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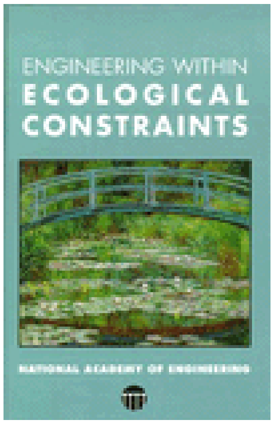

Engineering Within Ecological Constraints

Peter Schulze, Editor; National Academy of Engineering

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Engineering Within Ecological Constraints

Edited by Peter C. Schulze

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PREFACE

Advances in engineering and technology have historically been crucial to solving important societal problems, including those that result from the environmental impacts of humans. This pattern will undoubtedly continue into the future. Unfortunately, however, the application of some innovations has had undesirable, sometimes unanticipated, environmental consequences. Therefore, a primary challenge for the future is to maximize the benefits of technological innovation and use while minimizing undesirable environmental effects.

One response to this challenge is the recent efforts in business and industry that emphasize preventing environmental damage, a practice based on industrial ecology. Like traditional ecology, which is the study of natural and managed ecosystems, industrial ecology is the study of industrial systems and their relationships to natural and managed ecosystems. The foundation of industrial ecology is a systems approach to environmental design and management based on an understanding of the flows of materials and energy in industrial and consumer activities, the effects of these flows on the environment, and the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources. These efforts have made substantial progress in reducing pollution and the consumption of raw materials per unit of production. However, inefficiencies are only part of the problem.

Gains in efficiency can be overshadowed by concurrent increases in the scale of production that result from population growth or increased per capita consumption. For example, efficiency improvements in fishing technology have led to overfishing and the collapse of several fisheries. Fishing quotas designed to address this problem ideally are based on economic theory and on ecological data and reasoning. In fisheries as in other areas of economic activity, averting problems of overuse will require that insights from ecology, engineering, economics, and other fields be better integrated in devising technological and policy solutions.

The papers in this volume are the products of a National Academy of Engineering (NAE) meeting intended to take a small step toward promoting the necessary multidisciplinary approach.

They were contributed by engineers, ecologists, and social scientists. They provide a variety of perspectives on the challenges faced in efforts to engineer within ecological constraints. We hope these papers will contribute to efforts to find paths toward sustainability and will stimulate further cross-disciplinary interaction.

This volume originates from an April 1994 meeting we chaired based on a concept originated by Peter Schulze. Both the publication and the meeting are components of an ongoing NAE initiative exploring issues of technology and the environment. We are indebted to the authors for their excellent contributions, to a group of external reviewers of those contributions, and to an editorial team composed of Peter Schulze, Dale Langford, Jessica Blake, and Penny Gibbs. On behalf of Peter Schulze, thanks also go to Austin College for supporting his work on this volume. In addition, we thank Deanna Richards, who heads up the NAE's technology and the environment effort, and Bruce Guile, who directs the NAE Program Office, for excellent advice and assistance throughout the project.

Special appreciation also goes to the Andrew W. Mellon Foundation for supporting this project and related elements of the NAE's Technology and Environment Program. Finally, we would like to acknowledge the leadership at the NAE for the foresight to initiate and sustain the NAE's program that continues to play a catalytic role in examining the intimate connection between technology and the environment.

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OVERVIEW AND PERSPECTIVES

Peter C. Schulze, Robert A. Frosch,
and Paul G. Risser

The expectations placed on engineers shift with the cultural evolution of the societies in which they practice. An important shift has occurred with the growth of human impacts on the planet (Kates et al., 1990; Vitousek et al., 1986). When the cumulative impact of humans was small, the environmental implications of engineering designs were of less concern. Now that the impact of humans has reached a global scale, there is growing concern about the environmental implications of engineering designs. A new set of constraints has become important to engineers—ecological constraints.

Engineers are accustomed to contending with a variety of design constraints, from the most rigid thermodynamic laws to budgetary constraints to issues of social justice. Ecological constraints add one more set of considerations to the list. Engineering designs are now expected to result in products or management plans whose use or implementation will not endanger important ecological conditions and processes. This would be a tall order if the requirements in particular instances were precisely known. It is made all the more challenging by our only partial understanding of the set of important ecological conditions and processes, and what those conditions and processes require to persist.

One conclusion seems clear. Engineers and ecologists will need to work together more often than they have in the past. Progress in both engineering design and ecological understanding will be necessary if humans hope to keep (or bring) their impacts within the limits imposed by the desire for "sustainability."[1] Ecologists and other environmental scientists need to collaborate with engineers to describe the requirements of important ecological conditions and processes in terms that can be incorporated into engineering design considerations, and continue to work together to develop suitable engineering plans. Engineers and ecologists certainly can not solve these problems alone, but they do have important responsibilities in efforts to keep human environmental impacts within acceptable bounds.

With the exception of selected subdisciplines (Mitsch, in this volume), there is so little dialog between engineers and ecologists that it is hard to know where to start. What would it mean to engineer within ecological constraints? What are the ecological constraints? Which constraints are most important? Can some be ignored? How would one distinguish satisfactory and unsatisfactory designs? What does it mean to keep human environmental impacts within "acceptable" limits? Four related topics arise frequently during discussion of these broad questions: problem definition, uncertainty, lessons from environmental control efforts, and the difficulty of finding short-term solutions that do not aggravate long-term problems. We summarize key themes regarding these four issues below.

PROBLEM DEFINITION

> *"Everything should be made as simple as possible, but no simpler."*
>
> *attributed to Albert Einstein*

A plan is not likely to be successful if the problem that it is intended to solve is not accurately defined. Whether ecological constraints are met will depend upon whether the definition of the problem included those constraints. Moreover, when substantial consequences of a project, product, or management plan are not appreciated at the design stage, costly problems may arise later. For example, almost as soon as the Kissimmee River channelization project was completed, the severe ecological consequences became apparent and much more expensive work was begun to reverse the damage (Shen, in this volume; Wodraska and yon Haam, in this volume). Other examples could be cited, including the impacts of dams and forestry practices upon salmon and other fish, the tendency of pesticides to kill a pest's natural predators and lead to pesticide-resistant pests, transportation of exotic species by ships and airplanes, impacts of chlorofluorocarbons (CFC) on stratospheric ozone, and even the impact of carbon dioxide emissions on the global atmosphere. This is not to suggest that the activities that led to these problems should not have occurred, merely that had these consequences been appreciated and taken into consideration from the outset, it might have been possible to reduce or eliminate impacts through design or management modifications.

As the problem-definition stage of engineering efforts continues to expand in response to environmental concerns, and as our dependence on ecosystem "services" becomes better understood (Cairns, in this volume), these sorts of problems should become less frequent. To this end, several general criteria and guidelines have been offered. Schaeffer (in this volume) suggests that engineers adopt the medical oath to "do no harm," in this case to the environment. Norton (in this volume) suggests that engineers adopt the Pareto welfare criterion of economics, in which case an engineering design would be considered satisfactory if its effects were positive for some individuals and neutral for all others. Holling (1992) argues that efforts to identify ecological constraints may benefit from a focus in which the environment and its many components (including humans) are systematically viewed as a hierarchy of systems within systems.

Daly and his colleagues (Costanza et al., 1991; Daly, 1990) have suggested acceptable boundaries for human environmental impacts. Rates of extraction of renewable resources should not exceed regeneration rates. Rates of waste emission should not exceed the assimilative capacity of the environment.[2] Rates of extraction of nonrenewable resources should not exceed the rates at which substitutes are found and developed. These guidelines imply a variety of long-term performance standards. For example: pumping from aquifers should not exceed recharge rates; pollutant concentrations should not increase; soil depth should not decline; harvesting should not cause reductions in population sizes. These guidelines can be useful for identifying unsatisfactory circumstances, but it remains to be seen whether they will be elaborated in ways that will make them directly useful to engineers struggling to satisfy particular ecological constraints in the context of particular engineering problems.

Available evidence suggests that when ecological constraints are clearly defined, engineers can develop designs or management plans with the potential for meeting them. Shen (in this volume) describes two such examples. On the Niobrara River the challenge was to release water from a dam such that the downstream reaches of the river would maintain the broad shallow morphology that is required by migrating whooping cranes. In south Florida the challenge was to restore the Kissimmee River such that flood waters would inundate the floodplain frequently and return to the river channel slowly. In both cases seemingly satisfactory water management plans were developed. Lindstedt-Siva et al. (in this volume) describe another example from ARCO's experience of exploring for oil in tropical rain forests. Roads built into remote rain forest regions facilitate human immigration and subsequent forest destruction. Lindstedt-Siva and her colleagues were determined to explore for oil without building roads. They took their lead from offshore exploration operations, and used helicopters rather than trucks to move equipment.

These examples suggest potential for fruitful collaboration between ecologists and engineers. In all three examples, recognition of important ecological processes led to the identification of key ecological constraints, and engineers used those constraints to develop designs that appeared capable of satisfying them. Plans for the proposed dam on the Niobrara River were canceled because of budgetary constraints, and it is too soon to assess the success of the other designs. In addition, satisfaction of particular ecological constraints is not necessarily the same as satisfaction of all important ecological constraints. Nevertheless, these examples are encouraging.

Because natural systems are complex, it will not always be easy to identify key ecological constraints. The examples discussed by Shen and Lindstedt-Siva et al. are relatively simple. In other situations the challenge for designers will be greater, either because the ecological constraints are poorly understood, or because the connections between design options and ecological processes are indirect. Nevertheless, past efforts to identify key variables in ecological systems give some cause for optimism. For instance, the condition of a grassland can be predicted from five parameters: species composition, primary productivity, species diversity, organic material content of the soil, and nitrogen content of the plants (Risser, 1995). Likewise, the condition of river ecosystems can be assessed on the basis of a relatively small set of variables (Karr, in this volume). Once such key variables are identified, studies can begin to examine the types and magnitudes of impacts that environments can absorb without being unacceptably altered.

Other situations are even more complex. What are the ecological implications of the design of, for example, a radio? The answer to this question depends on a variety of factors, such as the methods of raw material acquisition, the ecological effects of manufacturing wastes, and the way the radios will be discarded (Allenby, 1994). When the ecological implications of an engineering design are obscure, it may be most productive to adopt the general approach of "life-cycle analysis" or "design for environment" in which there is a conscious effort to consider systematically the environmental implications of all aspects of engineering designs (Allenby and Richards, 1994). Such efforts may be assisted by Holling's systems perspective and by an identity recently suggested by Herman Daly (personal communication):

$$A = (B)(C)(D)(E)$$

where:

A = economic services gained/environmental services sacrificed
B = economic services gained/economic stock consumed
C = economic stock consumed/environmental throughput
D = environmental throughput/environmental stock exploited
E = environmental stock exploited/environmental services sacrificed

The above examples suggest that when specific constraints are identified and agreed on, suitable designs or management plans can be developed. The challenge for engineers and ecologists is to work together to identify key constraints and develop plans that satisfy those considerations. In many cases it will also be necessary to work together to convince others that the desirable environmental properties of those resulting designs warrant the necessary investment (Wurth, in this volume).

UNCERTAINTY

"And then what?"

Hardin (1993:16)

Because ecosystems are complex, the environmental consequences of human activities are uncertain (Brooks, 1986; Costanza, 1993; Holling, 1993; Ludwig et al., 1993). Thus, uncertainties are an important consideration in engineering designs and management plans. It can be useful to distinguish three types of uncertainty. "Risks" refer to situations where probabilities may be ascribed to various potential consequences. "Unknowns" refer to situations where the range of possible consequences is thought to be reasonably well understood, but the probabilities of the various consequences are unknown. "Unknown unknowns" are phenomena that one is not even aware one fails to expect or understand.

Even though new technologies are often environmentally preferable to those they replace, their large-scale adoption often results in unanticipated undesirable environmental impacts (Gray, 1989).[3] Hindsight suggests there is room for improvement in our ability to anticipate these impacts. Myers (1995) notes that neither global warming nor acid rain were major concerns at the 1972 United Nations conference on the environment in Stockholm, even though Arrhenius had warned of global warming 100 years earlier and biologists were aware that massive quantities of sulfur dioxide and nitrous oxides were being emitted into the atmosphere. Perhaps some unknowns would be better described as unappreciated knowns or ignored knowns. Whole cadres of environmental scientists, policy analysts, and others work on risk assessment, but few are studying approaches to anticipating that Which would otherwise come as a surprise.

Differences in approaches to uncertainty have major implications for environmental policy (Costanza, 1993). Approaches that focus on risks use quantitative models in attempts to identify most likely scenarios, and then use the results as the basis of policy recommendations (Committee on Science, Engineering, and Public Policy, 1992; Nordhaus, 1992). An alternative approach, focused on unknowns, attempts to identify the policy option that minimizes the likelihood of a catastrophic outcome. This approach, which is embodied in the precautionary principle, does not attempt to ascribe probabilities to alternative possible outcomes (Cameron and Abouchar, 1991; Costanza, 1989, in this volume; Daily et al., 1991).

At the extremes neither approach is perfect. Policies based on a most likely scenario will be unfortunate, if not catastrophic, if the eventual outcome is not the one that was deemed most likely. Conversely, reliance on the precautionary principle begs the question, "How much precaution?" Environmental impacts are but one of many important consequences of new technologies. An excess of precaution could reduce innovation and its associated benefits. In addition, even though a new technology may have unanticipated effects, its aggregate environmental impacts may be preferable to those of the older technology that it replaces.

Finally, there is an issue of opportunity costs. An excess of precaution directed toward one concern may reduce the potential effort available for investment in other concerns. Thus, opportunities to address ecological constraints could be harmed by being too cautious. Good policy requires explicit consideration of risks, unknowns, and unknown unknowns.

Approaches to dealing with uncertainty are particularly relevant to discussions among engineers and ecologists since both casual experience and the literature suggest that members of these two communities tend to have different expectations regarding the future consequences of human environmental impacts (Nordhaus, 1994; Schaeffer, in this volume). Differences in expectations may lead to differences in priorities and disagreements about appropriate actions. For example, Schaeffer (in this volume) describes the virtual stalemate between the Corps of Engineers and the representatives of various resource management agencies and environmental groups regarding studies to assess the ecological effects of increased barge traffic on the upper Mississippi River.

If there are indeed systematic differences in the expectations of engineers and ecologists, disagreements might not depend as much upon the particulars of the case in question as upon differences in fundamental disciplinary perspectives or assumptions, such as the time frames of consideration or expectations regarding future technological developments. Perhaps engineers who are accustomed to choosing design alternatives involving fairly well Understood phenomena may naturally tend to focus on risks while ecologists, who are not so accustomed to making precise predictions, are naturally inclined to focus on unknowns and the possibility of unknown unknowns. An effort to get at the roots of these differences in perspective and focus, if they are real, might lead to improved understanding all around and better mutual appreciation of ecologists for engineering perspectives and vice versa.

Engineers deal with uncertainty regularly in their design efforts. Safety factors are routinely used to minimize the risk of hazards due to variables outside the designer's control. In essence, safety factors represent one way to try to insure against catastrophe. This is not unlike conventional approaches to many everyday sources of uncertainty, where substantial sums are invested to protect against the consequences of potentially catastrophic but uncertain events such as personal illness, automobile accidents, or military aggression (Daily et al., 1991). One goal for collaborating engineers and ecologists could be to develop new ways to think about "safety factors" and other means to incorporate the possible effects of uncertainties into considerations of human environmental impacts.

APPROACHES TO ENVIRONMENTAL CONTROL: LESSONS FROM RESOURCE MANAGEMENT EFFORTS

There is no consensus regarding the precision with which humans can expect to manage ecosystems. Some feel that we can not expect to control the environment on scales larger than individual agricultural fields, whereas others are optimistic about regional control strategies, and still others are optimistic about the potential for control on global scales. Regardless of the ultimate potential of human control, analyses of past resource management efforts provide important lessons regarding pitfalls to avoid in control efforts. Like conventional engineering, resource management faces substantial challenges with regard to uncertainties, problem definition, and the need to maintain the flexibility to shift course if necessary.

Holling (1986, in this volume) describes the insights from a review of efforts to manage forest insects, forest fires, fisheries, and arid rangelands. Managers typically enjoyed initial success in efforts to constrain one variable within narrow bounds, but this success led to economic developments that depended on perpetuating those management strategies. These dependencies increased the pressure to maximize the productivity of particular components of the managed systems and made it difficult to modify management practices. Agencies shifted their focus toward increasing their efficiency in maintaining the initial programs, and in some cases larger socioeconomic objectives were neglected. As a consequence, systems became simpler and less resilient to perturbations. Disturbances that previously would have had little effect on the ecosystems began to have significant impacts on the simpler systems. Holling and his colleagues conclude that a loss of resilience is a consequence of the imposition of stability upon one component of a naturally dynamic system.

Wodraska and yon Haam (in this volume) argue that managers must continually monitor the effects of their efforts and enjoy the flexibility to modify strategies when necessary. They note that Congress dictated particular water flow rates into the Everglades, but the timing and magnitude of the prescribed flows exaggerated natural extremes and exacerbated existing environmental problems. Wodraska and yon Haam would have preferred an incremental approach that was flexible enough to make adjustments in response to new information.

Holling (in this volume) notes that the rigid control approaches used in the 22 cases he reviewed differ from natural ecological controls, which tend to be "soft" and overlapping. A variety of different controls tend to keep natural systems within loose boundaries. Though bounded, the systems are dynamic and resilient to disturbances. For example, temperature regulation in endotherms (loosely speaking, "warm-blooded" animals) is managed by at least five separate, mechanistically distinct sets of controls, evaporative cooling, metabolic heat generation, regulation of blood flow, insulation, and habitat selection. Endotherms have flourished even though their normal body temperatures are very near their lethal body temperatures.

Is it necessarily the case that control of one key variable leads to fragility of the larger system? Can management objectives be achieved without destroying the resilience of the system being managed? To what extent could future engineering and management efforts simply facilitate natural processes so that those processes serve the purposes (e.g., flood control) that have traditionally been served by single-variable control-based engineering efforts (Mitsch, in this volume)? It seems likely that significant progress toward answering these sorts of questions will require extensive, regular collaboration among engineers and ecologists.

SHORT-TERM SOLUTIONS THAT AGGRAVATE LONG-TERM PROBLEMS

The resource management programs reviewed by Holling represent situations where short-term solutions aggravated long-term problems. The same situation is probably the essence of most environmental problems. Inappropriate short-term actions sometimes appear sensible because their long-term consequences are either not recognized or not appreciated. Engineering within ecological constraints must anticipate when short-term solutions will exacerbate long-terms problems (Cairns, in this volume; Norton, in this volume).

Wodraska and yon Haam's description (in this volume) of the California water supply system provides an example of the tension between short-and long-term goals. To supply water to 16,000,000 residents of southern California, earlier managers of the water system stretched tentacles out to water sources in northern California and to other western states. Water flows through pipes as large as 6 meters in diameter in an area prone to earthquakes. This has solved the problem of providing water to the residents of the region, but it has led to a system whose operation depends on the integrity of a plethora of components, including long aqueducts and pumps that lift water more than 500 meters.

The problem of supplying water has been solved for the time being, but the solution has made the water distribution system brittle in the sense that it is sensitive to earthquakes and other disturbances. In addition, adequate present supplies relax immediate constraints on human immigration, which will lead to a larger regional population and concomitantly greater dependence on the water distribution system. (The present managers are now attempting to increase the system's resilience by building in redundancy of function through conservation and wastewater reclamation, rather than simply increasing capacity by obtaining new supplies.)

Herman (in this volume) refers to several other examples where short-term solutions aggravate long-term problems. His examples include highway "bypass" routes that attract development and thus result in greater traffic congestion, and pest control efforts that lead to the evolution of pesticide-resistant pests. These situations have been described as cases of "revenge" by the system and discussed under the rubric of "revenge theory" by Tenner (1991).

In other cases the conflict is not between the society's short- and long-term interests, but between the individual's interests and the society's interests, as in the case of CFC-based air-conditioning systems. Costanza (in this volume) refers to situations where short-term incentives conflict with long-term goals as social traps. He argues that our tendency to fall into social traps results from the speed of cultural evolution: societies change so rapidly that it is difficult to incorporate long-term considerations into day-to-day decisions. He argues that in order to eliminate social traps, short-term incentives must be brought into correspondence with long-term incentives.

Norton (in this volume) argues that decisions with long-term or widespread implications should be based on different criteria than decisions whose implications are only local or ephemeral. He contrasts the individual's roles as a consumer and as a member of a constitutional convention. Norton argues that while the consumer makes economic decisions based on individual utility in the relatively short run, the delegate to a constitutional convention must make decisions on the basis of the long-term best interests of the nation whose constitution is being drafted. In other words, different priorities must serve as the basis for decisions that have the potential for long-term effects, whether the issue is a nation's constitution or its environment.

This is not to suggest that the short-term problems discussed above should not have been "solved," merely that those searching for solutions should recognize the potential for "revenge" on the part of the system. As Garrett Hardin (1993:16) suggests, when contemplating the effect of a particular solution, one should ask, "And then what?" We believe that the following papers will help as engineers and ecologists consider Hardin's question in the course of future attempts to engineer within ecological constraints.

ACKNOWLEDGMENTS

These remarks are based on discussions and presentations during an April 1994 National Academy of Engineering meeting on engineering within ecological constraints. George Diggs, Alexander Flax, Hugh MacIsaac, Deanna Richards and three anonymous reviewers provided valuable comments on earlier drafts. Credit for any insights should be attributed to the meeting participants.

NOTES

1. Many definitions of sustainability have been proposed or implied. We use the term to refer to situations where the environmental impacts of present human activities do not reduce the potential for the environment to support future human activities. The laws of thermodynamics preclude truly infinite sustainability, but we consider this unimportant. With so many systems so far from sustainability at present, the concept is most useful as a guide in efforts to shift actions onto paths that appear to be more sustainable. Costanza (in this volume) elaborates on our conventional if loose definition by defining sustainability in terms of the expected life span of a system. Under his definition, if a system attained its expected life span, then it was sustainable. A species has a longer expected life span than a population, which has a longer expected life span than an individual, which has a longer expected life span than a cell.

2. Assimilative capacity is the rate at which the environment can render wastes innocuous.

3. New technologies could conceivably also have unanticipated desirable consequences.

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PERSPECTIVES ON ECOLOGY AND ENGINEERING

Determining the Balance Between Technological and Ecosystem Services

John Cairns, Jr.

