY/dt = g_y(A,N)Y(C_y(A,N) - Y) - h_y \qquad (2)$$

where Y is the size of the fish population and h_y is the harvest rate. Similarly, the mangroves M will have their own growth rate g_m, their own carrying capacity, and their own harvest rate h_m, leading to an equation of the form

$$dM/dt = g_m(A,N)M(C_m(A,N) - M) - h_m \qquad (3)$$

for the rate of change of biomass. Note that the growth rates of the state variables will depend on the area of the swamp, which is subject to change due to processes of growth and decline, as well as on nutrients and other variables not identified explicitly. The dynamics of these variables, in turn, may be affected by management decisions as well as by the dynamics of the state variables, providing nonlinear linkages whose complexity increases with the number of variables considered.

The Necessity of Simplification

Even supposing that we can determine the general forms of such systems, we still would not be prepared to make management choices until we determined the growth rate and capacity functions $g(.)$ and $C(.)$. The standard statistical method for estimating such functions involves cross sections; that is, one observes many different swamps with different state variable configurations and uses regression methods to identify variables. Unfortunately, this procedure is rarely useful for ecological systems because they are so idiosyncratic—the relationships that characterize one swamp may not generalize at all to another, so the common structure necessary for cross-sectional analysis is missing. The difficulties of cross-sectional analysis of ecosystems is discussed in detail in Cole et al. (*5*). Approaches to these problems include long-term observation and ecosystem experiments (see, for example, ref *6*). Alternatively, considerable progress has been made in mechanistic, individual-based approaches to assembling ecological systems (*7, 8*), although dimensional reduction remains an essential and difficult challenge. Such individual-based models begin from known biophysical relationships and allow systems to develop, producing ensembles of possible outcomes. It is essential in such approaches therefore to determine what dynamical features are robust and to develop statistical methods to extract regularities from masses of computer runs. To that end, statistical mechanical methods sometimes can be developed to reduce the complexity of the simulation models to the essential core (*9*−*11*).

The mangroves are not unique in their complexity; indeed, they probably represent ideal starting points for investigation just because the issues are simpler than they are for more extended ecosystems. For example, in modeling the Pacific Continental Shelf, we must include whales, kelp, plankton, sea otters, shellfish, finfish, seals, and birds intertwined in their dynamics through complex and intricate webs of interaction. Detailed modeling of such systems that attempted to account for every component would be at best misguided and at worst seriously misleading. One must seek out methods of simplification, choosing the scales of space, time, and organizational complexity that allow us to focus on the most important variables involved in the associated choice. The need for simplification applies to any ecosystem including, of course, the mangroves.

Simplification can take many forms, and appropriate steps will depend on the system considered as well as the questions being asked. Depending upon circumstances, one may treat some variables (such as the total area of the swamp) as being constant and more generally ignore the dynamics of slow variables (such as mangrove regeneration). This might enable us to focus on the dynamics of the fish equations and on valuing losses in protection from storms and erosion as well as other public services.

In this way, we are often able to cull out the most important factors in a management problem. But progress will depend on obtaining good characterizations of the dynamics of the fast variables; this is no easy feat for ecological systems. Even for the dynamics of fisheries, which have been the object of intense study because of their economic importance, considerable uncertainties remain. Many of these may be traced to particular critical stages in the process, such as the recruitment of new individuals; but due to the nonlinearities inherent in these systems, small uncertainties in some parameters can become magnified through the loop of interactions, leading to large uncertainties in system dynamics. In such circumstances, the best strategy may be to be precautionary and adaptive (*12*)—move in small steps, using continual monitoring to adjust harvesting and other management strategies. Thus, we could allow a small shrimp farm at the outset, monitor soil erosion and fish stocks, and proceed with a larger farm if the harms turn out to be small. Such adaptive policies are in general preferable to a “no change” strategy because they allow information gain through “adaptive probing” (*13*). In contrast, policies of no change do not allow us to learn about changes in character the system may be experiencing far from the particular equilibrium; they further necessarily assume that the status quo is good, which may not be the case.