> *The significant problems we face cannot be solved at the same level of thinking we were at when we created them.*
>
> *Albert Einstein*

> *Every country can be said to have three forms of wealth: material, cultural and biological. The first two we understand very well, because they are the substance of our everyday lives. Biological wealth is taken much less seriously. This is a serious strategic error, one that will be increasingly regretted as time passes.*
>
> *E. O. Wilson*

ECOSYSTEM SERVICES: A MATTER OF PERCEPTION

Society has become so accustomed to technological services that they are obvious only in their absence. This happened recently in the eastern United States during the ice storms and blizzards of 1994, in the Mississippi River drainage during the severe floods of 1993, in Florida following Hurricane Andrew in 1992, and in Georgia during the flooding of the Flint River in 1994. Technological services generally involve the substitution of fuels for human effort. They include delivering diverse foods independent of season or local climate; delivering potable water directly into homes; heating, cooling, and humidifying or dehumidifying the climate in buildings; delivering communications such as telephone calls and television and radio signals; and removing noxious wastes such as sewage and trash from homes. Civilization, especially in wealthy countries, has developed an extensive infrastructure for the delivery of technological services, including electrical transmission lines, roads, airports, telephone lines, satellites, and sewer systems.

Society also depends on ecosystem services that have existed for much longer, in fact, probably since the appearance of life on Earth. Ecosystem services are those functions of ecosystems that society deems beneficial, including the maintenance of atmospheric gas balance, flood control, carbon storage, capture of solar energy and subsequent production of food and fiber, maintenance of water quality, and maintenance of a genetic library that provides the raw materials for improved foods, materials, and drugs. While these services have long been taken for granted, society is beginning to realize that many functions of natural systems are not immutable and can be affected by human actions.

The definition of an ecosystem service is a matter of societal perception because it hinges on valuation. Of all the processes or functions carried on by ecosystems, only those contributing to the well-being of human society are considered services. On those rare occasions when the societal value of minimally managed functions of ecosystems is evaluated, different people reach different conclusions. The debate is even more heated when management actions to protect ecosystem services are proposed. What scientific evidence is necessary to facilitate the societal debate on value and help establish a reasonable level of management? Does the delivery of necessary ecosystem services depend on ecosystem health? Not only is additional, well-conceived research needed to clarify these relationships, but it is also crucial to be able to communicate the results of such research and its uncertainties to the wider society that is properly involved in the debate on values. These issues provide recurring themes in the following discussion of balance.

WHAT QUALIFIES AS AN ECOSYSTEM SERVICE?

All ecosystem functions could possibly be viewed as ecosystem services and any distinction between the two as a reflection of the limits of human knowledge rather than an actual difference. In addition to the term *ecosystem services*, the term *sustainable use* is often used to describe human benefits from ecosystems. When an ecosystem service is being provided at a rate that meets society's demands without compromising future use, there is sustainable use of the ecosystem. However, as Costanza notes (in this volume): "The problem is that one knows one has a sustainable system only *after the fact* . Thus, what usually passes for *definitions* of sustainability are actually *predictions* of what set of conditions will actually lead to a sustainable system." The alternative is an unsustainable use that not only may fail to meet the needs of society but also may damage the ecosystem and impair the rate at which the desirable service is provided.

The least controversial examples of ecosystem services are those for which an economic value is easily derived. These economic values can then be incorporated into existing decision making tools. The rapidly developing field of ecological economics (e.g., Costanza, 1989, 1991, and in this volume) has identified several useful approaches. There are problems with these approaches, but in their absence ecosystem services are too often completely ignored as externalities.

Some cases of free market respect for ecosystem services rather than technological ones can be cited. Natural systems are replacing chemical technology for waste treatment (Hammer, 1989). Natural systems complement energy-using technologies in local climate modification; for example, planting trees may save 200 billion kilowatt-hours annually in the United States by reducing the need for air conditioning (Committee on Science, Engineering, and Public Policy, 1992). Avise (1994) calculated the cost of Biosphere 2, which partially regulated the life-support systems for eight humans over a two-year period with an electricity subsidy from outside the sphere. The cost was $150 million (U.S.), or $9 million per person per year. The complications of calculating per capita ecosystem services at vast global or continental scales were definitely not present in this mesocosm experiment. Nevertheless, there is little doubt that practices tolerated in Biosphere 1 (the earth), such as human population growth, overexploitation of ecological capital, and massive destruction of habitats and species, could not be tolerated in Biosphere 2 even for a relatively short time (Avise, 1994). Clearly, some essential functions of natural ecosystems would be difficult or expensive to replace through technological systems.

ECOSYSTEM HEALTH AND THE PROVISION OF ECOSYSTEM SERVICES

Ecosystem health is a complex concept, but a consensus definition has been derived (Haskell et al., 1992; see also Karr, in this volume):

> An ecological system is healthy and free from "distress syndrome" if it is stable and sustainable—that is, if it is active and maintains its organization and autonomy over time and is resilient to stress.

It seems reasonable that a close correlation should exist between health and performance at any level of biological organization. Healthy plants capture more solar energy. Growing forests store more carbon. Indeed, one definition of stress demands that captured energy be diverted from growth into coping mechanisms (Calow, 1991). However, the relationship between ecosystem health and ecosystem services is not as well defined.

A number of interrelated hypotheses on the relationship between ecosystem health and ecosystem services deserve serious attention (Cairns and Pratt, 1995).

1. A close correspondence exists between ecosystem health and the production of ecosystem services.
2. Deterioration of ecosystem health does not affect the various ecosystem services uniformly.
3. Ecosystem services decline monotonically with declines in ecosystem health.
4. Decline of ecosystem services important to human society can be predicted accurately from measures of ecosystem health.
5. Ecosystem services of importance to human society may vary markedly even for ecosystems in robust health or condition.
6. For ecosystems in robust health with highly variable delivery of ecosystem

services, these changes can be predicted from climatic, life cycle, or other similar information.

7. Some ecosystem services are important globally and, therefore, must be maintained at a global level, while some ecosystem services are local or regional, so management at those levels could ensure appropriate delivery of services.

It has been suggested that some of these hypotheses are too broad to test, while others are truisms. However, because these ecosystem services play a role in contributing to the life-support system of human society, they are matters of vital importance. To test these broad hypotheses, it may be necessary to approach them, like other big and important issues, obliquely or piecemeal.

Bradshaw (1983) has said, "The acid test of our understanding is not whether we can take ecosystems to bits on pieces of paper, however scientifically, but whether we can put them together in practice and make them work." Bradshaw's statement is as valid today as it was more than a decade ago when it was written. There is, however, a second test for ecology; namely, whether ecologists can document the services ecosystems provide in sufficiently explicit terms that society will not only protect and preserve those ecosystems still delivering such services but repair to whatever degree possible those ecosystems capable of delivering services at a level far beyond their present capacity.

Quantifying ecosystem services, while a formidable task, may not be as esoteric as it appears. John Harte, of the University of California, Berkeley, has carried out studies at Rocky Mountain Biological Laboratory in Colorado on the effects of global warming. During this research, he found that the soils at the laboratory itself acted as a methane sink. He estimated that, if one extrapolates from that small patch to the entire county, the amount of methane assimilated by the soils approximately equals the amount of methane produced by the cattle in the county. Not only is this information ecologically useful, but it can be easily communicated to the ranchers and other inhabitants of the area. Put in a local context, ecosystem services are no longer regarded as an esoteric issue but as one of considerable interest to area residents.

Some more specific questions related to the documentation of ecosystem services follow.

1. What is the relationship between species richness and delivery of ecosystem services?

Biotic impoverishment, or loss of species, is fairly well documented (e.g., Wilson, 1988), but the relationship between delivery of ecosystem services and the number of species present is almost certainly not linear. There is some evidence of redundancy in function, which means that, if 10 or 12 species were carrying out roughly the same function simultaneously, the loss of one or two would not cause a serious decline in delivery of services because the deficiencies would be made up by the remaining species expanding their numbers.

The decrease in species diversity, and presumably services provided by ecosystems subject to sustained pressure by humans, appears widespread. Regier and Hartman (1973) provide an interesting account in which valued sport and commercial fish were exterminated in Lake Erie as a result of tremendous fishing pressure. These species were replaced by less valuable ecological equivalents. The substitute species still provide "services," though not of the same commercial value as those potentially contributed by the exterminated native species.

Other evidence indicates that what appears to be redundancy is not redundancy. For example, although two different species of zooplankton may feed on phytoplankton in lakes, one may be much more selective than the other, thus producing different ecological consequences. Selective feeders remove individuals of only certain species from a community. This gives the remaining species, those not chosen, a considerable advantage since their competitors are removed and the resources used by the competitors will almost certainly become available to the remaining species. This produces a marked alteration in community structure, as often occurs in rangeland cattle grazing when the most succulent plant species are removed and the less succulent species (e.g., thorny shrubs) become dominant or at least much more abundant. Nonselective feeding, on the other hand, is more equitable and is more likely to produce similar reductions in the various prey species. Thus, selective feeding is likely to alter the relative abundance of species present, whereas nonselective feeding is likely to have much less effect on the relative abundance of species.

2. How close is a crucial break point, or threshold, in the delivery of services by natural ecosystems?

There is good documentation of the increase in human population as well as the marked increase in technological and industrial activity, particularly energy consumption from fossil fuels. Since human population numbers, levels of affluence, and use of technology have increased dramatically in the past 10,000 years, and ecosystem services still appear adequate to support life (although regionally impaired here and there), one may ask whether delivery of ecosystem services is really an important problem?

3. To what degree are the ecosystem services of natural systems replaced by agroecosystems, managed forests, and even such things as vegetation on golf courses? As Harte (1993) notes:

> When trees are cut and all or some of the wood and foliage is left to rot, the carbon in the tree is oxidized to carbon dioxide. Since about one-third of a tree, by weight, is carbon, a good deal of carbon dioxide can be produced when a large area of forest is felled. Even if the cleared land is planted with crops, the carbon that can be stored in cropland is vastly less than that in the forest it replaced.

4. To what degree do natural systems provide global, regional, or local services?

For the maintenance of atmospheric gas balance, one could make a fairly strong case for hemispheric management. For protecting water quality, a regional management for services might be more effective and, for aesthetic purposes, highly local management is called for (see also Norton, in this volume).

5. Can one extrapolate from the services provided by one ecosystem to the services likely to be provided by another?

Of course, one would not expect to extrapolate ecosystem services from the Kalahari Desert to the California redwood forests with any substantive degree of correspondence. However, one might reasonably expect to be able to extrapolate from one East Coast temperate zone wetland to another. The degree of uniqueness of each ecosystem and the degree to which extrapolations can be made with confidence will require a robust database, which can probably be gathered relatively efficiently.

6. What is the relationship between ecological resilience and the delivery of ecosystem services (see Holling, in this volume)?

Ecosystems have, throughout their existence, been exposed to natural perturbations, such as drought, hurricane damage, fires, and floods. Resilience, as defined by Holling (1973), is the ability to regain normative or characteristic structural or functional attributes following a perturbation. Some ecosystems are thought to be perturbation-dependent and others perturbation-independent (e.g., Vogl, 1980). Will full ecosystem services resume more quickly in the former than in the latter?

7. To what extent do exotic invading species disrupt or impair ecosystem services?

As a result of human transportation, animals and plants now have means of dispersal that were not available previously. The new colonists can wipe out or displace native species, and are frequently dispersed alone, without the control measures (predators, parasites) that keep them in check in their original habitat. The rate of human transport of exotics to new habitats will increase markedly as the global marketplace develops. How will these assisted invasions affect delivery of ecosystem services?

COMMUNICATING THE LINKAGES BETWEEN NATURAL SYSTEMS AND HUMAN WELL-BEING

Any attempt to balance technological and ecosystem services must be supported by the general public. To be included in the debate, it is essential that the general public have access to the information that ecologists take for granted. It will be necessary to communicate convincingly to a majority of a country's inhabitants that they themselves are dependent on services provided by natural systems. If this dependence is not understood, then the drive to protect wild areas and ecosystem services will be characterized as an extravagance driven by religious beliefs rather than sensible self-interest. That is why scientific investigations of the linkages between environmental services and human quality of life are essential.

At present, environmental literacy is rudimentary for most members of human society, including college graduates in many disciplines (e.g., Wallace et al., 1993). There is a widespread belief that there are technological solutions to every problem and that stabilizing the size of human population will lead to economic stagnation.

Skinner (1983) argued persuasively that human behavior is selected or determined by its consequences and that substantial numbers of people cannot be expected to change their behavior as the result of information or advice alone, especially when the information is about a distant future. He further stated that people might follow advice when the information from the advice giver has led to beneficial consequences in the past; however, this situation requires that people have experienced reinforcing consequences of prior compliance with similar advice givers or similar rules. Such operant learning is difficult or impossible when reinforcement lies in the future or punishing consequences are unclear, uncertain, or remote. Lack of clarity, uncertainty, and remoteness are all common characteristics in the models scientists must use to make large-scale predictions about ecosystems. A major ecological disaster would provide persuasive evidence of the links between human and environmental health, and failures of some technological solutions would radically change human society's relationship to natural systems.

Rather than wait for severe consequences, what events are most likely to change human behavior with a modest increase in environmental literacy? Professionals in various disciplines must make the added effort to combine their contributions to facilitate policy and decision making. The obvious example of this is ecological economics. Professionals must also make their information and conclusions accessible to the public. Science reporting for the mass media is improving and has room to continue to do so. Another area of concern in environmental literacy is the way in which ecologists, managers, and engineers communicate the uncertainties inherent in their projects.

MANAGED COEVOLUTION

Although human society is well into the information age in world trade, economics, military strategy, marketing, investment, and a host of other activities, the use of information feedback loops to modify society's relationship to ecosystems has not progressed nearly as far as it has in other areas. A major reason for this curious discrepancy is that the consequences of failure in military, economic, and other sectors of society are more apparent to policymakers than are comparable failures in ecological systems. In contrast, the consequences of ill-coordinated responses to changes in ecosystems may not be intrusive until much time has elapsed.

In ecological systems, one form of information feedback is *coevolution*, a term first used by Ehrlich and Raven (1964) in examining the evolution of plants and the insects that feed on them. They defined coevolution as a pair-wise process in which the appearance of a trait in one species elicits a response in another species. For example, increased speed in a carnivorous mammal may result in increased speed in its prey, or a variety of other adaptations to offset the predator's speed, such as improved camouflage. Futuyama and Slotkin (1983) indicated that development of a particular trait in one or more species may result in a suite of traits in several other species. Ghersa et al. (1994) described the coevolution of agroecosystems and weed management. They postulate that weed-management practices have become closely linked to social and economic, rather than biological, factors. As Harlan and deWet (1965) have noted, *weeds and weed problems are* anthropocentric terms applied to populations of plants when they are considered undesirable.

Before the agricultural revolution, the needs of *Homo sapiens* were met in ways not dramatically different from the ways in which needs of other species were met. Human populations were comparatively small and kept from the explosive growth of the past century by disease, starvation, and even predation. These are, in fact, much the same population control factors affecting other species. Throughout history, ecosystems provided all the services necessary for the continuation of the human species: breathable air, potable water, food, and a consistent climate over the short-term. Now human society has a codependence on both a technological life-support system and an ecological life-support system. However, the maintenance needs of technological services get much more attention than those of ecosystem services. In a very real sense, natural systems and human systems are coevolving since only those opportunistic and communal species tolerant of the anthropogenic alterations of natural systems are likely to thrive. These may be opportunistic species resistant to pesticides and habitat fragmentation and tolerant of a wide range of ecological conditions—in short, pests.

Those species that are tolerant of anthropogenically changed conditions might provide some of the services that more complex natural ecosystems provided previously. However, it seems unlikely that they will perform in precisely the same ways. Kauffman (1993) proposes a bold hypothesis: complex, adaptive systems operate on the edge of chaos. He feels that not only organisms, but economic entities and nations, do not simply evolve, but rather coevolve, and that coevolving complex systems mutually operate at the edge of chaos. If the adapting system is itself in the ordered (rather than the chaotic or boundary) regime, Kauffman (1991, 1993) believes the system itself adapts on a smooth landscape (see Holling, in this volume). In the chaotic regime, the system adapts on a very rugged landscape, and, of course, in the boundary regime, it is intermediate.

Kauffman uses the word *landscape* in association with the *word fitness*,[1] a term commonly used in ecology to mean the degree of adaptation to the habitat or ecological niche of an individual species. I suspect it can also describe the goodness of fit of two complex, multivariate systems to each other. Kauffman uses *chaos* in a technical sense, whereas in this discussion it is used in a more colloquial sense. However, it seemed important to begin this discussion with Kauffman's publications.

With Kauffman's analysis in mind, this author draws three conclusions about the balance between technological and ecosystem services: (1) abrupt changes are not prudent in the coevolution of complex, multivariate systems, (2) in two coevolving systems with substantive interdependence, chaos in one is likely to result in chaos in the other, and (3) coevolution can drain energy and deplete resources of the coevolving partners, as in the case of predator and prey. This is also true for nations coevolving in a climate of hostility, as was the case for the USSR and the United States during the Cold War. Finally, coevolution is likely to proceed most smoothly if at least one of the parties recognizes the dynamics of the situation.

In the coevolution of a predator species and its prey (the prey evolving toward more elusiveness and the predator increasing its foraging efficiency), one might make the case that the relationship is beneficial to both species because the capabilities of each species are thereby improved. However, less benign forms of coevolution are also evident. Application of pesticides leads to pesticide resistance in the target organisms, thereby requiring more and more pesticides to achieve the same result and ultimately increasing the risks to nontarget species, including humans. Thus, the application of pesticides, if not done skillfully, can pose a serious threat to human health, a situation well documented in the literature. As a consequence, one might reasonably ask if the coevolution of human society and natural systems is mutually beneficial or mutually destructive. Since the beginning of the agricultural revolution, society has attempted to alter natural systems so that more and more of the energy captured by photosynthesis is converted to foodstuffs and other products of interest to human society (Vitousek et al., 1986). Not only has there been a substantial loss of space devoted to unmanaged production of diverse ecosystem services as a result of agricultural activities, but relatively natural ecosystems, particularly those adjacent to agroecosystems, have often been affected by runoff and airborne contaminants such as pesticides and dust, fragmentation, and, finally, changes in microclimate. It seems possible that this could represent hostile coevolution. Erwin (1991) states, "Within a few hundred years this planet will have little more than lineages of domestic weeds, flies, cockroaches, and starlings, evolving to fill a converted and mostly decertified environment left in the wake of nonenvironmentally adaptive human cultural evolution." The pesticide tolerance and increased pesticide use described earlier are one such example. In hostile coevolution, the deleterious effects of human society on natural ecosystems will select for those organisms and communities of organisms most resistant to this stress, with an equal selection for pioneering species capable of taking advantage of chaos. More than 100 years ago, Kew (1893) provided an eerie insight into the kinds of species that would coevolve with human society if hostile coevolution continues. He described the durability and colonizing potential of *Dreissena* (the zebra mussel), which relatively recently became a major problem in North America (Ludyanskiy et al., 1993), as follows:

> The *Dreissena* is perhaps better fitted for dissemination by man and subsequent establishment than any other fresh-water shell; tenacity of life, unusually rapid propagation, the faculty of becoming attached by string byssus to extraneous substances, and the power of adapting itself to strange and altogether artificial surroundings have combined to make it one of the most successful molluscan colonists in the world.

Thus, even if ecological losses or problems can be predicted, it seems as though society is often willing to trade these problems for jobs, particularly in uncertain economic times (i.e., during recessions). Pratt and O'Connor (1994) describe a situation at Gettysburg Historic Park, where certain conditions that existed at the time of Pickett's charge across a cornfield were to be maintained for historical reasons. The cornfield was located between two lines of trees. During the Civil War, only a few deer inhabited the area. Deer were controlled by hunters, who could harvest a substantial percentage of the population. At that time, deer were not protected either by legislation or by being adjacent to areas where hunting would be highly objectionable. For many years, farmers were willing to pay a modest fee to grow corn in this historic area because they could harvest enough to make a profit. Eventually, the deer herd expanded to a size that made harvesting corn no longer profitable. In addition, harvesting the deer at the necessary rate was objectionable to components of society for a variety of reasons. Replacing the cornfield with astroturf or some other nonhistoric condition was also unacceptable. Under the best circumstances, a substantial expenditure would be necessary to preserve the historic condition of the area by excluding the deer. Consequently, the coevolution of the deer herd and human society became more and more expensive with no socially acceptable alternative in view. In this example, the natural control measures regulating the deer population were removed and resulted in densities unlikely to have been achieved previously in natural systems. All this occurred because humans provided an extraordinary food base and freedom from predation for the deer.

Chaos at the interface can be manifested in a variety of ways. A contrasting illustration for an aquatic system is the invasion of North America by the Asiatic clam, the zebra mussel, and the quagga mussel (Russian mollusc, *D. bugensis*). These invaders from different parts of the world might well have taken hold in pristine systems in North America had they been able to get there. However, without the help of human society's transportation system, this would have been unlikely. Not only can these molluscs invade areas occupied by North American species, but they can also occupy habitats created by an industrial society, such as power plant cooling systems, irrigation canals, waste treatment ponds, and, in the case of the zebra mussel, surfaces such as ship hulls (e.g., Cherry et al., 1986; Garey et al., 1980; Hayward et al., 1982; Nalepa and Schloesser, 1993).

In addition to the problems caused in the technological portion of human society, there is also an increased risk to natural systems resulting from the marginally effective control measures designed to minimize the impacts of these species on the industrial system, including agro-industry. These invaders of North America have created chaos in both the technological and the ecological components of human society's life-support systems.

Thus, while there is ample cause for concern about biotic impoverishment (e.g., Wilson, 1988), there seems to be little concern about the ultimate consequences of this coevolutionary process. If the assumption is that humans are incapable of driving all species to extinction, those left will be highly adapted to exploit the new environmental conditions resulting from overemphasis on the maintenance of technological services. Pest species will be difficult to eradicate—those capable of invading habitats unsuitable for most other species; those selected for resistance to pesticides and other control measures; and, in many instances, those so intimately associated with human society (such as the Norway rat, the housefly, and the cockroach) that control measures may also be a risk to human health. However, failure to exercise the control measures may pose an equal danger to human health as a result of spread of disease.

Nonsuch Island provides excellent examples of the ability of exotic species to colonize, as do the Hawaiian Islands and many other island ecosystems. On Nonsuch, Wingate (1990) reported the necessity of a major and continuous effort to eliminate invading species. Plant invaders are brought to Nonsuch from other Bermuda islands by birds that feed there and then defecate the seeds and other propogules while roosting at night. Even reestablishing the species that existed on the islet before heavy colonization by Europeans would not enable that community to resist invasion by exotics if the sources of colonizing species were in either the conterminous or contiguous ecological landscape in which Nonsuch exists.

Although experimental evidence is not robust, one might still reasonably conclude that, once human society has created chaos in a natural system by destabilizing a complex system, the new system, whatever ecologists may think of it, is now a coevolutionary partner with human society. This plausible analysis provides grounds for persuading human society to consider the coevolutionary consequences of the impact of its technological life-support system on its natural life-support system.

The situation described as hostile coevolution is a form of "social trap." The social trap in this case is the feeling that any major change in human behavior will result in such chaos in the economic system that the natural systems will just have to take it. Besides, the reasoning goes, there is no "scientific proof" of any failure in ecosystem services, and most predictions of the consequences of loss of biodiversity, global warming, ozone holes in the atmosphere, and the like seem much less threatening than job loss, reduction in gross national product, or loss of present amenities resulting from high per capita energy consumption and lowered product costs because environmental externalities are not included in economic analyses. Substantial literature exists on social traps, but some illustrative materials are Brockner and Rubin (1985), Cross and Guyer (1980), Platt (1973), Teger (1980), and, particularly relevant to this discussion, Costanza (1987, and in this volume) and Geller (1994).

BALANCING TECHNOLOGICAL AND NATURAL SERVICES

In developing a guiding model for achieving a balance between technological and ecosystem services, it is helpful to see what humans did when the technology was primitive and human populations comparatively small. At least some preindustrial tribes revered their local environment, but Diamond (1992, 1994) has suggested that the relationships between primitive peoples and their natural environments were not always sustainable. Probably the best known, much earlier exponent of this outlook was Rousseau (1754), whose discourse on the origin of inequality traced humanity's degeneration from the golden age to the misery that now exists in all too much of the world.

Where peoples living in harmony with nature persist, they have been driven to areas that no one else wants. This is true of the Bushmen in the Kalahari Desert and some of the few remaining indigenous societies in the Amazon basin and parts of Australia. Since the agricultural revolution some 10,000 years ago, the agrarians have always outnumbered the hunters and gatherers and, even if they were less skillful in warfare, could overwhelm them by sheer numbers. Some of the literature that is particularly interesting in this regard is Hughes (1975), Kirch (1984), Martin (1973), Martin and Klein (1984), Mosimann and Martin (1975), Samuels and Betancourt (1982), and Yoffee and Cowgill (1988). Despite uncertainties and controversy about the literature from which these selections are taken, it is clear that even the primitive technologies of human society when used with teamwork and intelligence could cause considerable environmental havoc.

Ornstein and Ehrlich (1989) speculate that there could be no selective pressures likely to result in a genetic trait prohibiting excessive depletion of resources or conditioning an individual toward long-term sustainable use of a resource base. The rewards for exploitative behaviors are too immediate; the consequences too delayed. Even if the level of technology used by the hunters and gatherers was acceptable to human society (which is no longer the case), population densities alone preclude using such a model, at least for many generations. Of course, many species are left, so, as Diamond notes, the golden age may not have been as golden as it was thought to be, but neither was it all black. Human population growth cannot continue at present rates indefinitely without temporary and possibly irreparable damage to ecosystem services.

However, as a caveat, human society is probably unlikely to eliminate all the species on the planet, especially since some of them are capable of living in thermal vents on ocean floors and in other nearly equally inhospitable environments. It is also important to remember that much ecological damage has been done and is being done by people who are suddenly thrust into a new ecosystem and transpose methods suitable for an entirely different ecosystem to the new one. In this regard, much may be learned from examining society's response both to technological advances, such as the agricultural revolution, and to the displacement of large groups of people, such as pioneers, into new ecological systems and habitats.

Agriculture appears to have had its origins approximately 10,000 years ago in the Near East (Quinn, 1992). Probably the most positive feature of this revolution is that many times more people could be supported per unit area under an agricultural than a hunter/gatherer system. This concentration of people accelerated the spread of diseases but also made possible the division of labor, which could lead to either art or war. The agricultural revolution made it possible for a relatively few people to feed much larger numbers, and this in turn made the industrial revolution possible.

Multistory buildings, elevators, fossil fuel transportation, and the like made it possible for enormous numbers of people to live in a relatively small area—people who, for the most part, have infrequent interactions with natural systems and therefore are unfamiliar with how they work. This is particularly true of policymakers, elected officials, captains of industry, and others who may have high technological literacy but relatively low environmental literacy. Even people in agribusiness, mining, and ranching, though far removed from cities, may have only the most superficial interactions with systems that have substantial biological integrity. The people most familiar with natural systems are not usually in positions of power and are probably not frequently consulted by those who are. Balancing technological and natural life-support systems will be exceedingly difficult if the operational prerequisites of the natural systems are not well understood and the prerequisites of the technological system are.

PATH FORWARD

Unless the global population stabilizes, it seems unlikely that a balance between technological and ecosystem services can be achieved. The United Nations report *Children and the Environment* quoted in the *San Francisco Chronicle* July 20, 1990, noted that fewer than 1.5 billion people, less than half the number alive in 1968, have yet achieved the standard of living that most Americans (or citizens of other rich nations) would find acceptable. In short, the present technological and natural life-support systems of the planet are not functioning in a way that most inhabitants of developed countries would consider "necessary." Yet, the planet has a net gain of 95 million people annually. It is difficult to be optimistic about either stabilizing or reducing the human population when both men and women in many countries want a number of children far beyond the replacement rate. For example, in Niger, women still want 8.5 children, although men want 12.6 on the average (e.g., Sachs, 1994).

If the human population is stabilized or approaching stabilization, it would be worthwhile to attempt to achieve concomitantly a no-net-loss of ecosystem services locally, regionally, and globally. This would mean a balance between destruction and repair of ecosystems with the proviso that destruction is usually accomplished much more rapidly than repair, although in some cases both can be incremental. A stable human population coupled with a no-net-loss of environmental services would mean that, if there were equitable distribution of both, the ecosystem services per capita would not diminish from the time that stabilization and no-net-loss were simultaneously achieved and maintained. Ehrlich and Ehrlich (1991) have stated that the present population density and level of affluence are possible only because society is expending ecological capital, such as topsoil, old-growth forests, fossil water, and ocean fisheries, at rates that are not sustainable (i.e., far greater than the rates of replenishment) for many more years, let alone hundreds of years or millennia. Achieving a long-term, sustainable-use balance between technological and natural life-support systems will require replenishing ecological capital at the rate it is being used (Daly, 1990). One problem with this approach is that the rates of replenishment of soils and aquifers are difficult to calculate on a short-term basis, and, for some things such as old-growth forests, it is not clear whether even millennia will be adequate in some locations. Nevertheless, achieving a balance between replenishment and depletion of ecological capital will be an important consideration in achieving the balance discussed here.

The transition from expenditure of ecological capital to living entirely on ecological "interest" (i.e., services) might be improved by restoring a substantial number of damaged ecosystems, particularly those providing highly desirable services. It is worth emphasizing that these services can include recreational values or aesthetic values. The National Research Council (1992) provides illustrative targets for restoring aquatic ecosystems. This debate should focus on the types of ecosystems, the area or size of the restoration effort, the time frame within which the effort should be made (conditioned, of course, by the fact that biological systems may be capable of reaching a new equilibrium only after substantial time periods), and what should be done nationally, regionally, and locally. These are but a few of the many topics that should be discussed. Initially, restoration need not affect prime agricultural or urban sites. There are numerous abandoned or derelict damaged ecosystems, such as mined sites or floodplain farmlands (150 million acres in the United States), that could easily be restored without interfering with the technological life-support system, and these should, of course, be restored first. However, inevitably, the time will come when society must consider which should have the highest priority—the technological or the ecological life-support system. The technological life-support system is getting almost exclusive attention, and the ecological life-support system practically none for reasons already discussed. However, assuming that the damage to the ecological life-support system cannot continue indefinitely, a time will come when trade-offs must be made between the two systems.

Until there is more robust information on the services provided by the ecological component of society's life-support system, several steps can be taken to keep options open.

1. A diverse array of habitats should be maintained in as nearly pristine form as possible so that their ecosystem services can be measured. These will provide models for reconstructing damaged ecosystems and also furnish information on the impairment of ecosystem services, if any, when these habitats are used for a multiplicity of purposes as opposed to leaving them in their wild state. These pristine habitats also serve educational roles.
2. The biotic impoverishment, or loss of species, that is occurring globally at a disturbing rate should be substantially decreased as a matter of prudence until more is known about the relationship between biodiversity and ecosystem services. Of particular concern are migratory species, such as birds, which may provide a variety of ecosystem services, many of which are not yet recognized. The crucial issue for migratory species is the fact that a loss of habitat anywhere in their migratory cycle could result in their extinction or cause a dramatic reduction in population size and, thus, affect ecosystem services at points distant from the area of lost habitat.
3. If reaching the maximum possible number of humans on the planet is a societal goal, there should be at least some discussion of whether this goal is most likely to be achieved over a long period through sustainable use or through the depletion of ecological capital as is now being done. If achieving the maximum possible number of humans is not a goal, some discussion of the desirable population size and the human condition permitted by that size is necessary.
4. Enlightened discussion of the issues raised here will require a level of both environmental and technological literacy far beyond that now acquired by most graduates of educational institutions. Wholesale changes in beliefs may also be required to break the "jobs first, then environmental protection" mindset. These changes are likely to occur only following enhanced education.
5. As society moves toward a global economy, it is essential to move toward global consensus on society's relationship to the ecological portion of the life-support system.
6. Financial and other incentives should be devised to ensure that the appropriate data are gathered and that a group of professionals competent to make these measurements and judgments is produced by the educational system.

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NOTE

1. Ecologists use the *term fitness* in both a population and a genetic sense. Kauffman appears to have used it in the population sense in which the most fit species (i.e., those able to use the resources of a habitat most competitively) both increase their population size and have individuals in better physiological condition than individuals that are less "fit."

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Engineering Resilience versus Ecological Resilience

C. S. Holling

ECOSYSTEM STRUCTURE AND FUNCTION

Ecological science has been shaped largely by the biological sciences. Environmental science, on the other hand, has been shaped largely by the physical sciences and engineering. With the beginning of interdisciplinary efforts between the two fields, some of the fundamental differences between them are generating conflicts caused more by misunderstanding of basic concepts than by any difference in social purposes or methods. Those differences are most vivid in that part of ecology called ecosystem science, for it is there that it is obvious that both the biota and the physical environment interact such that not only does the environment shape the biota but the biota transforms the environment.

The accumulated body of empirical evidence concerning natural, disturbed, and managed ecosystems identifies key features of ecosystem structure and function (Holling et al., 1995) that probably are not included in many engineers' image of ecology:

- Ecological change is not continuous and gradual; Rather it is episodic, with slow accumulation of natural capital such as biomass or nutrients, punctuated by sudden releases and reorganization of that capital as the result of internal or external natural processes or of man-imposed catastrophes. Rare events, such as hurricanes, or the arrival of invading species, can unpredictably shape structure at critical times or at locations of increased vulnerability. The results of these rare events can persist for long periods. Therein lies one of the sources of new options that biological diversity provides. Irreversible or slowly reversible states exist—that is, once the system flips into such a state, only explicit management intervention can return its previous self-sustaining state, and even then success is not assured (Walker, 1981). *Critical processes function at radically different rates covering several orders of magnitude, and these rates cluster around a few dominant frequencies*.

- Spatial attributes are not uniform or scale invariant. Rather, productivity and textures are patchy and discontinuous at all scales from the leaf to the individual, the vegetation patch, the landscape, and the planet. There are several different ranges of scales each with different attributes of patchiness and texture (Holling, 1992). *Therefore scaling up from small to large cannot be a process of simple linear addition; nonlinear processes organize the shift from one range of scales to another. Not only do the large and slow variables control small and fast ones, the latter occasionally "revolt" to affect the former*.
- Ecosystems do not have single equilibria with functions controlled to remain near them. Rather, destabilizing forces far from equilibria, multiple equilibria, and disappearance of equilibria define functionally different states, and movement between states maintains structure and diversity. *On the one hand, destabilizing forces are important in maintaining diversity, resilience, and opportunity. On the other hand, stabilizing forces are important in maintaining productivity and biogeochemical cycles, and even when these features are perturbed, they recover rather rapidly if the stability domain is not exceeded* (e.g., recovery of lakes from eutrophication or acidification, Schindler, 1990; Schindler et al., 1991).
- Policies and management that apply fixed rules for achieving constant yields (such as constant carrying capacity of cattle or wildlife or constant sustainable yield of fish, wood, or water), independent of scale, lead to systems that gradually lose resilience and suddenly break down in the face of disturbances that previously could be absorbed (Holling, 1986). *Ecosystems are moving targets, with multiple potential futures that are uncertain and unpredictable. Therefore management has to be flexible, adaptive, and experimental at scales compatible with the scales of critical ecosystem functions* (Walters, 1986).

The features described above are the consequence of the stability properties of natural systems. In the ecological literature, these properties have been given focus through debates on the meaning and reality of the resilience of ecosystems. For that reason, and because the same debate seems to be emerging in economics, I will review the concepts to provide a foundation for understanding.

THE TWO FACES OF RESILIENCE

Resilience of a system has been defined in two different ways in the ecological literature. These differences in definition reflect which of two different aspects of stability are emphasized. I first emphasized the consequences of those different aspects for ecological systems to draw attention to the paradoxes between efficiency and persistence, or between constancy and change, or between predictability and unpredictability (Holling, 1973). One definition focuses on efficiency, constancy, and predictability—all attributes at the core of engineers' desires for fail-safe design. The other focuses on persistence, change, and unpredictability—all attributes embraced and celebrated by biologists with an evolutionary perspective and by those who search for safe-fail designs.

The first definition, and the more traditional, concentrates on stability near an equilibrium steady state, where resistance to disturbance and speed of return to the equilibrium are used to measure the property (O'Neill et al., 1986; Pimm, 1984; Tilman and Downing, 1994). That view provides one of the foundations for economic theory as well and may be termed *engineering resilience*.

The second definition emphasizes conditions far from any equilibrium steady state, where instabilities can flip a system into another regime of behavior —that is, to another stability domain (Holling, 1973). In this case the measurement of resilience is the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behavior. We shall call this view *ecological resilience* (Walker et al., 1969).

The same differences have also begun to emerge in economics with the identification of multistable states for competing technologies because of increasing returns to scale (Arthur, 1990). Thus, increasingly it seems that effective and sustainable development of technology, resources, and ecosystems requires ways to deal not only with near-equilibrium efficiency but with the reality of more than one equilibrium. If there is more than one equilibrium, in which direction should the finger on the invisible hand of Adam Smith point? If there is more than one objective function, where does the engineer search for optimal designs?

These two aspects of a system's stability have very different consequences for evaluating, understanding, and managing complexity and change. I argue that designing with ecosystems requires an emphasis on the second definition of resilience, that is, the amount of disturbance that can be sustained before a change in system control and structure occurs—ecological resilience. I do so because that interplay between stabilizing and destabilizing properties is at the heart of present issues of development and the environment—global change, biodiversity loss, ecosystem restoration, and sustainable development.

The two contrasting aspects of stability—essentially one that focuses on maintaining *efficiency* of function (engineering resilience) and one that focuses on maintaining *existence* of function (ecological resilience)—are so fundamental that they can become alternative paradigms whose devotees reflect traditions of a discipline or of an attitude more than of a reality of nature.

Those who emphasize the near-equilibrium definition of engineering resilience, for example, draw predominantly from traditions of deductive mathematical theory (Pimm,. 1984) where simplified, untouched ecological systems are imagined, or from traditions of engineering, where the motive is to design systems with a single operating objective (DeAngelis, 1980; O'Neill et al., 1986; Waide and Webster, 1976). On the one hand, that makes the mathematics more tractable, and on the other, it accommodates the engineer's goal to develop optimal designs. There is an implicit assumption of global stability, that is, that only one equilibrium steady state exists, or, if other operating states exist, they should be avoided (Figure 1) by applying safeguards.

Those who emphasize the stability domain definition of resilience (ecological resilience), on the other hand, come from traditions of applied mathematics and applied resource ecology at the scale of ecosystems. Examples include the dynamics and management of freshwater systems (Fiering, 1982), of forests (Holling et al., 1977), of fisheries (Waiters, 1986), of semiarid grasslands (Walker et al., 1969) and of interacting populations in nature (Dublin et al., 1990; Sinclair et al., 1990). Because these studies are rooted in inductive rather than deductive theory formation and in experience with the impacts of large-scale management disturbances, the reality of flips from one operating state to another cannot be avoided. Moreover, it becomes obvious that the variability of critical variables forms and maintains the stability landscape (Figure 2).

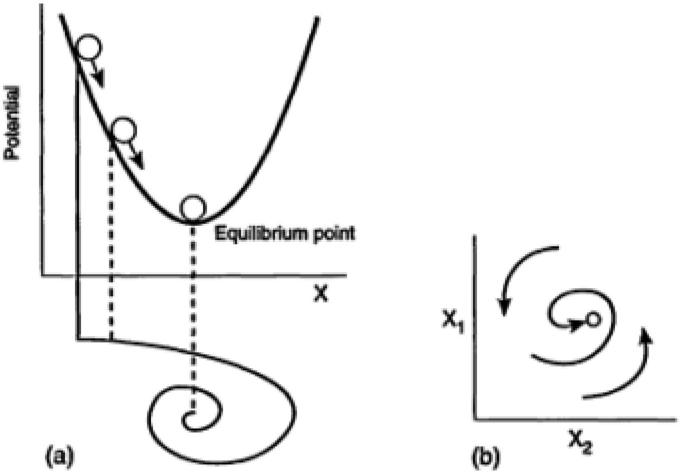

Figure 1 Two views of a single, globally stable equilibrium. (a) Provides a mechanical ball and topography analogy. (b) Provides an abstract state space view of a point's movement toward the stable equilibrium, with x_1 and x_2 defining, for example, population densities of predator and prey, or of two competitors. This is an example of engineering resilience. It is measured by the resistance of the ball to disturbances away from the equilibrium point and the speed of return to it.

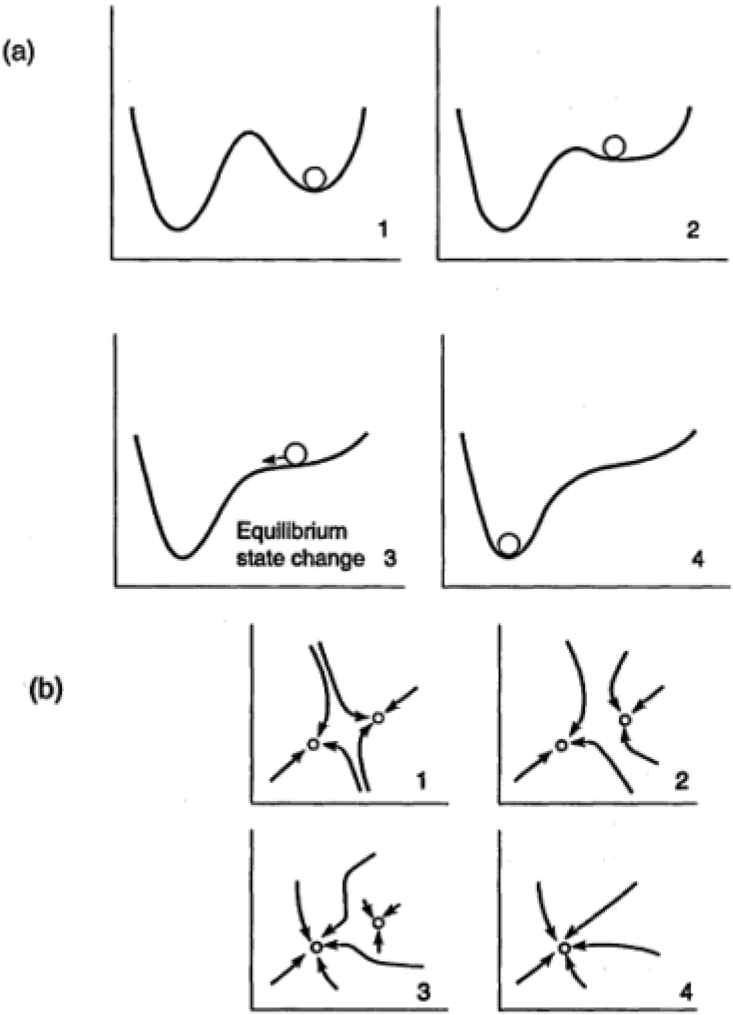

FIGURE 2 Topographic analogy and state space views of evolving nature. The system modifies its own possible states as it changes over time from 1 to 4. In this example, as time progresses, a progressively smaller perturbation is needed to change the equilibrium state of the system from one domain to the other, until the system spontaneously changes state. (a) Ball and topography analogy. (b) Equivalent state space representation.

MANAGING FOR ENGINEERING RESILIENCE

Management and resource exploitation can overload waters with nutrients, turn forests into grasslands, trigger collapses in fisheries, and transform savannas into shrub-dominated semideserts. One example, described by Walker et al. (1969) concerns grazing of semiarid grasslands. Under natural conditions in east and south Africa, the grasslands were periodically pulsed by episodes of intense grazing by various species of large herbivores. Directly as a result, a dynamic balance was maintained between two groups of grasses. One group contains species able to withstand grazing pressure and drought because of their deep roots. The other contains species that are more efficient in turning the sun's energy into plant material, are more attractive to grazers, but are more susceptible to drought because of the concentration of biomass above ground in photosynthetically active foliage.

The latter, productive but drought-sensitive grasses, have a competitive edge between bouts of grazing so long as drought does not occur. But, because of pressure from pulses of intense grazing, that competitive edge for a time shifts to the drought-resistant group of species. As a result of these shifts in competitive advantage, a diversity of grass species serves a set of interrelated functions— productivity on the one hand and drought protection on the other.

When such grasslands are converted to cattle ranching, however, the cattle have been typically stocked at a sustained, moderate level, so that grazing shifts from the natural pattern of intense pulses separated by periods of recovery, to a more modest but persistent impact. Natural variability is replaced by constancy of production. The result is that, in the absence of intense grazing, the productive but drought-sensitive grasses consistently have advantage over the drought-resistant species and the soil- and water-holding capacity they protect. The land becomes more productive in the short-term, but the species assemblage narrows to emphasize one functional type. Droughts can no longer be sustained and the system can suddenly flip to become dominated and controlled by woody shrubs. That is, ecological resilience is reduced. It is an example of what Schindler (1990, 1993) has demonstrated experimentally in lakes as the effect of a reduction of species diversity when those species are part of a critical ecosystem function.

There are many examples of managed ecosystems that share this same feature of gradual loss of functional diversity with an attendant loss of resilience followed by a shift into an irreversible state, such as occurs in agriculture and in forest, fish, and grasslands management (as summarized in Holling, 1986). In each case the cause is reduction of natural variability of the critical structuring variables such as plants, insect pests, forest fires, fish populations, or grazing pressure to achieve a social, economic, or engineering objective. The result is that the ecosystem evolves to become more spatially uniform, less functionally diverse, and more sensitive to disturbances that otherwise could have been absorbed.

That is, ecological resilience decreases even though engineering resilience might be great. Short-term success in stabilizing production leads to long-term surprise.

Moreover, such changes can be essentially irreversible because of accompanying changes in soils, hydrology, disturbance processes, and species complexes that regulate or control ecological structure and dynamics. Control of ecosystem function shifts from one set of interacting physical and biological processes to a different set (Holling et al., 1995).