The approach described above is a highly aggregated one, ignoring the power of individual incentives. Changes in individual behaviors, in the aggregated model, do affect rewards but in diffuse ways that dissipate incentives. In dealing with problems of the commons, in general, we must find ways to tighten feedback loops, increasing individual rewards and internalizing externalities (*4*, *14*). Such approaches provide public incentives to users of the ecosystems. For the fishery, this might mean the use of tradeable quotas and common property resource management that would both serve to limit the catch and to provide incentives for using least-cost methods of fishing.

Typical permit systems in fisheries, called individual transferable quotas, allocate percent shares of an annually defined (variable) total allowable catch (TAC) rather than a fixed tonnage. This approach provides an adaptive management mechanism by allowing the TAC to be redefined annually in response to changing ecological conditions. The use of individual transferable quotas (ITQs) also reduces overcapitalization in the fishery, releasing the capital for more productive uses. It provides an accurate valuation of the fishery, one necessary component in valuing its interdependency with the mangroves. These systems are now used with considerable success around the world (*15*).

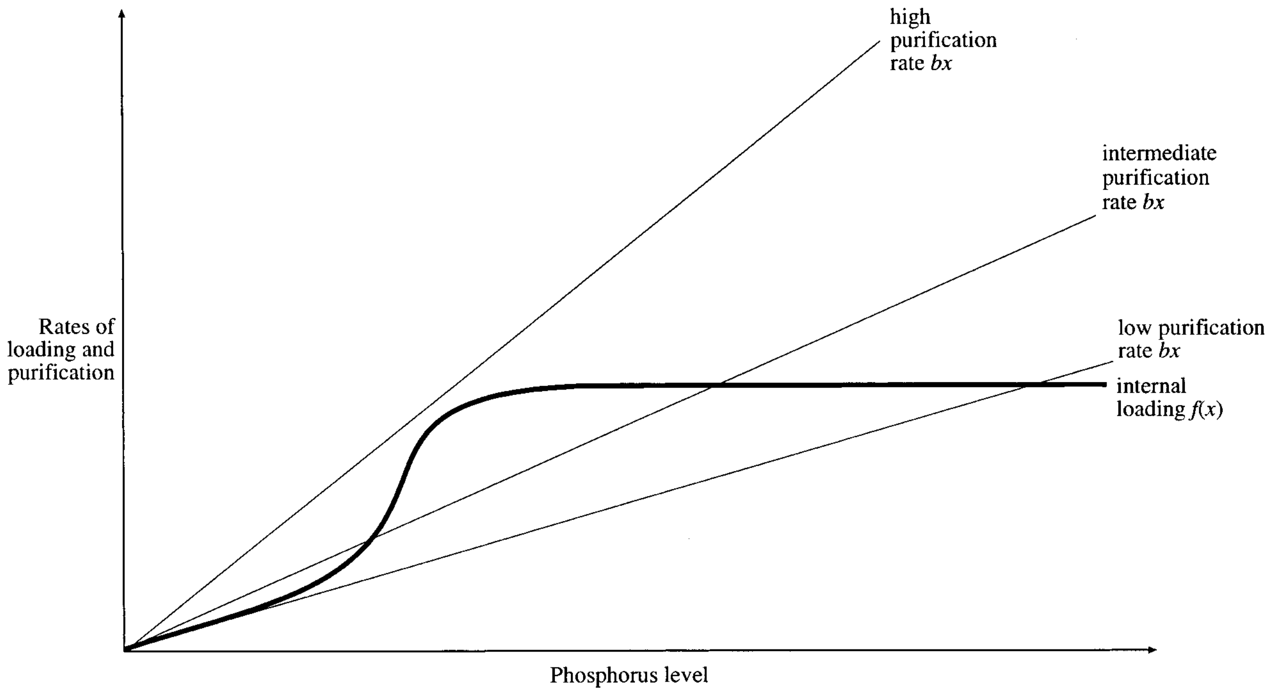

FIGURE 1. Phosphorus loading and purification rates at three levels of purification. Intersection points indicate equilibria. Note that there are three possible equilibria at intermediate purification rates.