In the examples of resource management that I have explored in depth, not only do ecosystems become less resilient when they are managed with the goal of achieving constancy of production, but the management agencies, in their chive for efficiency, also become more myopic, the relevant industries become more dependent and static, and the public loses trust (Gunderson et al., 1995). This seems to define an ultimate pathology that typically can lead to a crisis triggered by unexpected external events, sometimes followed by a reformation of policy. I first saw the form of this pathology emerging in the early stages of testing and developing theories, methods, and case study examples of adaptive environmental assessment and management. Those cases and their diagnoses were summarized in Holling (1986).

Those cases involved a number of different examples of forest development, fisheries exploitation, semiarid grazing systems, and disease management in crops and people. We have greatly expanded and deepened the case studies and tests since then, adding examples that are presented in a new book that explores both the dynamics of ecosystems and the dynamics of the institutions that attempt to manage them (Gunderson et al., 1995). Two of the original examples continue to provide insights.

In those two examples, the initial diagnoses of the pathology as I saw it in the early 1970s were as follows:

- Successful suppression of spruce budworm populations during the 1950s and 1960s in eastern Canada, using insecticide, certainly preserved the pulp and paper industry in the short-term by significantly reducing defoliation by the insect so that tree mortality was delayed. This encouraged expansion of pulp mills but left the forest, and hence the economy, more vulnerable to an outbreak that would cause more intense and more extensive tree mortality than had ever been experienced before. That is, the short-term success of spraying led to moderate levels of infestation and partially protected foliage that became more homogeneous over larger areas, demanding ever more vigilance and control.
- Effective protection and enhancement of salmon spawning through use of fish hatcheries on the west coast of North America quickly led to more predictable and larger catches by both sport and commercial fishermen. That triggered increased fishing pressure and investment in both sectors, pressure that caused more and more of the less productive natural stocks to become locally extinct.

That left the fishing industry precariously dependent on a few artificially enhanced stocks, whose productivity began declining in a system where larger-scale physical oceanic changes contributed to unexpected impacts on the distribution and abundance of fish.

In both those cases, however, by the 1980s I began to realize that the phase of a growing pathology was transient and could be broken by a spasmodic readjustment, an adaptive lurch of learning that created new opportunity. It is that creation of something fundamentally novel that gives an evolutionary character to development of a region that might make sustainable development an achievable reality rather than an oxymoron.

The heart of these two different views of resilience lies in assumptions regarding whether multistable states exist. If it is assumed that only one stable state exists *or can be designed to so exist*, then the only possible definitions for, and measures of, resilience are near-equilibrium ones—such as characteristic return time. Prod that is certainly consistent with the engineer's desire to make things work, not to make things that break down or suddenly shift their behavior. But nature is different.

There are different stability domains in nature, and variation in critical variables tests the limits of those domains. Thus, a near-equilibrium focus seems myopic and attention shifts to determining the constructive role of instability in maintaining diversity and persistence and to designs of management that maintain ecosystem function in the face of unexpected disturbances. Such designs would maintain or expand ecological resilience. It is those ecosystem functions and ecological resilience that provide the ecological "services" that invisibly provide the foundations for sustaining economic activity.

MANAGING FOR ECOLOGICAL RESILIENCE

There is a puzzle in these examples and this analysis. It implies that efficient control and management of renewable resources in an engineering sense leads initially to success in managing a target variable for sustained production of food or fiber but ultimately to a pathology of less resilient and more vulnerable ecosystems, more rigid and unresponsive management agencies, and more dependent societies. But there seems to be something inherently wrong with that conclusion, implying, as it does, that the only solution is humanity's radical return to being "children of nature." The puzzle needs to be clarified to test its significance and generality.

The above conclusion is based on two critical points. One is that reducing the variability of critical variables within ecosystems inevitably leads to reduced resilience and increased vulnerability. The second is that there is, in principle, no different way for agencies and people to manage and benefit from resource development. Both points are explored in more detail in a new book on barriers and bridges to ecosystem and institutional renewal (Gunderson et al., 1995), so here I will deal only with highlights.

Puzzles can sometimes be solved by searching for counterexamples. Oddly, nature itself provides such counterexamples of tightly regulated yet sustainable systems in the many examples of physiological homeostasis. Consider temperature regulation of endotherms (warm-blooded animals). The internal body temperature of endotherms is not only tightly regulated within a narrow band, but among present-day birds and mammals, the average temperature is perilously close to lethal. Moreover, the cost of achieving that regulation requires ten times the energy for metabolism that is required by ectotherms (cold-blooded animals). That would seem to be a recipe for not only disaster but a very inefficient one at that. And yet evolution somehow led to the extraordinary success of the animals having such an adaptation—the birds and mammals.

To test the generality of the variability-loss/resilience-loss hypothesis, I have been collecting data from the physiological literature on the viable temperature range within the bodies of organisms exposed to different classes of variability. I have organized the data into three groups ranging from terrestrial ectotherms, which are exposed to the greatest variability of temperature from unbuffered ambient conditions, to aquatic ectotherms, which are exposed to an intermediate level of variability because of the moderating attributes of water, to endotherms, which regulate temperature within a narrow band. The viable range of internal body temperature decreases from about 40 degrees centigrade for the most variable group to about 30 degrees for the intermediate, to 20 degrees for the tightly regulated endotherms. Therefore resilience, in this case the range of internal temperatures that separates life from death, clearly does contract as variability in internal temperature is reduced, just as in the resource management cases. I conclude, therefore, that reduction of variability of living systems, from organisms to ecosystems, inevitably leads to loss of resilience in that part of the system being regulated.

But that seems to leave an even starker paradox for management; seemingly successful control inevitably leads to collapse. But, in fact, endothermy does persist and flourish. It therefore serves as a revealing metaphor for sustainable development. This metaphor contains two features that were not evident in my earlier descriptions of examples of resource management.

First, the kind of regulation is different. Five different mechanisms, from evaporative cooling to metabolic heat generation, control the temperature of endotherms. Each mechanism is not notably efficient by itself. Each operates over a somewhat different but overlapping range of conditions and with different efficiencies of response. It is this overlapping "soft" redundancy that seems to characterize biological regulation of all kinds. It is not notably efficient or elegant in the engineering sense. But it is robust and continually sensitive to changes in internal body temperature. That is quite unlike the examples of rigid regulation by management where goals of operational efficiency gradually isolated the regulating agency from the things it was regulating.

Examples of similar regulation of ecosystem dynamics in nature include the set of herbivorous antelope species that structure the vegetation of the savannas of East Africa at intermediate scales from meters to kilometers (Walker et al., 1969) or the suite of 35 species of insectivorous birds that, through their predation on insect larvae, set the timing for outbreaks of spruce budworm in the forests of eastern Canada (Holling, 1988). In these examples, each species performs its actions somewhat differently from others, and each responds differently to external variability because of differences in habitat preference and the scales of choice for its resources (Holling, 1992). As an example, some species of insectivorous birds exert modest predation pressure over a broad range of prey densities, whereas others exert strong pressure over narrow ranges of density and still others function between those extremes. The densities at which the predation impact is maximal also differ between species. Competition occurs among these species such that the aggregate predation effect is inefficient when predators are abundant and prey scarce and efficient when the reverse is true. As a consequence, the result of their joint action is an overlapping set of reinforcing influences that are less like the redundancy of engineered devices and more like portfolio diversity strategies of investors. The risks and benefits are spread widely to retain overall consistency in performance independent of wide fluctuations in the individual species. That is at the heart of the role of functional diversity in maintaining the resilience of ecosystem structure and function.

We chose the *term functional diversity to* describe this process, following the terms suggested by Schindler (1990) and by Holling et al. (1995). Such diversity provides great robustness to the process and, as a consequence, great resilience to the system behavior.

The second feature of nature's way of tightly regulating variability that is different from traditional management is the tendency to function near the edge of instabilities, not far away from them. That is where information and opportunity are the greatest. Again endothermy provides an example. Endothermy is a true innovation that explosively released opportunity for the organisms that evolved the ability to regulate their body temperature. Maintaining high body temperature, just short of death, allows the greatest range of external activity for an animal. Speed and stamina increase and activity can be maintained at both high and low external temperatures. A range of habitats forbidden to an ectotherm is open to an endotherm. The evolutionary consequence of temperature regulation was to open opportunity suddenly for dramatic organizational change and the adaptive radiation of new life forms. Variability is therefore not eliminated. It is reduced in one place and transferred from the animal's internal environment to its external environment as a consequence of allowing continual probes by the whole animal for opportunity and change. Hence the price of reducing internal resilience, maintaining high metabolic levels, and operating dose to an edge of instability is more than offset by that creation of evolutionary opportunity. Nature's policy of ecological resilience, if we can call it that, seems far from those of traditional engineering safeguards or economic efficiency, where operating near an equilibrium far from an instability defines engineering resilience.

But ascribing that designation to engineering is to stereotype the field with only one face of its activities, just as ecological resilience represents only one face of ecology. At least some aspects of ecologically resilient control are equally familiar to the control engineer, for operation at the edge of instability is characteristic of designs for high-performance aircraft. Oddly, the result is opportunity. Effective control of internal dynamics at the edge of instability generates external options. Operating at the edge of instability generates immediate signals of changing opportunity.

That surely is at the heart of sustainable development—the release of human opportunity. It requires flexible, diverse, and redundant regulation, early signals of error built into incentives for corrective action, and continuous experimental probing of the changes in the external world. Those are the features of adaptive environmental and resource management. Those are the features missing in the descriptions I presented of traditional, piecemeal, exploitive resource management and its ultimate pathology.

CONCLUSION

There are indeed strong suggestions that management and institutional regimes can be designed to preserve or expand resilience of systems as well as provide developmental opportunity. It is a central issue that only now is beginning to be the focus of serious scholarship and practice. Of the cases I know well, management of the forests of New Brunswick seems most clearly to demonstrate the cycles of crisis and learning and the hesitant emergence of a more sustainable path.

In the New Brunswick example, one major crisis and several minor ones have occurred since the early 1950s. During this period, the new technologies of airplanes and pesticides developed in World War II were adapted for spraying operations and their use was progressively refined to achieve high mortality of insects while reducing environmental side effects. These procedures for pesticide control of budworm synergized with other technological developments in tree harvesting, pulp production chemistry, and mill construction and resulted in large investments in pulp production. Minor crises occurred when effects on human health were linked to the pesticides. Key pieces of integrated understanding of the natural system were achieved by the teams of Morals (1963) and the modelers of the 1970s (Clark et al., 1979). The brittleness that developed (defined by a loss of ecological resilience together with an increase in institutional efforts to control information and action) reflected the complacent belief among agency staffs that budworm damage was controlled in an efficient and cost-effective manner and that there was plenty of wood available for harvest. In reality, the costs of using pesticides were rapidly increasing because of increases in oil prices and because of modification of pesticide application in response to public pressure. In addition, available stocks of harvestable trees were decreasing because of past harvests and because more and more mature stands over larger areas were gradually deteriorating from the pressure of moderate but persistent budworm defoliation. The major crises occurred during the late 1970s when a forest inventory report finally indicated that there would not be sufficient stock to support the current mills, thereby confirming an earlier prediction of the models. This led to a new law that restructured the licensing and forest management policies and freed the innovative capacity of local industries within a regional set of goals and constraints. A sequence of adaptive responses among the actors began to develop regional forest policy in a way that now engages local industrial, environmental, and recreational goals.

The examples of growing pathology are caused by the very success of achieving near equilibrium behavior and control of a single target variable independently of the larger ecosystem, economic, and social interactions. When that orientation or goal is abandoned, it happens suddenly, in response to perceived or real crises. The scale of the issues becomes redefined more broadly from a local to a regional setting and from short-term to long-term. The scientific understanding of the natural system becomes more integrated, and the issues themselves are not posed in response to needs to maximize constancy or productivity of yield, but to ones of designing interrelations between people and resources that are sustainable in the face of surprises and the unexpected. If there is such a thing as sustainable development, then that is it. The key features are integration of knowledge at a range of scales, engagement of the public in exploring alternative potential futures, adaptive designs that acknowledge and test the unknown, and involvement of citizens in monitoring and understanding outcomes. That is possible only in situations where ecological resilience and public trust have not been degraded. If they have, as in many situations, then the initial goal has to be the restoration of both resilience and trust.

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A Scalar Approach to Ecological Constraints

Bryan G. Norton

ENVIRONMENTAL PROBLEMS IN PERSPECTIVE

Environmental problems arc basically problems of scale. This is especially true of environmental problems that involve ecological constraints as important elements. This chapter considers scale in a broad social sense. In particular, it examines the effect of social values on the scale at which we experience the world; conversely, it explores the role of objective determinations of scale in shaping social values. These two aspects of scale apparently represent a complex and highly interactive dynamic. We can think of these interactions as posing problems in the phenomenology of space—the study of space as experienced, which is itself an important, if somewhat neglected, branch of geography (Seamon and Mugerauer, 1989; Tuan, 1971, 1977). This approach emphasizes sense of place values and sentiments, recognizing that all people value objects from a particular perspective; further, the scale of space that people perceive as their sphere of action imposes a shape on their consciousness and their valuations.

The "objective" concept of space that is favored in the modernist, Newtonian perspective has fallen on bad times in this century; in the postmodernist period, time and space have been relativized and complexified in ways that could not be imagined within the Newtonian tradition (Prigogene and Stengers, 1984). Our conceptions of space and time are undergoing rapid flux as it has become clear that one cannot think of space as a unified, continuous plenum on which events can be unambiguously located. It turns out, on the contrary, that there are many— possibly incommensurable—correct characterizations of spatial relationships, depending on the perspective specified and the scale chosen. The world as described from the viewpoint of a mite that lives on a beetle differs fundamentally from a description of the world as viewed by large-bodied mammals such as ourselves. If our descriptions of multiscalar natural systems inevitably involve a choice regarding the perspective from which, and scale on which, to measure and monitor natural systems, how can we avoid the apparent implication that our human values and perspectives may influence the scales we observe and describe in nature? If this implication is accepted, it seems also to follow that the "descriptive" models we use to characterize natural processes actually express, in a less explicit but nevertheless profound sense, the values we pursue and the actions we take in pursuing them.

While a full exploration of this less objectivist approach to scale would be beyond the scope of this paper, these general ideas set the background for the more particular explorations undertaken here. I believe that conservation biology, restoration ecology, and ecological engineering are all "normative sciences" and that choices of models to understand interactions between humans and nature are either explicitly or implicitly based on value considerations. One of the important ways—perhaps the most important way—in which values affect science is in our choice of scales on which to characterize and address ecological risks and problems. For this reason I undertake, with some trepidation, an examination of scalar aspects of human values as my contribution to the discussions of engineering and ecological constraints central to this volume.

This paper addresses three important aspects of scalar problems in environmental values and policy. First, I explore the idea that the nonnative disciplines of conservation biology, restoration ecology, and ecological engineering use a "scientific" language that must have normative as well as descriptive content. Further, I believe that this valuational element is often embodied in decisions regarding the scale we choose to employ and the scale of the models we construct in our observation and manipulation of our environment. Second, building on empirical and theoretical work by Holling (1978, 1992, 1994, and in this volume), I propose a multiscalar analysis of social values and argue for a pluralistic approach to environmental policy. This approach recognizes multiple, irreducible values derived from nature by humans, seeks to associate particular values and classes of values with specific natural dynamics that are dominant on various scales of the environment, and organizes human values according to scale, providing multiple criteria of good management guided by multiple values. Finally, I will offer a series of devices called risk decision squares, which help to sort decisions affecting the environment according to an ecologically—that is, spatially and temporally—sensitive typology of risks involved in a given decision.

ENVIRONMENTAL PROBLEMS AS SCALAR PROBLEMS

One important consequence of the rise of modernism and the Newtonian, objectivist model of the physical universe is that choices of scale and perspective become an essential element in every description of nature. Observation is necessarily *from* some place, and the relevant scale must be specified. These general conclusions follow from relativity theory (Prigogene and Stengers, 1984). But ecological processes, especially, can also be described on countless alternative scales (Levin, 1992). How do we know the scale on which to model an environmental "problem" and measure our progress toward solving it? Pure ecology cannot be the only guide because the descriptions of nature it provides are too numerous and also incommensurate because of the differing scales they embody. An important goal of environmental ethicists and policy analysts should therefore be to ascertain which natural dynamics are associated with important social values. What is needed is a more encompassing, interdisciplinary discussion of environmental values and goals. Of course such a discussion must be based on the best science, but establishing *crucial* links between ecological processes and environmental policy can be understood only in conjunction with a process of articulating important social values. In the process, the boundary between theoretical ecology and applied disciplines, such as restoration ecology and ecological engineering, will no doubt be blurred.

Determining which dynamics require special protection is an evaluative task that can only be done from a perspective; and identifying scales and bifurcation points is on this view a *crucial* aspect of management. All of this is part of defining what is a healthy system and when a system maintains its integrity.[1] Scale is at the heart of all these problems, but we cannot choose appropriate scales to focus on until we understand *both* how ecological functions and processes work at various levels *and* how these functions and processes are associated with social values. Fully understanding this point will require that we reconsider the assumptions of "value-neutral science." In the modern, Cartesian-Newtonian period, and especially in the positivist era of science since 1900, description and evaluation have been regarded as separable steps in the process of understanding and acting in nature. It has been thought that natural systems and their products can first be described and that evaluations can then be applied to these "objective" descriptions as a separable step in the process of judgment and choice of actions. What we know now is that our choice of descriptive concepts shapes our perceptions (Kuhn, 1962; Quine, 1960). Even more important, conceptual and theoretical choices are colored by our values because we choose our theories in the process of accomplishing conscious or unconscious goals through action.

The recognition that some of our concepts embody both factual and evaluative content is really only a special case of a much more general phenomenon— description and prescription are so entwined in our use of language that it is often impossible to separate them in ordinary discourse (Nelson, 1995; Williams, 1985). This interpenetration of values and facts in ordinary discourse can be cited as one of the reasons scientific disciplines create more precise vocabularies; but, however useful an introduced special vocabulary, such formalistic languages cannot ultimately achieve pure description and at the same time be rich enough to guide behavior, as Nelson argues. Every choice of a vocabulary to describe nature requires an exclusion of other facets of reality. Every choice to measure features x or y involves a choice *not* to measure some other features, *w* and *z*. Languages are in this sense more like spotlights than floodlights (Norton, 1991). They highlight certain aspects of our experience and push other aspects into the unmeasured shadows. Thus, while measurements of aspects of nature might be carried out with precision and "objectivity," the choice to measure one aspect and ignore others nevertheless reflects an implicit or explicit evaluation of the comparative importance of the aspects.

In this sense, the emergence of an ecological approach to environmental management embodies a shift in language and hence a resolution to pay attention to different aspects of nature as we examine management options. Because nature is irreducibly complex and there exist countless correct descriptions of nature, we focus on only a few of these as helpful in deciding how to live. These choices to focus on a particular dynamic to measure involve, however subtly, value judgments, which are embodied in our decisions regarding what variables to monitor. Let us begin our exploration of values implicit in scalar decisions with a well-known example—attempts to protect the Chesapeake Bay—that will illustrate how social values and physical scale interact in the formulation and response to an environmental problem. In the 1960s, a number of observers declared that unhealthy changes were taking place in Chesapeake Bay. Early alarms were expressed in many different vocabularies. One state legislator, for example, decried the fact that he could no longer see his toes when standing in waist-deep water (Horton, 1987). These varied expressions of concern did not yet amount to a well-formulated environmental problem because the problems of bay water quality had not yet been characterized and modeled with sufficient precision to allow a description and evaluation of changing trends. In the wake of a major U.S. Environmental Protection Agency study (1983), public and scientific opinion united behind a "model" of the problem of bay water quality as affected by nutrient loading from stationary and nonpoint sources. In the course of focusing on the processes affecting bay water quality, an important scalar, boundary issue was also resolved: management attention moved from the bay stem and tributaries to the widespread lands that form the watershed. The formulation of the "problem" with the Chesapeake involved important choices about what processes were *crucial* for defending social values, as well as scientific attempts to measure and monitor those important processes.

While this example represents a complex process of problem articulation in simplified form, it illustrates how a society, by focusing on certain trends as environmental problems, implicitly builds important value judgments into its choice of scales. The complex process of formulating environmental problems is diagrammed in Figure 1. The triangle must embody both evaluative and empirical inputs. The horizontal bar represents the point at which a full-blown environmental problem can be addressed.

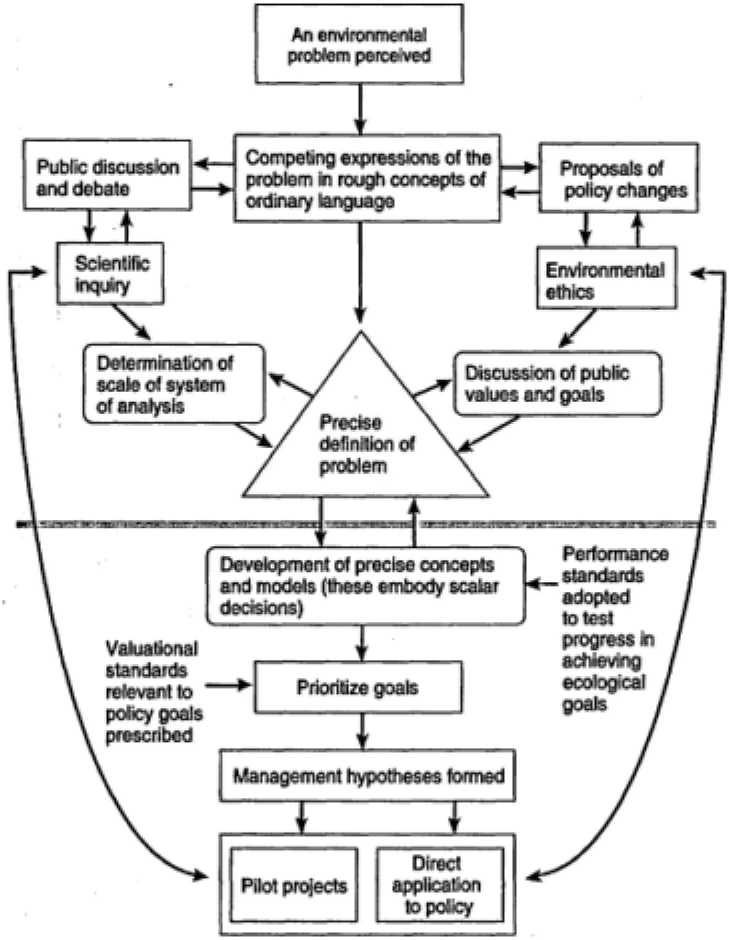

FIGURE 1 The environmental policy process. Environmental problems are not clearly formulated when they first emerge in public discourse. Determination of the proper scale at which a problem should be "modeled" requires an interactive, public process in which public values guide scientific development of models. Once the problem is precisely defined and models developed, the process of experimentation with solutions can begin. Source: Reproduced from Norton and Ulanowicz (1992) by permission of *Amnbio*.

Consider another, even more schematic, "environmental problem"—Garrett Hardin's tragedy of the commons (1968). Hardin's parable, while introduced as applicable to human reproductive decisions and human population, is remarkable in its broad applicability to virtually every environmental problem. Hardin's parable achieves such generality because environmental quality is so often a public good that must be achieved in spite of individual interest, rather than because of it. No matter how large a finite commons, the unfettered exercise of individual, self-oriented values will lead eventually to its destruction; as the "herd" is expanded by individual choice, the individual-scale decisions will add up to a total effect too great for the carrying capacity of the commons. Individuals, motivated by short-term profits, will not adequately consider the longer-term consequences of their actions, because these are delayed and diffused throughout the community—they exist on another scale in time and space. Unless individual action is limited by mutually agreed-upon constraint, the public interest will be destroyed by individual choices. Hardin's scenario is *our* scenario, because we are at that point in history at which human population and industrial growth are approaching or surpassing the carrying capacities of many systems. In this unprecedented situation, even the functioning of ecosystems essential to regional economies and communities become public goods. They represent resources that cannot be owned—they are available to everyone if they are available to anyone—and they can be destroyed by aggregate action in which each individual actor seeks his or her self-interest exclusively. Hardin's parable, by modeling environmental problems as community-scale problems resulting from individually motivated decisions, therefore illustrates in general terms how environmental problems are most basically problems of scale.

HOLLING'S WORLD

Recent groundbreaking work by Holling has hypothesized, and provided significant empirical evidence, that the dynamics of natural systems "are controlled and organized by a small set of key plant, animal, and abiotic processes." He further argues that "the geometry of landscapes and ecosystems is organized into a small number of quanta with distinct architectural attributes," attributes that are especially relevant from a human perspective (Holling, 1992, p. 449; also see Allen and Starr, 1982; Norton and Ulanowicz, 1992; O'Neill et al., 1986).

Holling's work supports, both theoretically and empirically, a broadly hier*archical* approach to understanding physical and ecological processes, suggesting that the human tendency to understand complex systems hierarchically (noted by Allen and Hoekstra, 1992; Allen and Starr, 1982) is not adventitious. It is a structural aspect of natural systems *as they are experienced by human observers*. Indeed, Holling's evidence suggests that all mammals of roughly human body size must perceive the world as organized according to similar scalar properties. Holling concludes that "The landscape is structured hierarchically by a small number of structuring processes into a small number of levels, each characterized by a distinct scale of 'architectural' texture and of temporal speed of variables" (Holling, 1992, p. 484). This hypothesis, if verified by further research, may have important consequences for the way we think about environmental values as well. Holling's model suggests (a) that environmental values are shaped, perhaps even genetically, within an architecturally structured natural world; (b) that human valuation may therefore exhibit scientifically describable scalar characteristics; and (c) that an examination of scalar aspects of environmental valuation may illuminate the perplexing problems of intertemporal evaluation.

Further, these theoretical ideas can be developed into a general approach to managing ecological systems as developed in Holling's contribution to this volume. Holling argues that, since systems exhibiting these characteristics can function in more than one equilibrium, and since changes in these structural features can occur abruptly, switching systems into alternative equilibria, it will be necessary to modify traditional engineering approaches to stability. As a system is controlled (to maximize production of a particular species, for example) it becomes more brittle, setting it up for pathologies and "flips" into a new steady state. He concludes that in the face of such flips and pathologies, near-equilibrium behavior and control (engineering resilience) seems irrelevant and the prescriptive goal shifts from questions of maximizing constancy of yield to one of designing interrelations between people and resources that are sustainable in the face of surprises and the unexpected. On this view, management attention "shifts to determining the constructive role of instability in maintaining diversity and persistence and to designs of management that maintain ecosystem function in the face of unexpected disturbances" (in this volume, p. 38). This general approach is sometimes referred to as "adaptive management" (Holling, 1978; Lee, 1993; Walters, 1986). Holling's ideas, and those of others who are exploring similar approaches, may usher in a new era in thinking about environmental management, an era that is more concerned with processes, functions, and thresholds, and less concerned with system behavior near equilibrium.

And yet (as I think Holling realizes), there is a confounding paradox at the heart of this new and promising approach to management. Where do human values and choices fit into this complex system of analysis? Can humans, by managing their own behaviors, shaping them consciously in response to ecological information, "choose" to forbear from certain actions to protect processes crucial to ecological structure and function. Since most applications of hierarchical organizational structures emphasize that control and constraints flow down spatiotemporal systems, with the larger and slower-changing processes constraining the behavior of individuals at lower levels, hierarchical reasoning is therefore best suited to treat human choices as *effects* of natural changes. And yet humans are today, without question, important, even dominant, actors in every "natural" hierarchy. Looked at in this way, it is often the accumulation of many individual human choices (based in human "values") that drives changes in ecosystem states.

It is possible to characterize this dual nature of human activity—as free choices of individuals on one level and as reaction to constraints imposed from the above level—in terms of hierarchical organization (Koestler, 1967; Simon, 1969).

Hierarchy theory embodies two formative assumptions. First, it is perspectival; every measuring or modeling effort takes place from some specified viewpoint, and a scale must be specified from that viewpoint. Second, as noted above, hierarchy theory correlates spatial and temporal scale, positing that smaller subsystems change more rapidly than do the larger systems in which they are embedded. Hierarchy in ecology also assumes that the dynamics of nature are sufficiently distinct that different levels can be described in relatively discrete terms. Hierarchy theory therefore provides a useful formalization of spatiotemporal relationships in complex systems such as natural and managed systems. Humans act freely on the scale of individual choice; and yet these choices are constrained by environmental conditions imposed from above. Freedom occurs within constraints imposed by ecological and physical systems that change more slowly. Free action is also, of course, constrained by political and culturally based rules.

What is unusual about my approach is the use of hierarchical thinking to inform an explicitly value-laden search for models that will help us to understand and manage natural systems to support important social values. This search requires a normative science, and I think conservation biology and restoration ecology should be understood within an activist, normative context. The search is for models of natural and physical systems that illuminate the interactions of human choices and policies with larger features of a landscape. And, to the extent these models can reflect human values in the structural hierarchies they posit, they are intended as "prescriptively" adequate as well as descriptive and informational.

Taking perspective seriously may require that, from a management perspective, the hierarchy will be constructed from many local perspectives. Hannon (1994) has therefore proposed that we understand human values as "discounted" across space as well as time; this concept may make it possible to measure more precisely the relationship of location and intensity of valuation, encouraging a more empirical study of the spatial scale on which social values are experienced and articulated. In this context, Hannon's result suggests that environmental values will be highly place-relative and that the perspective and valuations of one community may differ significantly from values as expressed in another community.

If Holling and Hannon are correct, humans have evolved special sensitivities to patterns perceived in nature. Holling's version sees the individual, human perspective as organized on three environmental scales. For an organism of human size and longevity, the microscale (centimeters to tens of meters in space and days to years) is dominated mainly by processes that determine vegetative structure and by immediate structures (including artificial ones) that shape individual behavior. At the macroscale (from hundreds to thousands of kilometers and centuries to millennia), the system is structured by slow geomorphological processes that define the basic edifice and topographic structure. Processes on this level are normally so slow that they can be considered constants from the perspective of human choices. The middle, or mesoscale (tens of meters to hundreds of kilometers and years to decades), is dominated by natural processes such as outbreaks of fire and plant disease and by human decisions and policies such as grazing and forestry. The mesoscale is therefore of crucial importance to human habitation; but it is also this scale that exhibits the crucial discontinuities identified by Holling as changes in ecosystem organization.

Clearly, human choices now shape the environment in countless ways; one of the consequences of Holling's argument is that it emphasizes not just the constraints that work their way down natural hierarchies—the limits on searching procedures available to specimens of an animal species of a given body size, for example—but also on the impacts that work their way up the hierarchy, such as the cumulative effects of many clear-cuts by many agents on crucial variables such as regional hydrology. Humans, who make conscious choices and who are armed with technology and stored fossil energy, can disrupt processes and rapidly introduce discontinuities into the crucial mesoscale systems. The question is whether human societies will be able to adapt and thrive when the ecological context in which they have evolved changes ever more rapidly. Technological optimists accept the disturbance-response cycle as inevitable, seeking to ameliorate unexpected negative outcomes of accelerating environmental change through investment. But Holling's conclusions seem to imply that ecological systems can be "swamped" by human impacts on productive cycles that will gradually become more brittle and collapse; his view is therefore more supportive of technological pessimism than optimism (Holling, 1994).

Be that as it may, the point here is that our perception of scale represents a curious mix of imposed, "objective" structure on the one hand and of "human" construction on the other. Hierarchy theory provides a powerful tool for characterizing natural systems as architecturally structured, nested dynamics that fall into discrete portions of temporal and spatial possibilities. This aspect provides structure *both* to physical space as studied by scientists *and* to space as it is experienced by conscious human actors. But this "objective" treatment of space and time is only one side of the story. It is also true that humans have, within this fixed structure, consciously developed, formulated, and pursued values—embodied in actions and goals—that create a mental or phenomenological representation of physical structures in their experience. I now turn to a brief discussion of the other side of the story.

ARE HUMAN VALUES SCALED?

In this section, I explore the possibility that human values are "scaled" in the sense that different human values have distinctive "natural habitats" in somewhat different contexts and scales. A scalar theory of human valuation has as its goal the illumination of choices that are made in different time contexts. If we can make sense of shifting temporal contexts in decision making, we may be on the way toward a rational means of setting priorities by deciding which human values are appropriately emphasized in different temporal situations. It will be useful to introduce this idea by contrasting scaled values with the nonscalar values that form the basic building blocks of the value theory of mainstream economics. There is an interesting sense in which the welfare values of mainstream economists are nonscalar—all values that will be experienced in the future are expressed in a present-preference system of value (Norton, 1994). The process of discounting costs and benefits across time, in essence, reduces all future values to present equivalents. The protection of values that will be experienced in the future is expressed as the willingness of present consumers to forgo consumption today to improve the welfare of future generations. The methodological advantages of this reduction are unquestionable—comparing present values is all we can do if we must make a decision in the present. Discounting also provides a general explanation of the widespread human behavior of favoring present consumption over future consumption and delay of unpleasant consequences.

But a case can be made that, while values can only affect present decisions if they are experienced in the present, some values are experienced *multigenerationally* in the present. These values express themselves in evaluations of characteristics that emerge across multiple generations in a culture. Different human values come to the forefront as the context of decision making shifts. Consider, for example, a country that solemnly undertakes a constitutional convention (Page, 1977; Toman, 1994). In the ideal situation, delegates to a constitutional convention are able to step outside daily cares of the present and consider the consequences of various activities and policies on their social and civil life over longer periods of time, over multiple generations. If the constitutional convention is successful, it is because the delegates have adopted a more timeless perspective. The point of the example is that we do, quite naturally, shift time scales and emphasize shifting motives as we consider different questions in different contexts. Neither the present-value model of the economist nor the timeless deliberations of constitutional delegates is appropriate in every situation. As our motives shift, we vary the scale of our decision making.

Thinking about sustainability may be more like thinking about constitutions —multigenerationally—than it is like thinking about immediate consumer choices in free markets. Preliminary evidence suggests that individuals, in considering large-scale decisions affecting the landscape, tend to react as "citizens" rather than as "consumers" (Common et al., 1993; Sagoff, 1988). Varying the temporal scale, or horizon, of a decision shifts the focus of discussion, emphasizing some values and focusing on different dynamics; different information becomes relevant in this shift. If environmental problems are problems of scale, it seems reasonable to expect that there is a subtle interplay between human values and the temporal and spatial horizons we construct to bound our experienced space. If environmental problems are problems of scale, it makes sense to think explicitly about how we construct mental models of the space in which we value nature.

In this spirit, I emphasize the horizon of concern expressed in environmental problems as setting a rough context for understanding and interpreting data in the search for a more harmonious relationship with ecological and physical systems. Horizons of concern are temporal scaling devices. Our operating assumption here is that, if Holling is correct, we should be able to construct an objective model of crucial ecological processes *as viewed from the perspective of an animal of human lifespan and body size.* Could we (a) define a set of dynamic, physical models that describe nature from a human perspective and then (b) choose that subset of possible spaces that reflect human values. This process of analysis, if successful, might result in an "association" of important social values with particular temporal horizons, and in turn an association of temporal horizons with physical dynamics of a particular scale. For example, Norton and Ulanowicz (1992) have shown, using a hierarchical analysis, that the protection of biodiversity is best modeled and pursued at the landscape ecosystem level. This follows from the temporal horizon of the goal of biodiversity protection—to protect biological resources for many human generations into the future.

But we have now deserted traditional "pure" and "value-free" science; we have recognized that the choice of boundaries for our physical models can express values and concerns that are shaped by our value-laden experience of space. The goal of this examination is to think more explicitly about this interaction between values and modeling and the ways in which our representations of natural processes and environmental problems embody spatial aspects of an action-oriented model for articulating environmental policy problems (a process that is represented abstractly in Figure 1).

Since it is a goal of model building in environmental management that the models inform environmental decision making to improve communication between scientists and the public, we conclude that any model for this purpose must be fairly simple in structure. It must, that is, be a simple enough representation of multiscaled natural processes to serve as an aid in public discussion of the goals of a forest management plan or a plan for ecological restoration of a river system. Our prescriptive, multiscalar models must provide a publicly useful vocabulary for discussing environmental goals. We can in this way shape our models of management by associating them with the temporal and spatial scales of the natural dynamics that generate the values guiding our choice of goals. In this sense we are searching for a spatiotemporally organized, and ecologically informed, phenomenology of the space in which individuals formulate and pursue personal and environmental values.

To initiate discussion, I suggest three basic scales, each of which corresponds to a temporally distinct policy horizon: (1) locally developed values that express the preferences of individuals, given the established limits and rules—

physical laws, governmental laws, and market conditions, for example—within which individual transactions take place; (2) a longer and larger community-oriented scale on which we hope to protect and contribute to our community, which might be taken to include the entire *ecological* community; and (3) a global scale with essentially indefinite time scales on which humans express a hope that their own species, even beyond current cultures, will survive and thrive. Table 1 exhibits these scales and shows how they correlate with different dynamics in the social and physical world.

On the first scale, which unfolds in the relatively short and local space in which individuals make economic choices, the economics of costs and benefits, if supplemented with a sense of individual justice and equity, can provide a useful model. The middle scale, in which we feel concern for our cultural connection to the past and the future, is especially important for two reasons. Viewed socially, this mesoscale, multigenerational level is the one on which we protect, develop, and nurture our sense of who we are as a culture.[2] It is on this level that a society decides what kind of a society it will be. These decisions are expressed in art, in religion and spirituality, and in governing political institutions such as a constitution. It is on this scale that concern emerges regarding a culture's interaction with the ecological communities that form its context. The second scale is doubly important because it corresponds roughly to the ecological time scale on which multiple generations of human individuals, organized into communities, must relate to populations of other species that share our habitat. It also corresponds to the mesoscale of ecological organization emphasized by Holling. It is this scale that is crucial in understanding interactions between humans and nature on landscape scales.

The point of this paper has been to suggest that, in addition to single-scale valuation systems such as the one offered by economists, there exists an alternative, scale-sensitive framework in which to evaluate human actions that reshape the landscape. That approach attempts to associate a triscalar conception of human valuation with Holling's triscalar landscape, suggesting that we can sort

TABLE 1 Correlation of Human Concerns and Natural System Dynamics at Different Temporal Scales

Temporal Horizon of Human Concern	Time Scales	Temporal Dynamics in Nature
Individual and economic concerns	0-5 years	Human economies
Community, intergenerational bequests	Up to 200 years	Ecological dynamics; interaction of species in communities
Species survival and our genetic successors	Indefinite time	Global physical systems

environmental problems and decisions according to the temporal and spatial scale of the impacts of those decisions. Since the system is pluralistic and the spatial levels are governed by relatively discrete dynamics, the features of the mesoscale landscape that are important to humans on intergenerational scales may depend on protecting processes at different scales. The injunction not to change natural processes irreversibly into new equilibria that are unproductive, or otherwise undesirable from a human perspective, represents a commitment to conceive management ecologically.

Modern ecological knowledge forces us to conclude that we must act as members of natural communities as well as the human social community; it follows also that we must pay attention to the context in which our values are formulated and acted on. That context is best understood as the interaction between a culture and its habitat that is described in the natural history of a place. That natural history must reach back into time and project itself creatively into the future. Good management requires, in the immortal words of Leopold, learning to "think like a mountain," on the scale of time, that is, in which wolves, deer, and hunters interact as populations on a mountainside (Leopold, 1949; Norton, 1991). Thinking intergenerationally apparently requires that we pay special attention to the mesoscale of the landscape, the scale at which human populations interact as parts of ecological communities.

A METAMODEL FOR DECISION MAKING IN A DISCONTINUOUS AND UNCERTAIN WORLD

In this paper more questions have been raised than answered. I hope only that they are fruitful questions and that answers may begin to point toward a more systematic, scientific, and value-sensitive approach to the difficult problems of scale and human valuation. This last section offers a practical proposal in the form of a series of devices—I call them risk decision squares—which purport to represent in a general and abstract way the decision space encountered by decision makers in the uncertain and discontinuously changing physical space that humans necessarily encounter when they contemplate, and alter, their multiscalar environment.

If I cut one tree and plant another in its place, have I changed the natural world in a way that might be held blameworthy by some member of a future generation? In most cases of cutting and replacing one tree, I think I have not harmed the future—at least not in any morally significant way. At least two features of this simple scenario suggest the cutting of the tree is an intertemporally blameless act. First, I have taken immediate steps to replace the tree, thereby initiating restoration and ensuring, insofar as I could, that my damage would be reversed in the course of nature's time. Second, the description of my act was to cut a single tree, which apparently limits the scale of my destruction to a single, specifiable locale.

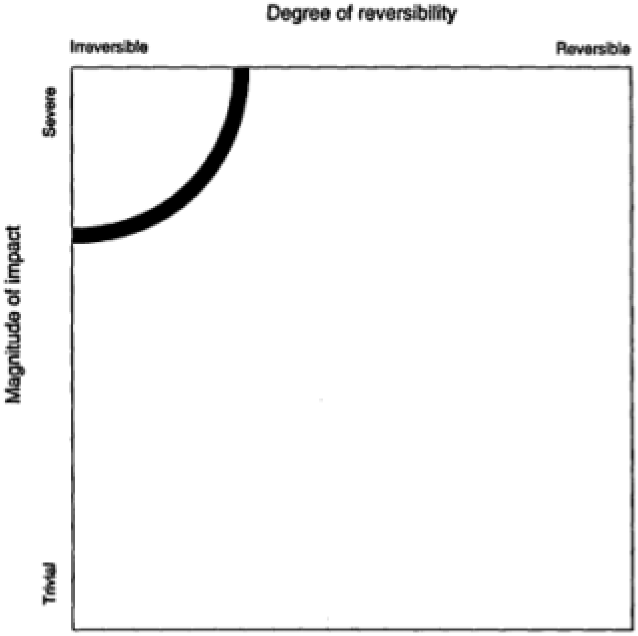

FIGURE 2 Risk decision square: neutral version. Source: Norton (1995a).

Let us build on these two ideas that the moral gravity of an action affecting the environment is determined by *the irreversibility of its effects* and by the *spatial scale of those effects*. We can do so by introducing a decision space defined by two continua, each of which ranks possible outcomes of a policy or action—one ranks the impacts according to how long natural processes will require to "heal" negative alterations to the environment, and the other ranks the spatial scale of the impact. These two scales are combined in Figure 2. Decisions with quickly reversible impacts and decisions affecting small scales probably do not raise questions of intergenerational moral importance. They fall in the northeast, the southeast, or the southwest quadrants of our decision space; they can be decided on normal, individualistic criteria of economic efficiency, balanced, we hope, by considerations of interpersonal equity. Ecological economists and environmental managers should, according to this analysis, categorize environmental problems according to the irreversibility and scale of the risks involved as a first step in any problem analysis, because this categorization determines the horizon of concern involved in the decision.

Note that the first continuum calibrates the temporal scale of our actions—the temporal horizon of possible impacts of an action helps us to define the outer limits of our responsibility. The second continuum locates decisions according to the potential spatial scope of their effects. This ensures that we distinguish between the act of cutting down and replacing one tree and a case in which cutting and replanting that tree is one incident in an ongoing process that will result in the clear-cutting of a whole watershed. In this latter case, we must consider the scale of the act not as that of cutting a single tree, but as part of a larger-scaled action—clear-cutting a whole watershed—which is sure to affect an entire ecosystem.

We can dramatize the difference between the decision model of economists and that of Holling and the ecologists by comparing Figures 3 and 4. Because they measure all values as present values, economists treat every possible loss as potentially compensable, which is justified if every resource has a suitable substitute.[3] The decision space of economists is therefore confined to the dimension-less present, resulting in an economists' version of the decision space. Exploiting hierarchy theory's organizing assumption—that large spatial scale of a system is

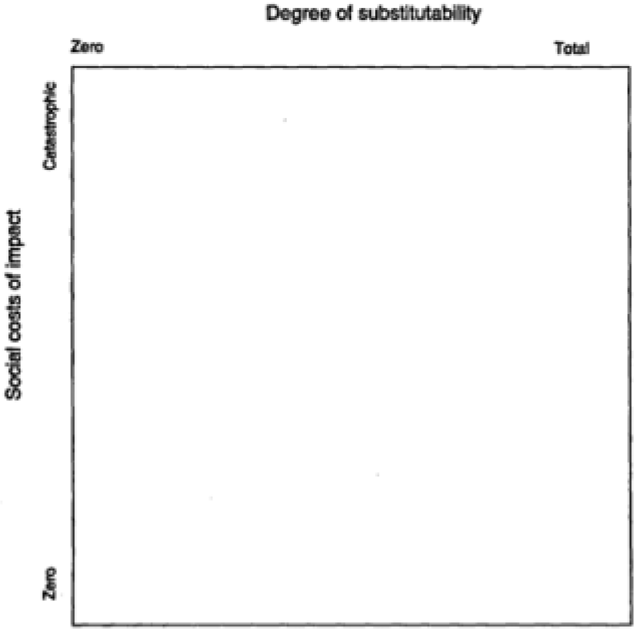

FIGURE 3 Risk decision square: economists' version. Source: Norton (1995a).