Simplification through elimination of slow time scale dynamics can be helpful in many situations; but ultimately, there may be a price to pay if one does not consider the coupling between dynamics on multiple time scales. Ludwig et al. (*16*) demonstrated the importance of such phenomena in their consideration of the dynamics of the spruce budworm in Canadian forests. The dynamics of slow variables hold the key to resilience and potential domain shifts. Although identification of such variables and potential loss of resiliency is problematical, their importance is fundamental to management.

Discontinuities and Multiple Time Scales: The Case of Temperate Lakes

Precautionary and adaptive approaches are well-justified techniques for dealing with uncertainty. Unfortunately, even the most cautious of adaptive management policies cannot protect against the potential for catastrophic changes in system character. It has long been a dream of theoreticians and managers alike to be able to detect hints of impending system collapse in measures of current system performance, but efforts to do so have been no more successful than efforts to predict when the stock market will experience meltdowns. There are many examples where seemingly small changes in one place have quite large impacts on the overall system, and these may be irreversible. Fisheries provide prototypical examples of such potential disasters—overfishing, for example, can reduce fish populations below sustainable levels, engendering collapses that may be difficult or impossible to reverse. More generally, ecosystems typically respond nonlinearly to perturbation; their supply of services may hardly appear to change with incrementally increasing human (or natural) impacts up until a point, whereupon the response can be dramatic and very refractory to efforts to reverse.

These dangers are well illustrated by the ecology of phosphorus-limited shallow lakes in the border area between the United States and Canada, but apply more generally to temperate lakes worldwide. As with mangrove swamps, an accurate model would need to keep track of many variables: fish populations, phosphorus suspended in the water, algal blooms, and other plant life, phosphorus embedded in the mud of the lake bottom, and more. However, much as for the mangrove swamp, a sensible way to begin is through the development of simplified models incorporating macroscopic and highly aggregated variables.

As an example, Carpenter et al. (*17*) model the dynamics of a lake in terms of the store of phosphorus (x) suspended in algae, according to a relation of the form

$$dx/dt = a - bx + f(x) \tag{4}$$

Here a denotes phosphorus inputs from the watershed (sometimes referred to as the "loading"); b is the purification rate—the rate of loss of phosphorus per unit stock (through sedimentation, outflow, and sequestration in organisms other than algae); and $f(x)$ is internal loading. This function is assumed to be "S-shaped"; that is, for low stocks of phosphorus, additions tend to be stored in the lake bed so that there is a relatively low marginal return to the water. For higher stocks this marginal return increases, only to fall again when maximal suspension is approached. This equation represents a "minimal state variable" approximation to the complex food web of a real lake. Carpenter et al. (*17*) provide a justification for this abstraction, including a rationale for the form of the "recycling curve", $f(x)$. The recycling curve reflects natural positive feedback processes that are triggered inside a typical lake when phosphorus load becomes too high.

In the absence of external loading ($a = 0$), this system essentially has three behaviors (Figure 1). At low purification rates (low b), the only stable equilibrium is a eutrophic one, corresponding to a high level of phosphorus. In this state, the water would be turbid even without external loading due to natural processes.

At the opposite extreme of high purification (high b), it is clear from Figure 1 that natural processes will completely clear phosphorus from the system. As external loading (a) is increased, effectively shifting the still-sigmoidal total loading curve upward until it crosses the purification curve, a range of loading levels will be entered in which two stable states exist—an oligotrophic (clear water) state, which is highly valued by the lake's users, and a eutrophic one, which is disliked by the lake's users but indirectly valued by agricultural interests because it allows them high fertilizer use. Which state is reached for a given constant loading depends on the initial stock of phosphorus, with high initial stocks leading to a eutrophic long-run equilibrium. Note that all long-run outcomes are reversible in this case—sufficiently low loading rates will always restore the clear-water state if it is maintained for a sufficiently long time. However, the economic barriers to reversibility, for example, as agricultural interests become dependent on the high rate of fertilizer use, may be substantial.