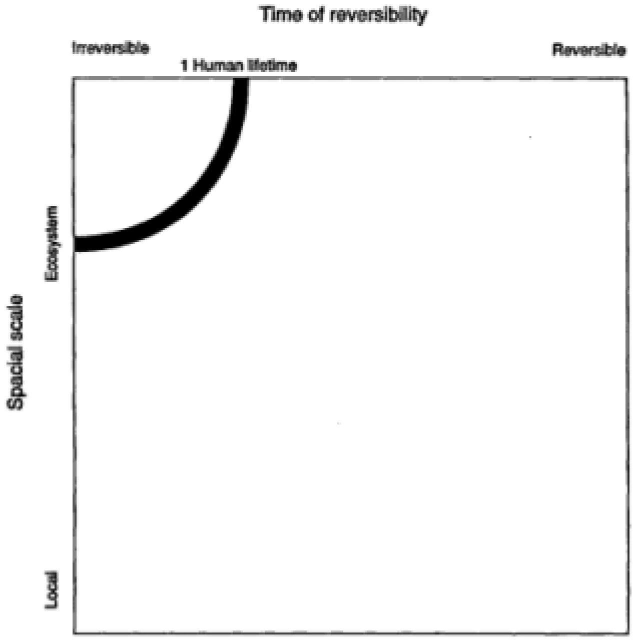

FIGURE 4 Risk decision square: ecologists' version. Source: Norton (1995a).

correlated with relatively slower rates of change—we can superimpose a hierarchical model on the decision space landscape, allowing us to locate risks on an ecologically defined decision space. One way to take scale seriously in environmental problems is to employ models such as this to identify risk decisions according to their *ecological and social* significance. These are both most difficult tasks.

I believe Holling's models take us a long way toward identifying *ecologically significant* processes to monitor and protect when he introduces the idea of "keystone processes," which he defines as processes that structure the landscape at different scales (Holling, 1992, p. 478; also see Harwell et al., 1994). And he describes the crucial variables in the decision of what to protect, and how: "The question for issues of human transformation from the scale of fields to the planet, therefore, is how much change does it take to release disturbances whose intensity and extent are so great that the renewal capital is destroyed or regeneration of the existing plant species is prevented" (Holling, 1992, p. 482). This poses the question of ecological significance in a way that allows us to specify in general terms what we mean by "ecologically sustainable activities." The difficult questions remaining on the ecological side are therefore to verify and refine Holling's results and to begin to specify the limits of risk to ecological communities consistent with a sustainable use of ecological resources for specific systems, because Holling's result implies that limits will be different in every locale.

But despite offering progress in defining *ecologically* significant change, Holling's model is not designed to address the other crucial variable in decisions regarding what natural processes to protect—the role of human values in the transformation of evolving landscapes. Besides determining whether an action is "ecologically significant" in Holling's sense, we must also make judgments regarding which near-equilibrium states are desirable, which may require balancing advantages and disadvantages of various policy proposals across multiple scales. I have suggested that humans may experience their world on roughly three scales: the individual, short-term scale; the intergenerational, community scale; and a global scale. It is useful to understand environmental management as occurring within such a three-tiered phenomenological space. I have also suggested that distinct and irreducible human values are supported on different levels of the hierarchical system. It may be possible to conceptualize environmental decision making within such a phenomenological space and also to improve on our mental representations—make them more sound, ecologically—by superimposing Holling's "natural" hierarchy on the hierarchy of human values. This description of the new focus of ecologically informed management points toward a new research program—determining which social values are associated with particular ecological dynamics. The triscalar system of human value may prove useful in organizing this research program.

This pluralistic value analysis of course implies that there will sometimes be conflicts among values that are experienced on different levels (as well as conflicts, such as value conflicts among human individuals, which take place on one level); for example, our first choice as an economic policy, as measured by its expected impact on social welfare in the short-term, may cause rapid alteration of a key ecosystem process, threatening longer-term well-being on a larger and longer scale. The proposed policy has negative impacts on ecological structure, posing an apparent conflict. But the scalar analysis, while it cannot resolve all these conflicts, does offer a constructive means to address them. There will be a class of policies that will improve individual welfare by improving economic efficiency, another class of policies that will improve the functioning of ecological communities, and another that will have no impact on the stable, geomorphological features of the landscape that, in normal times, provide the stable background for economic, cultural, and genetic evolution and adaptation.

A wise policy can be described as one that has positive impacts on some levels and negative impacts on none of the levels, a criterion I call the Scalar Pareto Optimality criterion (Norton, 1995b). The Pareto Optimality criterion, when applied by economists to individual participants in an economic choice, insists that an action is good if it helps some individuals and harms nobody. But applying this policy criterion results in no action if any individual is harmed by a proposed policy. Because there are in fact few, if any, policies that harm nobody, the Pareto Optimality criterion, applied at the individual level, has therefore been honored not in practice but only in principle, because it would result in policy gridlock. By abstracting from individuals—treating the individuals on level one as "representative" individuals and resolving their disagreements according to traditional ethical concepts—and by applying the Pareto Optimality criterion in a scalar fashion, it is possible to define a good environmental policy as one that has a positive impact on socially desired variables at some levels of the spatiotemporal hierarchy, and negative impacts on none of those socially desirable variables. This formulation of the decision criterion is equivalent, I believe, to the outcome that would occur if "representative" individuals of each community applied, from their own local perspective, the three-tiered decision space outlined in the ecologists' version of the risk decision space. Risk decision squares therefore provide a methodology for relating impacts of human choices on the landscape to dynamics that are associated with important social values.

NOTES

1. See Karr (in this volume) and Costanza et al. (1992) for further discussion of these concepts.
2. John Rawls (1971) and others (Norton, 1989, 1991; Page, 1977) have explored the idea that this intergenerational aspect of decision making can be simulated by imagining rational individuals who design fair rules to govern resource depletion from behind a "veil of ignorance" regarding which generations they will inhabit.
3. See Norton and Toman (1995) for a discussion of the importance of views on substitutability of resources in determining policy concerns.

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A Perspective on the Relationship Between Engineering and Ecology

Robert Herman

NEW AWARENESS

As the twenty-first century approaches, humanity finds itself at the dawn of new awareness. Throughout recent human history technological development has largely focused on solutions to specific problems with important outcomes affecting human existence, such as the freedom to live, develop ideas, and move about freely in relative comfort, provided that, in principle, others are not injured. It is mainly from the perspective of the individual that the world has almost reached the twenty-first century. This point of view is no longer thought to be valid by many people, and environmental justice now appears to require the consideration of collective effects—that is, the concept of the "commons." Unfortunately, this concept is mainly human centered and often does not take into account the well-being of other living creatures.

It is generally recognized that the quality of the environment must be maintained so that living creatures can survive, that is, extract oxygen and water and give off waste products. Our living conditions are intended to give us warmth, comfort, and safety and serve as a place for physical and spiritual nourishment, while at the same time their creation influences the collective environment, causing such problems as air pollution, solid-waste accumulation, and the greenhouse effect. The subtle and insidious nature of the impacts resulting from greenhouse gas buildup makes a truly equitable societal response very difficult. This is especially so when we recall that the contribution of human effluents in many instances is a small part of the natural balance. Unfortunately, however, we humans are not yet in a position to understand all the intricacies of the biogeochemical balances that exist within the world's ecosystems and the influence that small perturbations may have, such as an annual El Niño whose effects persist for 10 years.

PRINCIPLES FOR ENGINEERING WITHIN ECOLOGICAL CONSTRAINTS

New applications of technology and engineering must come to terms with the social and ethical values of the society in which they are to be made. Engineering must be applied in such a way that innovations make proper contributions to the greater community at large. The development of sound engineering practices can help conserve and restore the environment through a proper balance between engineering principles and environmental considerations. Principal among these considerations must be a strengthening of engineering accounting to include properly the value and costs to the affected ecosystems. Over and above that, societies must avoid becoming technologically overcommitted. It is preferable if engineering know-how is applied sparingly, with the goal of simplifying tasks and enhancing the quality of life. Engineers should not be encouraged to pursue the application of complicated and ingenious devices for unimportant functions. The appropriate criterion for the ethical application of engineering within ecological constraints is conservatism, while operating within the natural system rather than infringing on it or overcoming it, having a sense of the whole of the environment, and abstracting no more than a particular function warrants. Systems should be developed to be as flexible and forgiving as possible to avoid drastic and irreversible consequences when something goes wrong. This is counter to the traditional Baconian view, often held even now in some segments of our society, that nature should be conquered.

An ecological approach to engineering must take into account that nature responds systematically, continuously, and cumulatively. In support of these concepts, ecologists should make available to the engineering community as much knowledge as possible on the ecosystems that could be affected, their vulnerabilities, and the specific technical reasons for caution. Perhaps the ecological community should develop a new applied subject area in which consideration is given to engineering applications of a specific type and the resultant stresses, costs, and effects on related ecosystems are evaluated, using various generic cases. It is beyond the capability or intent of the average engineer to become both a creative technologist and an ecologist.

As alluded to earlier, when engineering applications are planned, care should be taken to consider the social and ecological costs. Today much depreciation of environmental capital is going unrecorded. For example, Passent (1994) states that between 1970 and 1989 Costa Rica's forest, soils, and fisheries depreciated by more than U.S. $4 billion. He goes on to say many authors believe that resource depletion would be obvious if ecological accounting were included within the national income accounting framework. Such depreciation takes an enormous toll on a country's capacity to generate future income. In fact, in a developing country a lower per capita income involving sound, ecologically focused business may actually produce a higher standard of living for its people. The United Nations Development Program has devised the Human Development Index, which ranks countries on the basis of a combination of adjusted per capita gross national product, longevity, and educational attainment. From this is derived an average deprivation index. It is interesting that according to this index the United States ranks sixth worldwide, after Japan: Canada, Norway, Switzerland, and Sweden. With regard to the depreciation of environmental capital, engineers must also be aware of any remote effects of their works.

In the development of complex systems, careful consideration should be given to what should be automated and what should not. Many times in an automated system (e.g., telephone marketing) the function is performed badly and conceals the essence of the situation. Automation commonly treats everything in an inanimate way. Incommensurable factors, individual differences, local context, and the weighting of evidence are often overlooked though embedded in these factors may be the essence of what is important. With automation the process may be subtly transformed; the process may run smoothly, it may be productive, but it may also be out of line with the nature of things and the essential problems. Such a situation can lead to artificial or unnatural boundary conditions with regard to interactions with other systems.

On the other hand it is ethically proper that engineering be applied in a timely manner to ensure survival by diminishing human disease, drudgery, and the threat of starvation; but in so doing the application of engineering concepts takes on an ethical component as well, to ensure that new approaches improve the quality of human life. In the developing world, technological applications should seek to employ native labor and local resources as much as possible, should serve to maintain the natural environment as well as traditional customs, and should focus on teachable know-how. This may not be an easy assignment and will require an application of social knowledge beyond what is commonly taught or expected of the engineer today. Perhaps a new discipline of social engineering should be considered in which the mix of the two topics would take on a more integrated structure.

These considerations suggest some key research goals and policy objectives.

- The "built environment" should have long-term integrity that can enhance the quality of life while taking into account the interactions among the various elements, namely, energy, transportation, communication (or information), public health and safety (e.g., water and waste), industry, construction, the environment, and others. The idealist's future goals for infrastructure development must consider such features as quality, flexibility, adaptability, reliability, cost-effectiveness, and, perhaps most important, crisis management, especially for the complex city.

- We need to develop and understand "industrial metabolism" to make industrial processes more efficient through the proper use of by-products and wastes generated during technological processes. In this context we need to aim to lessen environmental impacts through flexible management practices that involve innovative reuse, remanufacturing, and recycling of "wastes" (Ayres, 1989; Frosch, 1993).
- Future engineering policy should focus on environmentally friendly design. It is at the design stage that strategies can be developed to address environmental issues, since it is during design that consideration can be given to the types of resources and manufacturing processes to be employed, which in the final analysis determine the detailed character of the by-products and the waste stream. Such considerations may often lead to the added benefits of improved efficiency and quality, reduced costs, and increased industrial competitiveness (U.S. Congress, Office of Technology Assessment, 1992). Proper cost accounting of industrial processes and their ecological impacts will assist industry to justify environmentally sound business practices.
- There should be an aggressive public education effort to explain the scientific basis for concerns regarding air pollution, stratospheric ozone depletion, global warming, and pollution of the oceans, land, and groundwater, especially as these matters relate to choices in human behavior.
- We need better understanding of the effects of government regulations and public relations on the interaction of engineering with ecology, and better understanding of the impact of the media in generating and influencing the public mind-set, which is a significant determinant of public policy. A realistic approach must take into account the politicization of technical and scientific problems as well as the reality that in our highly litigious culture, constraints are considered to be anathema.
- Administrative structures should allow for processes to readjust decentrally with a minimum of central intervention or control, except, of course, for cases of catastrophic breakdown.
- Land planners need a clearinghouse of information on the ecology of an area, continually updated. The same information should be available to the public and should precede any environmental impact studies once land use decisions have been made.
- Detailed environmental hazard contingency plans should also be drawn up and made available to governmental authorities for all scales of impacts, local, county, state, regional, and beyond. This would help to ward off improper responses to emergencies. It would also be especially important as it relates to jurisdictional responsibilities in times of emergency, both domestic and foreign.

AN EXAMPLE: TRANSPORTATION SYSTEMS

The many-faceted nature of these various considerations may be demonstrated by considering a particular engineering-based aspect of modern society, transportation systems. One of the principal greenhouse gases, carbon dioxide, is released whenever fossil fuel is burned. In addition, gasoline internal combustion engines release nitrous oxides, carbon monoxide, and volatile organic compounds. These gases, in turn, lead to the production of smog and tropospheric ozone, the latter also being an important greenhouse gas. Some vehicles also emit chlorofluorocarbons, which both act as a greenhouse gas and catalyze the destruction of stratospheric ozone. Chlorofluorocarbons serve as the thermodynamic working fluid in all but the most modern vehicle air conditioners and are constituents of the foam cushioning used in car seats. They are also important as degreasing agents and fire extinguishing agents. While these effluents can have an impact on human health and comfort, their effects are not immediate nor are they restricted exclusively to the user. It is in the context of their spatial effects as well as the long duration of their effects on the commons that the release of chlorofluorocarbons to the atmosphere takes on great significance for the biosphere.

As more and more people migrate to cities and life is developed in an increasingly global economy, the design of transportation and communication systems provides us with the greatest flexibility for the mitigation of global climate change. It is particularly important that these considerations be taken into account as the developing world begins to expand its use of fossil fuel and advanced transportation systems. The future climate of the globe may be strongly dependent on these technological decisions. It is with these ideas in mind that a number of critical areas require intensive study and that various critical questions can be raised:

- Should travel and transportation be priced to cover the costs of impacts on the environment? Should work trips be excluded? Should communication that reduces travel be subsidized?
- Should there be an excise tax on raw materials transported great distances, since energy is required to transport them and ecological risks may be enhanced during their transport? Should there also be a special environmental impact tax on items transported great distances when they could be produced closer to their destination?
- Should the cost of a new car reflect the value of the useful materials abandoned in the old car that is being replaced?
- Should individual and business taxes reflect the impact of transportation emissions on the global commons?
- Should much greater effort be made to explore and exploit the possible benefits of telecommunication?

  Since vehicular transportation requires massive investment in infrastructure as well as provision for frequent refueling, there are other fundamental and ethical questions to be considered.

- What means of transportation is fair and equitable in the context of the commons?

- What land development and transportation principles should be practiced to ensure the most efficient infrastructure and to maintain the environmental commons?
- What complementary role should communication play?

All of these types of questions must be considered in spite of our inadequate knowledge of the detailed character of urban traffic. In this context there is a strong interaction possible between communication and transportation —"telecommunication" as it is now called. Communication can sometimes replace travel, and communication may make travel more efficient and safe, for example, through the control of traffic in systems such as ITS (Intelligent Transportation Systems, formerly IVHS, Intelligent Vehicle Highway Systems) (Catling, 1993; ITS America, 1995; IVHS America, 1992; Whelan, 1995). On the other hand, it should be kept in mind that communication can also raise travel demand with a resultant offsetting effect.

We focus on transportation in an attempt to illuminate some of the general points made earlier. In practice, all components of the civic infrastructure should be examined as a single system to understand the interactions between the various elements of the system. The infrastructure is a reflection of our human characteristics and, therefore, we need to understand the dynamic evolution of cities to move forward in an effective social and technological manner, one that is compatible with our human character.

COMPLEXITY

The human enterprise is critically dependent on our understanding of, and ability to address and solve, highly complex problems. These are problems whose description must be specified in terms of an intermediate number of variables, not just two or three variables which would generally be tractable, nor an extremely large number such as can be handled by the methods of statistical physics. Systems with an intermediate number of variables are least well understood. There is an urgency to learn how to handle such problems, since the future development of human society will be progressively more dependent on their solution. Perhaps with skill and application it will be possible to discover simplifications that result from collective effects, so that the number of pertinent independent variables can be reduced.

One of the first systems with an intermediate number of variables to enjoy substantial progress is vehicular traffic (Herman, 1992; see also Johnson, 1993, and Zuckermann, 1991). Even though traffic systems are complex, with individual actors independently operating independent machines, 75 percent of the variance in the fuel consumed per unit distance for an automobile with a gasoline combustion engine in an urban street network can be explained by a single variable, average speed. In addition, it is also possible to describe the overall traffic in an urban street network through a two-fluid model with only two parameters. The main assumption in the model is simply that the average speed of the moving traffic is proportional to the average fraction of the vehicles that are moving (Herman, 1992; Herman and Prigogine, 1979). These are but two examples of the great simplicity resulting in some cases where many variables in a complex problem are nonlinearly intertwined. In spite of the large number of variables and effects, including stochastic effects and fluctuations, the net results can be formulated in an extremely simple, compact manner. On the other hand, there are situations in which a result is dependent on a large number of interacting variables, each of which is responsible for only a small percentage of the total effect. Such is the case for the decline of the salmon population in North America, for which fixing one of a relatively large number of pertinent factors not only may not do any good but may actually cause harm, since one does not fully understand the interrelationship among the variables (see Karr, in this volume).

It is apparent that when we deal with such complex problems we do not understand in advance all the consequences of our decisions. In this context we refer to Edward Tenner, who recently wrote a very interesting article that addresses some of the above-mentioned difficulties when dealing with complex problems (Tenner, 1991). The article is entitled "Revenge Theory or why new highways develop gridlock, labor saving appliances create more housework, simplified tax regulations are harder to follow, paperback books cost what clothbound books used to, and why Murphy was an optimist." While it is not easy to classify all the types of outcomes that cause us difficulty, Tenner suggests the following set: repeating, recomplicating, recongesting, regenerating, and rearranging. We might suggest reconstituting as well.

With regard to repeating, we are all familiar with the fact that having a time-saving device often induces us to use it more frequently and thus use more time. Recomplicating is exemplified by a new device such as the push-button telephone, which makes some operations easier and is then overpowered by elaborate systems developed to take advantage of it. In recongesting, technological change opens new possibilities but concomitantly encourages new demand that soon clogs the system again, as in the case of the automobile. Regenerating appears after a problem seems to have been solved. This is apparent in connection with pest control, which may work for a while and then revert to the original situation because the pesticide also kills the pest's natural predator or selects for pesticide-resistant pests. Tenner finally discusses rearranging, which is the revenge effect that *shifts* a problem in space or time. Thus, air-conditioned subway cars may provide a cooler ride, but the stations and tunnels become considerably warmer, which in turn can cause the air-conditioning units in the train to break down.

With respect to reconstituting, we note that when a significant new element is introduced into a system, it can generate total change. If you add or subtract something, the overall system may be altered. Examples are the removal of some vital species from the environment or the introduction of a new technology (Postman, 1993). It is possible to cite numerous other examples that involve sociocultural as well as technological systems. While we cannot anticipate all the effects that might arise from some new technology or methodology, we certainly should give far more thought to some of the arcane possibilities. It is impossible to imagine that the first humans who could create and control fire could have foreseen even a few of the simple, practical applications of the fireplace and the forge. They certainly had experienced the ravages of fire. However, in the not-distant past the scientists who developed the first nuclear pile clearly understood the potential of the nuclear bomb as a devastating weapon of destruction.

DISCUSSION

Engineering, together with technology, is the day-to-day driving force that shapes our destiny (Russell, 1953). It creates the overall infrastructure and in time evolves as the reflection of our detailed human character. In fact, as we have said in the past, the infrastructure is us. It expresses the history of our lives and the technological and social evolution of humankind through its various societies. More pointedly it reminds us that we are what we were and will be what we are. To quote more precisely,

> We should not allow the infrastructure to develop only on the basis of individual utility and short-term measures of cost and benefit, or narrowly measurable attributes that are tractable with current analytic tools. We require longer-range goals of a creative and inspirational kind that blend technological and aesthetic considerations. The future of quality of life is to some considerable degree in our hands when we debate decisions about infrastructure. Are beautiful structures ever obsolete? (Herman and Ausubel, 1988, p. 21)

It is clear that we must somehow generate a social imperative that will provide inspirational leadership so that our society can strive to reach the highest quality of life with integrity and equality. In this regard it is important once and for all to turn to the question of how much it costs society as a whole that there exists a significant level of legal, moral, and ethical criminality over a wide spectrum at all levels. We have been surprised to find that when this question is raised it appears to be essentially taboo in our culture. However, the central issue of this volume, engineering within ecological constraints, cries out to have precisely such questions scrutinized. It implies that there are goals to be set that will in fact improve the quality of life as we go forward with all of our human enterprises. There is no question but that this focuses on deep philosophical issues. It is not our purpose here to delve into the details but rather to raise the issue in the hope that our collective minds might set a course toward what can be done to develop better understanding and subsequently establish methodologies for improvement. We all know that the failure of a bolt costing a few cents, whether the result of incompetence or criminality, can cause a disaster, and when the failure is the result of criminality, we need to invent new descriptive words since malicious and venal causes are very different from failure arising from incompetence or random stochastic events.

To return to the subject of engineering within ecological constraints, we must remember the importance of science. Science is the wellspring that provides the knowledge we require to realize our engineering and technological goals. This is not to say that new pathways have not arisen from applied research. It is fortunate that early humans were curious about the world around them and appreciated the profound value of the knowledge they had acquired. Not only does science provide the basic knowledge to solve applied problems, it also generates the philosophical outlook for further exploration and helps us appreciate that there is new knowledge beyond the known boundaries. This new knowledge most often comes as the serendipitous result of the curiosity of creative people who have the insight to ask unusual questions that they sense are meaningful to probe (Reines, 1993).

Engineering within ecological constraints may generate more fundamental questions than answers. The present administration has set national priorities for scientific research to strengthen industry, protect the environment, improve the educational enterprise, create jobs, and the like. These, of course, are lofty goals worthy of the attention and effort of our scientific and engineering community. However, we believe the approach must be developed with extreme care to maintain the freedom necessary for creativity to flourish, in both the fundamental and applied sciences, and to limit micromanagement of fundamental science that until now has flourished under a system of freedom to explore the "endless frontier." The reason that micromanagement can be so detrimental, certainly in the case of complex problems, was well expressed by the American poet Brewster Ghiselin (1955) when discussing the creative process:

> It is essential to remember that the creative end is never in full sight at the beginning and that it is brought wholly into view only when the process of creation is completed. It is not to be found by scrutiny of the conscious scene, because it is never there.[1]

There are those who believe, for example with Starr (1993), that

> Sustaining and improving the quality of life for a diverse global population over the next 200 years will not be limited by the availability of resources, in spite of the likely massive increases in population and economic demands over this time span. The key resource that makes this possible is science and technology. The supply potentials for food, water, and energy appear adequate even with today's menu of available technologies provided they are fully implemented and chosen to minimize environmental degradation.