If the external loading *a* is increased yet further (still in the case of high purification rate), a second threshold level will be reached where the oligotrophic equilibrium vanishes and only the eutrophic equilibrium remains. Even if the system was previously nestled comfortably in an oligotrophic state, the increase in loading can cause a jump to the eutrophic state. As long as the purification rate is high, however, this state (and hence that described in the previous paragraph) is reversible—reduction in the loading rate (*a*) will restore the system to a stable oligotrophic equilibrium whose clear water can be enjoyed by users.

This reversibility of eutrophy is lost, however, at intermediate purification rates (*b*). In this case, even without external loading, the system has two possible stable states—an oligotrophic one and a eutrophic one. In this case, like that described in the previous paragraph, increased loading can suddenly flip a system from oligotrophy to eutrophy. The difference is that now reduction of loading back to low levels will leave the system in a eutrophic state, since the high internal loading rates associated with eutrophication are now sufficient (relative to the intermediate purification rate) to maintain this condition. In this case, even very cautious adaptive management may fail to preserve the system in its oligotrophic state since indicators of impending qualitative shifts are in general lacking in such situations. This case emphasizes the point made by Arrow and Fisher (*18*) that, in the face of irreversibilities, precaution in making additional development investments is advisable lest they turn out in retrospect to have been inappropriate. It may argue for the imposition of "safe minimum standards" [e.g., Berrens et al. (*19*)] as a measure to maintain the system far from qualitative shifts.

Property Rights and Externalities

If one firm were to have the sole ownership of all the services provided by the mangroves or lakes, it could sell these services on markets and in effect operate as would any multiproduct firm (such as a farm). As a result, the ensuing management of the mangrove forest or the lake would be efficient; if the firm further were operating in competitive markets, it would also maximize the nominal social well-being. However, one important characteristic of these systems is that it is in general impossible to privatize all the services (i.e., assign private property rights to them) and that in practice most services are not assigned property rights.

Another example is provided by an open access fishery. Quite often, coastal fisheries supported by mangrove swamps or lake fisheries are open access; that is, anyone can use the fishery. This corresponds to a situation when there are no property rights whatsoever to the fishery. In this case, any fisherman will enter the fishery until all rents accruing to the fish stocks have been dissipated. Note that the net social revenue from the fishery is equal to the rent generated by it. Thus, with open access, the fishery does not provide any social good, and one component of the services provided by the mangrove forest has simply the value zero. In this case, the prime objective of the coastal or lake management must be to limit the access to the fishery in order to let the fish stocks recover and thereby generate a positive rent. ITQs, as mentioned earlier, provide one possible mechanism, but only one.

Discussion

Managing ecological systems raises challenges both old and new. In principle, the issues involved are those that apply to the management of any capital asset, but the relative importance of these is changed. Management involves in a fundamental way elements that may exist in traditional economic approaches but are given inadequate attention. In particular, traditional markets may not adequately reflect externalities and social costs. Furthermore, ecological systems are highly nonlinear, constrained by historical behavior, and with the potential for dramatic shifts in dynamics. The greatest challenge perhaps is in the valuation of the manifold services ecosystems provide humanity and in maintaining the resiliency that sustains them. To this end, we recommend precautionary and adaptive approaches coupled with mechanisms to tighten cost and benefit loops and to internalize externalities, including local empowerment and common property resource management.

The management of ecological systems is neither beyond the reach of economic analysis nor neatly treated within conventional frameworks. The particular challenges faced can lead to new dimensions of economic theory and new partnerships between economists and ecologists. The path is not straightforward, but the journey is one well worth making.

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