Starr goes on to say that "neither science, nor technology, nor politics, nor religion, nor any ideology is likely by itself to provide the best answers or absolute criteria for governmental actions, either regionally or globally, that would be adequate for two centuries." In contrast, we are well aware that various global scenarios put forward by Forrester (1971) as well as by Meadows and others (1992), have reached conclusions quite different from those of Starr with regard to global well-being based on our present levels of science and technology. More recently, Pimentel and coauthors (1994) have claimed that to spread the equivalent of Western World quality of life ubiquitously over the entire globe, the current word population would have to be reduced significantly. These authors ask, "Does human society want 10 to 15 billion humans living in poverty and malnourishment or 1 to 2 billion living with abundant resources and a quality environment?" Answers to such profound questions, of course, involve social, religious, political, and philosophical outlooks that probably will never come to closure.

These differing results are some of many examples that could be cited when considering complex sociotechnical problems whose projections critically depend on the assumptions that are made and the character of the mathematical model. It should come as no surprise that there is a difference of opinion among competent and honest scientists regarding how to address complex problems. It is difficult to find the proper management and encouragement by governmental bodies to bring efficiency and understanding into such considerations. The overall politicization and often unrealistic promises of our scientific and technical enterprise cannot be of long-term benefit to any one.

How then can we approach the task of addressing the manner in which engineering should proceed within the sensible boundaries of ecology? A democracy will always have myriad discussions of any issue on technical, social, and political levels. This is especially true when decisions must be made regarding the allocation of resources. However, science is the fountainhead of new knowledge. If we must prove in advance that all of our inquiries will be productive or even sensible, the greatest drying forces for science will be frustrated. So-called pure research is risky, rarely efficient. Yet it is the solution to individual fundamental problems that makes possible great advances in science and mathematics with consequent disciplinary and social value for the future.

We are all very familiar with the intense scrutiny received by new ideas and results, especially if they are disjoint with respect to conventional wisdom and especially so if the work is perceived to have importance. As a rule this is a healthy competitive process, although some of the resistance comes from the conservative nature of the technical communities; and, of course, there is the not-invented-here syndrome.

An interesting example of the impact of governmental thinking on science and technology is Thomas Jefferson's concern with social utility when the United States was very young (Martin, 1952). In 1800 Jefferson organized a rank ordering of the utility of the sciences for Joseph Priestley. The list was headed by botany and chemistry, with natural philosophy, mathematics, and astronomy in the middle of the list, and the fine arts at the end. He had an especially high regard for chemistry as one of the most useful sciences with great potential for future discoveries, and he expressed the opinion that agriculture was the most useful of the sciences for America. He qualified his recommendation for geology because he felt its conclusions were uncertain and that it had no obvious utility, but he certainly showed a keen interest in mineral exploration. However, regarding the branch of knowledge that deals with the formation and history of the earth, he wrote as follows:

> The dreams about the modes of creation, inquiries whether our globe has been formed by the agency of fire or water, how many millions of years it has cost Vulcan or Neptune to produce what the fiat of the Creator would effect by a simple act of will, is too idle to be worth a single hour of any man's life.

Jefferson went so far as to remark that it made little difference whether the earth is 600 or 6,000 years old. We mention these thoughts because in Jefferson we have an example of a true Renaissance genius focusing on practical benefits for valid reasons but with a somewhat less than open mind regarding the value of improbable fluctuations from which important knowledge does frequently arise. Perhaps we can be sympathetic to Jefferson's outlook since in those early days of our country there were not sufficient resources and time to indulge in what might have appeared to be the luxury of theoretical speculation. We are now living in a mature sociotechnical culture, and if we were to support only those works which appeal because we see pragmatic results, we had better beware. Nobody is sufficiently prescient to know where new important developments may lie, and we surely must shun an outlook that smothers human receptivity to new thoughts and pathways.

All of us, especially those in positions of power and control over resources, should take careful note of some of these ideas so beautifully and succinctly expressed by Leonardo da Vinci in his notebooks:

> Those who fall in love with practice without science are like a sailor who enters a ship without a helm or a compass and does not know whither he is going .... Science is the captain, practice the soldiers .... All sciences are vain and full of errors that have not been born by experience, mother of all certainty, and that are not tested by experience.

To return again to our central theme, we might propose that the title of the workshop on which this volume is based could just as well have been, "Engineering Within Ecological and Scientific Constraints." Engineering, which is the day-to-day expression of human activity in advancing the overall infrastructure, should proceed in such a way that at a minimum it is essentially compatible with the best scientific understanding of the time and, in addition, takes into account the existing social mores and philosophical and ethical outlook of the particular socioculture. It is difficult to ignore the educational enterprise in such considerations. We desperately need new young people properly trained across disciplines to carry out engineering research within the constraints of ecology. Apart from any specific training, it is imperative that our education system mainly encourages students to focus on learning how to learn, learning how to use what they know, to have a sense of the ethical dilemmas, to view information for what it is, and to appreciate the meaning of understanding and knowledge. Our education system is flawed in that it stresses information and prescriptive learning, providing students with a "bag of tricks," the value of which decays rapidly. In our ever-advancing high-technology society, we will be faced with problems of ever-increasing complexity that will require lifelong development in order that we acquire the judgment necessary to make any substantial inroads into problems of critical importance to society and the individual as well.

Our eternal struggle for new knowledge that on the one hand adds to the inner core of our understanding and on the other has useful consequences for humanity requires a great and constant effort as well as a high level of devotion. This is an extremely difficult task since as the ancient Greek philosopher Heraclitus said, "Nature seeks to hide." Science is not an isolated pursuit, it is embedded in society and intertwined with all knowledge, especially engineering, and all of human experience. Science as we know it, which has been the creative Aladdin's lamp for humanity, would not be possible if it were not for our deepest conviction both as individuals and as a society that the pursuit of science is a great and uplifting endeavor, essential and relevant to both our material and spiritual evolution. We believe that it is mainly through science coupled with technology that we will eventually learn how to tackle the extremely complex problems that we have been discussing and whose solution is so vital for human progress.

In conclusion we feel impelled to state that we are fully cognizant of the importance of solving practical and timely problems that focus on our daily well-being. Nobody would deny the significance of improving the quality of life for all humans everywhere and at the same time living peacefully with one another and with nature. Moreover, we must face the Herculean task of conducting our local engineering enterprises in the face of an almost impossibly complex global problem and doing the best we know how at the time. However, on the other hand, we must never forget that on the long time scale we must continue our striving for the knowledge that comes from all the sciences and, when coupled with philosophical and ethical principles, is the key to our continued evolution and freedom. How better to say this than to paraphrase Socrates, who more than two millennia ago said

> We must rise above the Earth to the top of the atmosphere and beyond, for only then will we fully understand the world in which we live.

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NOTE

1. Another difficulty for the scientist or any creative artist has been most elegantly expressed by Gertrude Stein (1969, p. 9) in her own inimitable manner:

> One does not ever understand, before they are completely created, what is happening and one does not at all understand what one has done until the moment when it is all done. Picasso said once that he who created a thing is forced to make it ugly. In the effort to create the intensity and the struggle to create this intensity, the result always produces a certain ugliness, those who follow can make of this thing a beautiful thing because they know what they are doing, the thing having already been invented, but the inventor because he does not know what he is going to invent inevitably the thing he makes must have its ugliness.

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Designing Sustainable Ecological Economic Systems

Robert Costanza

DEFINING SUSTAINABILITY

There is a huge amount of discussion in the literature these days about how one "defines" sustainability, sustainable development, and related concepts (see Costanza, 1991; Pezzey, 1989; World Commission on Environment and Development, 1987). Many argue that the concept is useless because it cannot be "adequately defined." Most of this discussion is misdirected because it (1) attempts to cast the problem as definitional, when in fact it is a problem of prediction, and (2) fails to take into account the many time and space scales over which the concept must apply.

Defining sustainability is actually quite easy: a sustainable system is one that survives for some specified (non-infinite) time. The problem is that one knows one has a sustainable system only *after the fact*. Thus, what usually pass for *definitions* of sustainability are actually *predictions* of what set of conditions will actually lead to a sustainable system. For example, keeping harvest rates below rates of natural renewal should, one could argue, lead to a sustainable system for extracting natural resources—but that is a prediction, not a definition. We know if the system actually *is* sustainable only after we have had the time to observe whether the prediction holds. Usually there is so much uncertainty in our ability to estimate natural rates of renewal and our ability to observe and regulate harvest rates that a simple prediction such as this is, as Ludwig et al. (1993) correctly observe, always highly suspect.

Likewise, sustainable economic development can only be observed after the fact. Most "definitions" of sustainable development, encompassing elements of (1) a sustainable *scale* of the economy relative to its ecological life-support system, (2) a fair *distribution* of resources and opportunities between present and future generations, as well as between agents in the current generation, and (3) an efficient *allocation* of resources that adequately accounts for natural capital, are thus really predictors of sustainability and not really elements of a definition. Like all predictions, they are uncertain and are subject to much discussion and disagreement.

The second problem is that when one says a system has achieved sustainability, one does not mean an infinite life span, but rather a life span consistent with its time and space scale. Figure 1 indicates this relationship by plotting a hypothetical curve of system life expectancy on the y axis as a function of time and space on the x axis. We expect a cell in an organism to have a relatively short life span, the organism to have a longer life span, the species to have an even longer life span, and the planet to have a longer life span. But no system (even the universe itself in the extreme case) is expected to have an infinite life span. A sustainable system in this context is thus one that attains its full expected life span.

Individual humans are sustainable by this definition if they achieve their normal life span. At the population level, average life expectancy is often used as an indicator of health and well-being of the population, but the population itself is expected to have a much longer life span than any individual and would not be

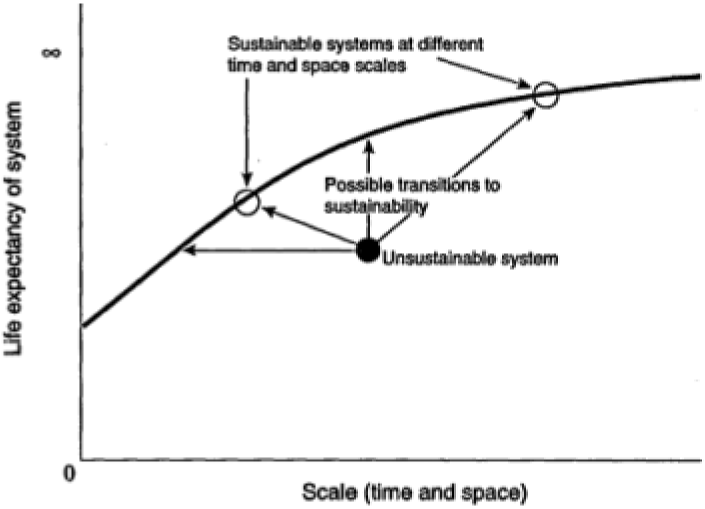

FIGURE 1 Sustainability as scale (time and space) dependent concepts.

considered to be sustainable if it were to crash prematurely, even if all the individuals in the population were living out their full "sustainable" life spans.

Since ecosystems experience succession as a result of changing climatic conditions and internal developmental changes, they too have a limited (albeit fairly long) life span. The key is differentiating between changes due to normal life span limits and changes that cut short the life span of the system. Things that cut short the life span of humans are obviously contributors to poor health. Cancer, AIDS, and a host of other ailments do just this. Human-induced eutrophication in aquatic ecosystems causes a radical change in the nature of the system (ending the life span of the more oligotrophic system while beginning the life span of a more eutrophic system). We would have to call this process "unsustainable" using the above definitions since the life span of the first system was cut "unnaturally" short. It may have gone eutrophic eventually, but the anthropogenic stress caused this transition to occur "too soon."

Sustainability is thus most accurately viewed as a long-term *goal* over which there is broad and growing consensus. Establishment of this goal is fundamentally a social decision about the desirability of a survivable ecological and economic system. Defining sustainability as a *goal* is relatively straightforward— we want the system to last as long as possible (remembering that it is necessary to specify the time and space scale for the system in order to interpret "as long as possible"). The real problems are not so much defining the goal as they are predicting what policies will lead to its achievement. Here there is ample room for, and need of, vigorous discussion, debate, analysis, and modeling to determine which policies have the best chance of achieving the goal.

ECOSYSTEMS AS SUSTAINABLE, NONPOLLUTING PRODUCERS

Ecological systems play a fundamental role in supporting life on Earth at all hierarchical scales. They form the life-support system without which economic activity would not be possible. They are essential in global material cycles, such as the carbon and water cycles. They provide raw materials, food, water, recreation opportunities, and microclimate control for the entire human population. In the long run a healthy economy can exist in symbiosis only with a healthy ecology. The two are so interdependent that isolating them for academic purposes has led to distortions and poor management.

Ecological systems are also our best current models of sustainable systems. Better understanding of ecological systems and how they function and maintain themselves can yield insights into designing and managing sustainable economic systems. For example, there is no "pollution" in mature ecosystems— all waste and by-products are either recycled and used somewhere in the system or they are fully dissipated. "Pollution" is defined as material or energy that is a by-product of the activity of one part of the system that has an unintentional disruptive effect on another part of the system. Some activities such as predation or the scent of a skunk intended to drive away predators are intentionally disruptive, so these are not pollution by the above definition. In general the lower the entropy of the pollution (the higher its organization), the more potentially disruptive it can be. On the other hand, some forms of pollution (i.e., anthropogenic CO_2 emissions) are fairly high in entropy per unit emitted, but the sheer volume can be enough to cause major problems. The disruptive potential of a given pollutant can be thought of as the product of the quantity of production and its organization (negative entropy) per unit.

This implies that a characteristic of sustainable economic systems should be a similar "closing the cycle" by finding productive uses and recycling currently discarded "pollution," rather than simply storing it, diluting it, or changing its state and allowing it to disrupt other existing ecosystems and economic systems that cannot effectively use it. Those things that have no possible productive uses should not be produced at all.

Ecosystems have had countless eons of trial and error to evolve these closed, nonpolluting loops. Early in the earth's history there was certainly pollution in natural systems, and even today, early successional ecosystems have pollution under our definition. A general characteristic of closing the loops and building organized nonpolluting natural systems is that the process can take a significant amount of time. The connections in the system must evolve, and there are *characteristics* of systems that enhance and retard evolutionary change. Humans have the special ability to perceive this process and potentially to enhance and accelerate it.

The first pollutant was probably oxygen, an unintentional by-product of photosynthesis that was very disruptive to anaerobic respiration. There was so much of this "pollution" that the earth's atmosphere eventually became saturated with it and new species evolved that could use this former pollution as a productive input in aerobic respiration. The current biosphere represents a balance between these processes—a balance that has evolved over millions of years to ensure that the formerly unintentional by-product is now an absolutely integral component of the system.

Eutrophication and toxic stress are two current forms of pollution that can be seen as resulting from the inability of the affected systems to evolve fast enough to convert the "pollution" into useful products and processes.

Eutrophication is the introduction of high levels of nutrients into formerly lower nutrient systems. The species of primary producers (and the assemblages of animals that depend on them) that were adapted to the lower nutrient conditions are outcompeted by faster-growing species adapted to the higher nutrient conditions. But the shift in nutrient regime is so sudden that only the primary producers are changed and the result is a disorganized collection of species with much internal disruption (i.e., plankton blooms, fish kills) that can rightly be called pollution. The introduction of high levels of nutrients into a system not adapted to them causes pollution (called eutrophication in this case), whereas the introduction of the same nutrients into a system that *is* adapted to them (i.e., marshes and swamps) would be a positive input. We can minimize pollution by finding the places in the system where it represents a positive input and placing it there.

Toxic chemicals represent a form of pollution because there are *no* existing natural systems that have ever experienced them, so there are no existing systems to which they represent a positive input. The places where toxic chemicals can most readily find a productive use are probably in other industrial processes, not in natural ecosystems. The solution in this case is to encourage the evolution of industrial processes that can use toxic wastes as productive inputs, or, if these cannot be found, to eliminate their production and replace them with alternatives that do have positive uses.

The Role of Diversity and Organization

One strategy that natural systems have evolved to cope with pollution is diversity. The most disruptive pollutants are relatively low entropy. Low-entropy matter and energy also represent a potential resource. Given enough time, a species will evolve to take advantage of this potential. Thus, diversity may be linked to efficiency at the system level. A higher diversity system wastes fewer potentially productive resources by taking advantage of all the "pollution." Early successional systems with low diversity are wasteful of resources in the name of rapid growth and colonization. Later successional systems recycle more, close more of the loops, and require higher diversity to do this. A possible analogy in economic systems is competitive markets. To be "competitive" and efficient, markets must have a large and diverse set of participants. Monopolies can get the big jobs done,. but without diversity the system does not satisfy all the smaller product niches and is less efficient at producing what it does produce.

But it is not simply the diversity of species that is important to minimizing pollution, it is how that diversity is organized into a coherent whole system. The degree of organization of a system is contained in the network of interactions between the component parts (Ulanowicz, 1980, 1986). This means that diversity is a *necessary* component for minimizing pollution, but it is not sufficient. The parts must also be organized so that the waste products from one process are productive inputs to other processes (Allenby and Richards, 1994).

Energy, Entropy, Organization, and Embodied Energy

Economists often think of energy as a *commodity* (i.e., oil, gas, coal) rather than as a *property* (the ability to do work), which is a characteristic of all commodities. Discussing the substitutability of energy for other factors of production makes sense if energy is a commodity, but not if it is a property of all commodities.

The first law of thermodynamics tells us that energy and matter are conserved. But this refers to heat energy and mechanical work (call it *raw* energy or the bomb calorimeter energy), not to the useful part of the energy. The ability to do work is in general related to the degree of *organization* or order of a thing, the amount of information stored in it, not its raw energy content. Heat must be organized as a temperature gradient between a high-temperature source and a low-temperature sink before useful work is possible. Likewise, complex organized structures like cars or books have an ability to do work that is not related to their raw energy content, but is related to their degree of organization. Pollution, too, has an ability to do work (albeit unwanted, destructive work) that is proportional to its degree of organization.

The second law of thermodynamics tells us that useful energy (organization) always dissipates (entropy or disorder always increases) in an isolated system, and to maintain organized structures (like trees, cars, books, and, in general, natural and man-made capital), one must constantly add energy from outside the system.

But how does one measure the degree of organization of complex structures? Information theory holds some promise in this regard, but it has yet to live up to its potential. One way to *approximate* the degree of organization of complex structures is to calculate the amount of raw energy it takes, directly and indirectly, to build and maintain them. To do this, one must look at the complex web of interconnected production processes that are ecological and economic systems.

Ecology is often defined as the study of the relationships between organisms and their environment. The quantitative analysis of interconnections between species and their abiotic environment has therefore been a central issue. The mathematical analysis of interconnections is also important in several other fields. Practical quantitative analysis of interconnections in complex systems began with the economist Wassily Leontief (1941) using what has come to be called input-output (I-O) analysis. More recently, these concepts, sometimes called the materials balance approach, or flow analysis, have been applied to the study of interconnections in ecosystems (Costanza and Neill, 1984; Finn, 1976; Hannon, 1973, 1976, 1979; Harmon et al., 1991). Related ideas were developed from a different perspective in ecology, under the heading of compartmental analysis (Barber et al, 1979; Funderlic and Heath, 1971). Isard (1972) was the first to attempt combined ecological economic system analysis using input-output methods. We refer to the total of all variations of the analysis of ecological or economic networks as *network analysis*.

Network analysis holds the promise of allowing an integrated quantitative treatment of combined ecological economic systems. One promising route is the use of "ascendancy" (Ulanowicz, 1980, 1986) and related indices (Wulff et al., 1989) to measure the degree of organization in ecological, economic, or any other networks. Measures like ascendancy go several steps beyond the traditional diversity indices used in ecology. They estimate not only how many different species there are in a system but, more important, how those species are organized. This kind of measure may provide the basis for a quantitative and general index of system organization applicable to both ecological and economic systems.

Another promising avenue of research in network analysis has to do with its use for "pricing" commodities (both productive commodities and pollution) in ecological or economic systems. The "mixed units" problem arises in any field that tries to analyze interdependence in complex systems that have many different types and qualities of interacting commodities. Ecology and economics are two such fields. Network analysis in ecology has avoided this problem in the past by *arbitrarily* choosing one commodity flowing through the system as an index of interdependence (i.e., carbon, enthalpy, nitrogen, etc.). This ignores the inter-dependencies between commodities and assumes that the chosen commodity is a valid "tracer" for relative value or importance in the system. This assumption is unrealistic and severely limits the comprehensiveness of an analysis whose major objective is to deal comprehensively with whole systems.

There are evolving methods for dealing with the mixed units problem based on analogies to the calculation of prices in economic input-output models. Starting with a more realistic *commodity by process* description of ecosystem networks, which allows for joint products, one can calculate *ecological interdependence factors* (EIFs) to convert the multiple commodity description ultimately into a pair of matrices that can serve as the input for standard (single-commodity) network analysis. The new single-commodity description incorporates commodity and process interdependencies in a manner analogous to the way economic value incorporates production interdependencies in economic systems (Costanza and Hannon, 1989). This analysis allows the degree of organization of commodities in the system to be approximated as their direct and indirect energy cost, or embodied energy. To the extent that "organization" so defined is correlated with economic value,[1] this approach may allow valuation of components of combined ecological and economic systems without resorting to subjective evaluations, which are inherently limited when applied to ecological commodities.

Ecological networks evolve to use the low-entropy, high-embodied-energy by-products of processes in positive, productive ways. Economic systems may also evolve in this general direction, but we may wish to accelerate the evolutionary process to minimize the costs and disruptions inherent in trial and error. In addition, some of the possible "trials" could lead to destruction of our species, and we would not want to risk that. There are several problems and constraints that limit this accelerated but informed economic evolution. To develop sustainable, nonpolluting ecological economic systems, we need to understand and remove these constraints.

PROBLEMS AND CONSTRAINTS OF ECONOMIC EVOLUTION

Human beings, like all other animals, make decisions based on responses to local, immediate reinforcements. They follow their noses, with some mediation by *genetic* (and in the case of humans and some other species *cultural*) programming. To understand the human population problem, one needs to understand how this complex of local reinforcements and programmed responses interacts over several different time scales with the ecosystem within which humans are embedded.

Biological evolution has a built-in bias toward the long run. Changing the genetic structure of a species requires that *characteristics* (phenotypes) be selected and accumulated by differential reproductive success. Characteristics learned or acquired during the lifetime of an individual cannot be passed on genetically. Biological evolution is therefore an inherently slow process requiring many generations to significantly alter a species' physical characteristics or behavior. Of course if the species goes through many generations rapidly (like bacteria or fruit flies), then the real time required for evolution can be much shorter than for slow-breeding species. Larger, slow-growing species inherently take more time to evolve genetically than small, fast-growing ones.

Cultural evolution is much faster than genetic evolution for large, slow-growing species like humans, and in recent years it has accelerated to hyperspeed. Learned behaviors that are successful can be almost immediately spread to other members of the culture and passed on in the oral, written, or video record. The increased speed of adaptation that this process allows has been largely responsible for *Homo sapiens*' amazing success at controlling the resources of the planet. For example, Vitousek and coauthors (1986) estimate that humans now directly control 25 to 40 percent of the planer's primary production. But there is a significant downside. Like a car that has picked up speed, we are in much more danger of running off the road or over a cliff. Human activity is beginning to have an effect on global climate and the planet's protective ozone shield. We have lost the built-in, long-run bias of biological evolution and are susceptible to being led by our hyperefficient short-run adaptability over a cliff into the abyss.

Social Traps

This process of short-run incentives becoming out of sync with long-term goals has been well studied in the last decade under several rubrics (Axelrod, 1984; Hardin, 1968), but the one I like best is John Platt's notion of "social traps" (Brockner and Rubin, 1985; Costanza, 1987; Cross and Guyer, 1980; Platt, 1973; Teger, 1980). In all such cases the decision maker may be said to be trapped by the local conditions into making what turns out to be a bad decision viewed from a longer or wider perspective. We go through life making decisions about which path to take based largely on "road signs," the short-run, local reinforcements that we perceive most directly. These short-run reinforcements can include monetary incentives, social acceptance or admonishment, and physical pleasure or pain. In general, this strategy of following the road signs is effective, unless the road signs are inaccurate or misleading. In these cases we can be trapped into following a path that is ultimately detrimental because of our reliance on the road signs. For example, cigarette smoking has been a social trap because by following the short-run road signs of the pleasure and social status associated with smoking, we embark on the road to an increased risk of earlier death from smoking-induced cancer. This particular positive reinforcement has in the last few years begun to turn into a negative one. As smoking becomes less socially acceptable, we should expect the number of new smokers to fall and many old smokers to escape the trap. But the process of escape is much more difficult than the process of avoidance, Once this road has been taken, it is difficult to change to another (as most people who have tried to quit smoking can attest).

Pollution is a social trap because the long-term and distributed costs of pollution (and benefits of not polluting) are not incumbent on the economic actors in the short run. The speed of cultural evolution has adversely affected our ability to adequately incorporate the long run.

The Importance of Uncertainty and How to Deal with It

One key element that has limited our perception of the long run and frustrated environmental policy is the enormous degree of uncertainty about long-run human impacts on the biosphere. Ignorance about the consequences is a particularly effective cause of social traps (Cross and Guyer, 1980).

As regards resources, the environment, and technology, the argument can be summarized as differing opinions about the degree to which technological progress can eliminate resource constraints and solve pollution problems. Current economic world views (capitalist, socialist, and the various mixtures) are all based on the underlying assumption of continuing and unlimited economic growth. This assumption allows a whole host of very sticky problems, including population growth, equity, and sustainability to be ignored (or at least postponed), since they are seen to be most easily solved by additional economic growth. Indeed, most conventional economists define "health" in an economy as a constant and high *rate of growth*. Energy and resource limits to growth, according to these world views, will be eliminated as they arise by clever development and deployment of new technology. This line of thinking is often called technological optimism.

An opposing line of thought (often called technological pessimism) assumes that technology will *not* be able to circumvent fundamental energy and resource constraints and that eventually economic growth will stop. It has usually been ecologists or other life scientists who take this point of view largely because they study natural systems that *invariably do* stop growing when they reach fundamental resource constraints. A healthy ecosystem is one that maintains a stable condition. Unlimited growth is cancerous, not healthy, under this view.

The technological optimists argue that human systems are fundamentally different from other natural systems because of human intelligence. History has shown that resource constraints can be circumvented by new ideas. Technological optimists claim that Malthus's dire predictions about population pressures have not come to pass and that the "energy crisis" of the late 1970s is behind us.

The technological pessimists argue that many natural systems also have "intelligence" in that they can evolve new behaviors and organisms (including humans themselves). Humans are therefore a part of nature, not apart from it. Just because we have circumvented local and artificial resource constraints in the past does not mean we can circumvent the fundamental ones that we will eventually face. Malthus's predictions have not come to pass *yet* for the entire world, the pessimists would argue, but many parts of the world are in a Malthusian trap now, and other parts may well fall into it.

This debate has gone on for several decades now. It began with Barnett and Morse's (1963) *Scarcity and Growth* and really went into high gear with the publication of *The Limits to Growth* by Meadows et al. (1972) and the Arab oil embargo in 1973. There have been thousands of studies over the last 15 years on various aspects of our energy and resource future and different points of view have waxed and waned. But the bottom line is that there is still an enormous amount of uncertainty about the impacts of energy and resource constraints, and I doubt that the argument will ever be decided on scientific grounds.

In the next 20-30 years we may begin to hit *real* fossil fuel supply limits as well as constraints on production due to global warming. Will fusion energy or solar energy or conservation or some as yet unthought of energy source step in to save the day and keep economies growing? The technological optimists say yes and the technological pessimists say no. Ultimately, no one knows. Both sides argue as if they were certain, but the worst form of ignorance is misplaced certainty.

The optimists argue that unless we *believe* that the optimistic future is possible and behave accordingly it will never come to pass. The pessimists argue that the optimists will bring on the inevitable leveling and decline sooner by consuming resources faster and that to sustain our system we should begin to conserve resources immediately. How do we proceed in the face of this overwhelming uncertainty?

We can cast this optimist/pessimist choice in a classic (and admittedly oversimplified) game theoretic format using the payoff matrix shown in Figure 2. Here the alternative policies that we can pursue today (technologically optimistic or pessimistic) are listed on the left and the real states of the world are listed on the top. The intersections are labeled with the results of the combinations of policies and states of the world. For example, if we pursue the optimistic policy and the world really does turn out to conform to the optimistic assumptions, then

		Real state of the world	
		Optimists right	Pessimists right
Current policy	Technological optimist policy	**High**	**Disaster**
	Technological pessimist policy	Moderate	Tolerable

FIGURE 2 Payoff matrix for technological optimism vs. pessimism.

the payoffs would be high. This high potential payoff is very tempting and this strategy has paid off in the past. It is not surprising that so many would like to believe that the world conforms to the optimists' assumptions. If, however, we pursue the optimistic policy and the world turns out to conform more closely to the pessimistic technological assumptions, then the result would be "Disaster." The disaster would come because irreversible damage to ecosystems would have occurred and technological fixes would no longer be possible.

If we pursue the pessimistic policy and the optimists are right, then the results are only "Moderate." But if the pessimists are right and we have pursued the pessimistic policy, then the results are "Tolerable."

Within the framework of game theory, this simplified game has a fairly simple "optimal" strategy. If we *really* do not know the state of the world and if the game is only played once (which is the case at the global level), then we should choose the policy that offers the maximum of the minimum outcomes (i.e., the MaxiMin strategy in game theory jargon). In other words, we analyze each policy in turn, look for the worst thing (minimum) that could happen if we pursue that policy, and pick the policy with the best worst case. In the case stated above, we should pursue the pessimist policy because the worst possible result under that policy ("Tolerable") is preferable to the worst outcome under the optimist policy ("Disaster").

Given this analysis, what can one recommend for pollution policy? Because of the large uncertainty about the long-term impacts on ecological sustainability, we should *at least provisionally assume the worst*. We must assume that the dire predictions are correct and plan accordingly. If they are right we will still survive. If they are wrong we will be pleasantly surprised. This is a much different scenario than the consequences of provisionally assuming the best about the impacts. If we assume the optimists are right and they are not, we will have irreversibly degraded the planet's capacity to support life. We cannot rationally take that risk.

TOWARD A SUSTAINABLE, NONPOLLUTING ECOLOGICAL ECONOMIC SYSTEM

How then do we communicate these conclusions to the people who make the decisions--the economic actors--and escape the pollution trap? The elimination of social traps requires intervention--the modification of the reinforcement system. Indeed, it can be argued that the proper role of a democratic government is to eliminate social traps (no more and no less) while maintaining as much individual freedom as possible (Costanza, 1987). Cross and Guyer (1980) list four broad methods by which traps can be avoided or escaped. These are education (about the long-term, distributed impacts); insurance; superordinate authority (i.e., legal systems, government, religion); and converting the trap to a trade-off by correcting the road signs.

Education can be used to warn people of long-term impacts that cannot be seen from the road. Examples are the warning labels now required on cigarette packages and the warnings of environmentalists about future hazardous waste problems. People can ignore warnings, however, particularly if the path seems otherwise enticing. For example, warning labels on cigarette packages have had little effect on the number of smokers.

The main problem with education as a general method of avoiding and escaping from traps is that it requires a significant time commitment on the part of individuals to learn the details of each situation. Our current society is so large and complex that we cannot expect even professionals, much less the general public, to know the details of all the extant traps. In addition, for education to be effective in avoiding traps involving many individuals, *all* the participants must be educated.

Governments can, of course, forbid or regulate certain actions that have been deemed socially inappropriate. The problem with this approach is that it must be rigidly monitored and enforced, and the strong short-term incentive for individuals to try to ignore or avoid the regulations remains. A police force and legal system are very expensive to maintain, and increasing their chances of catching violators increases theft costs exponentially (both the costs of maintaining a larger, better-equipped force and the cost of the loss of individual privacy and freedom).

Religion and social customs can be seen as much less expensive ways to avoid certain social traps. If a moral code of action and belief in an ultimate payment for transgressions can be deeply instilled in a person, the probability of that person's falling into the "sins" (traps) covered by the code will be greatly reduced, and with very little enforcement cost. On the other hand, the problems with religion and social customs as means to avoid social traps are that the moral code must be relatively static to allow beliefs learned early in life to remain in force later, and it requires a relatively homogeneous community of like-minded individuals to be truly effective. This system works well in culturally homogeneous societies that are changing slowly. In modem, heterogeneous, rapidly changing societies, religion and social customs cannot handle all the newly evolving situations or the conflict between radically different cultures and belief systems.

Many trap theorists believe that the most effective method for avoiding and escaping from social traps is to turn the trap into a trade-off. This method does not run counter to our normal tendency to follow the road signs; it merely corrects the signs' inaccuracies by adding compensatory positive or negative reinforcements. A simple example illustrates how effective this method can be. Playing slot machines is a social trap because the long-term costs and benefits to the player are inconsistent with the short-term costs and benefits to the player. People play the machines because they expect a large short-term jackpot, while the machines are in fact programmed to pay off, say, $0.80 on the dollar in the long-term.[2] People may "win" hundreds of dollars playing the slots (in the short ran), but if they play long enough they will certainly lose $0.20 for every dollar played. To change this trap to a trade-off, one could simply reprogram the machines so that every time a dollar was put in $0.80 would come out. This way the short-term reinforcements ($0.80 on the dollar) are made consistent with the long-term reinforcements ($0.80 on the dollar), and only the dedicated aficionados of spinning wheels with fruit painted on them would continue to play.

INNOVATIVE INSTRUMENTS FOR ENVIRONMENTAL MANAGEMENT

Current command-and-control systems of environmental regulation are not very efficient at managing environmental resources for sustainability, particularly in the face of uncertainty about long-term values and impacts. They are inherently reactive rather than proactive. They induce legal confrontation, obfuscation, and government intrusion into business. Rather than encouraging long-range technical and social innovation, they tend to suppress it. They do not mesh well with the market signals that firms and individuals use to make decisions and do not effectively translate long-term global goals into short-term local incentives. They do not effectively turn environmental traps into trade-offs.

We need to explore promising alternatives to our current command-and-control environmental management systems, and to modify existing government agencies and other institutions accordingly. The enormous uncertainty about local and transnational environmental impacts needs to be incorporated into decision making. We also need to understand better the sociological, cultural, and political criteria for acceptance or rejection of policy instruments.

One example of an innovative policy instrument currently being studied is a flexible environmental assurance bonding system designed to incorporate environmental criteria and uncertainty into the market system and to induce positive environmental technological innovation (Costanza and Perrings, 1990; Perrings, 1989, 1991).

In addition to direct charges for known environmental damages, a company would be required to post an assurance bond equal to the current best estimate of the largest potential future environmental damages due to its activities; the money would be kept in interest-bearing escrow accounts. The bond (plus a portion of the interest) would be returned if the firm could show that the suspected damages had not occurred or would not occur. If they did, the bond could be used to rehabilitate or repair the environment or to compensate injured parties. Thus, the burden of proof would be shifted from the public to the resource-user, and a strong economic incentive would be provided to research the true costs of environmentally damaging activities and to develop technologies that cause little pollution and provide innovative and cost-effective pollution control. This is an extension of the "polluter pays" principle to "the polluter pays for uncertainty as well."

In addition, we need to develop innovative instruments to handle transnational pollution problems and the costs of natural resource depletion. Two suggestions for handling these problems are the system of ecological tariffs and the natural capital depletion tax mentioned briefly below.

CONCLUSIONS

Balancing the human species in the ecosystem and developing sustainable, nonpolluting ecological economic systems is, in principle, a simple problem. Simply make the long-run, distributed, whole-system costs and benefits of human activities, *including uncertainty*, incumbent on all individuals in the short run and locally, at least provisionally until the uncertainty can be lowered. This will greatly accelerate the natural evolutionary processes and force a "closing of the loops" to happen more quickly. If this whole-system cost accounting (including uncertainty) is in place, we can expect individual decisions about pollution control and resource consumption to help move the system toward a sustainable and nonpolluting condition.

Of course, *in principle* is very far from *in practice* in this particular case. The problems of devising cultural mechanisms to *effectively* communicate ecological costs to individual actors are daunting. The next stage of our cultural evolution must be the development of just this capacity to put back *in the* long-run constraints that the initial phase of cultural evolution appeared to release us from. We need to develop and use cultural "road maps" and "scouts" to counter our dependence on "road signs" in the tricky terrain where we now find ourselves. I offer the following summary suggestions toward the goal of developing sustainable, nonpolluting, ecological economic systems.

1. Establish a *hierarchy* of goals for national and global ecological economic planning and management. Sustainability should be the primary long-term goal, replacing the current GNP growth mania. Issues of justice, equity, and population are ultimately tied in with sustainability as preconditions. Only sustainable levels of human activity are desirable. Economic growth in this hierarchy

is a valid goal only when it is consistent with sustainability. The goals can be put into operation by having them accepted as part of the political debate and implemented in the decision making structure of institutions that affect the global economy and ecology (for example, the World Bank).

2. Develop better *global ecological economic modeling* capabilities to allow us to see the range of possible outcomes of our current activities, especially the interrelated impacts of population, pollution, per capita resource use, and wealth distribution.
3. Adjust current incentives to reflect both short- and long-run, local and global ecological costs, *including uncertainty*. To paraphrase the popular slogan, we should model globally and adjust local incentives accordingly. Below I list three broad, mutually reinforcing policy instruments that have a high likelihood of ensuring that economic *development* (as distinct from economic *growth*) is ecologically sustainable (Costanza, 1994). They use market incentives to produce the desired results (sustainable scale, fair distribution, and efficient allocation). These incentives are as follows:

a. **Ecological tax reform**. A natural capital depletion tax aimed at reducing or eliminating the destruction of natural capital would assume more of the tax burden instead of taxes on labor and income. Use of nonrenewable natural capital would have to be balanced by investment in renewable natural capital to avoid the tax. The tax would be passed on to consumers in the price of products and would send the proper signals about the relative sustainability cost of each product, moving consumption toward a more sustainable product mix. This policy will encourage the technological innovation that optimists are counting on while conserving resources in case the optimists are wrong.

b. **The precautionary polluter pays principle (4P)** would be applied to potentially damaging products to incorporate the cost of the uncertainty about ecological damages as well as the costs of known damages (Costanza and Cornwell, 1992; Costanza and Perrings, 1990). This would give producers a strong and immediate incentive to improve their environmental performance to reduce the size of the environmental bond and tax they would have to pay. The 4P approach can allow long-term worst-case ecological costs to be made apparent to individual actors in an efficient and culturally acceptable way.

c. **A system of ecological tariffs** aimed at allowing individual countries or trading blocks to apply incentives a and b above without forcing producers to move overseas to remain competitive. Countervailing duties would be assessed to impose fairly the ecological costs associated with production on both internally produced and imported products. Revenues from the tariffs would be reinvested in the global environment, rather than added to general revenues of the host country. The ecological tariffs should be proportional to the environmental damages that occur anywhere in the world as a by-product of the product's production. They can be unilaterally applied by any country without damaging that country's trade balance or economic performance. Countries that do not implement systems to ensure ecologically benign production would be at a competitive disadvantage since their products will be harder to sell abroad in countries that have ecological tariffs. In other words, the ecological tariff system would protect local producers of ecologically benign products as well as discouraging ecologically destructive production abroad. Once a few large countries implemented the system, the rest of the world would be forced to follow suit.

The ecological tariffs, in conjunction with the 4P system and the natural capital depletion tax, would provide the appropriate incentives to turn many of our current ecological traps into trade-offs and provide the appropriate constraints to lead to a sustainable ecological economic system.

NOTES

1. Recent studies (Cleveland et al., 1984; Costanza, 1980; Costanza and Herendeen, 1984; Gever et al., 1986; Hall et al., 1986) indicate that in fact this correlation is surprisingly strong.

2. Slot machines are obviously not a trap for the owners of the machines.

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Ecological Integrity and Ecological Health Are Not the Same

James R. Karr

THE FOLLY OF THE STATUS QUO

Environmental issues are not merely a concern of extremists; healthy biological systems are critical to the success, perhaps even survival, of the human species. Although notable progress has been made in a few areas of environmental protection (e.g., agreement to limit CFC releases), current planning programs and legislative initiatives are not adequate to protect natural or human environments.

The complex reasons for failure center on the hubris of a society that behaves as if it could repeal the laws of nature, Plans generated by economists, technologists, engineers, and ecologists have too often assumed that lost or damaged components of ecological systems are unimportant or can be repaired or replaced. We see the consequences of this attitude everywhere. In the Pacific Northwest, for example, hatcheries are built to sustain salmonid stocks while minimal effort is made to restore degraded habitat, reduce excessive harvests, or protect seasonal river flow. Throughout the world, expensive fertilizers are added to replace nutrients in depleted soils. Groundwater is depleted to supply unsustainable amounts of water. These and other examples demonstrate the folly of maintaining the status quo.

Interdisciplinary initiatives seeking to improve environmental policy are cropping up in many contexts. These initiatives are driven by goals such as environmental justice (Bullard, 1994), protection of biodiversity (Wilson, 1992), and pollution control (Colborn and Clement, 1992); they are grounded in concepts such as ecological economics (Costanza, 1991; Jansson et al., 1994), conservation biology (Meffe and Carroll, 1994), and industrial ecology (Allenby and

Richards, 1994; Richards and Fullerton, 1994). A core societal vision should be integrating all these initiatives to protect ecological integrity (Karr, 1993; Westra, 1994) and ecological health (Costanza et al., 1992; Rapport et al., 1994). Ecologists and engineers alike must become more aware of the need to protect biological systems as integral components of human welfare; ecologists as well as engineers must better understand and respond to societal needs. Failure to do so holds ominous consequences.

GROWING ENVIRONMENTAL CONCERNS

For most of the twentieth century, the most visible demonstration of public concern for the environment was the conservation movement in the developed world. But voices now coming from all corners of society draw attention to the severity of present ecological crises. A Health of the Planet Survey by the Gallup Organization (Dunlap et al., 1993) asked more than 28,000 individuals in 24 countries (including industrialized and developing nations) about their environmental attitudes. The results show "strong public concern for environmental protection throughout the world, including regions where it was assumed to be absent."

Scholars too are calling for shifts in human behavior. A worldwide collection of 1,575 scientists, including 99 Nobel Prize winners, noted that "human beings and the natural world are on a collision course.... A great change in our stewardship of the earth, and life on it, is required if vast human misery is to be avoided and our global home on this planet is not to be irretrievably mutilated" (Union of Concerned Scientists, 1992). In the same year, the National Academy of Sciences and the Royal Society of London (1992) issued a joint statement recognizing the need for industrial countries to modify their behavior radically to avoid irreversible damage to the earth's capacity to sustain life. A 1993 Population Summit held in New Delhi explored issues of population growth, resource consumption, socioeconomic development, and environmental protection; 58 of the world's national academies of sciences (Science Summit, 1993) called for action to turn 1994 into "the year when the people of the world decided to act together for the benefit of future generations." The Ecological Society of America (Lubchenco et al., 1991) and the International Association of Ecology (Huntley et al., 1991) called for research initiatives to move society toward sustainable use of ecological resources; so have Sigma Xi (1992) and the Carnegie Commission (1992a,b,c; 1993).

Universities and governments have also joined the chorus. In the 1990 Talloires Declaration (Cortese, 1993), the leaders of hundreds of universities from throughout the world expressed their deep concern "about the unprecedented scale and speed of environmental pollution and degradation, and the depletion of natural resources." The 1992 Earth Summit in Rio de Janeiro was an unprecedented gathering of representatives from 170 nations (the largest meeting ever of world leaders) and grassroots organizations to explore international dimensions of environmental issues and define steps necessary to run our economies and secure our future (Center for Our Common Future, 1993).

Business and labor also recognize the need for change. Forty-eight international industrialists and business leaders from more than 25 countries recently called for renewed efforts by business and government to make ecological imperatives part of the market forces governing production, investment, and trade (Schmidheiny and Timberlake, 1992). In 1990 the *Sunday Times* of London reported (Fallon, 1990): "Sir James Goldsmith--corporate predator extraordinary, scourge of board rooms, one of the most feared men on Wall Street--[is] retiring from business. From now on, he said, he would devote his energies and much of his fortune of more than $1 billion to ecological and environmental causes." Great wealth, the 57-year-old billionaire argued, was of no value in a crumbling world.

The United Steelworkers of America (1990) overwhelmingly endorsed a report that says, "We cannot protect steelworker jobs by ignoring environmental problems." Further, the "greatest threat to our children's future may lie in the destruction of their environment," and "the environment outside the workplace is only an extension Of the environment inside." At the August 1993 Parliament of World's Religions (Briggs, 1993), the leaders of Christianity, Buddhism, Islam, Judaism, Hinduism, and other faiths developed a "global ethic." Among other things, that ethic condemns environmental abuses. In an age of unparalleled technological progress, poverty, hunger, the death of children, "and the destruction of nature have not diminished but rather have increased."

A recent report by the Commission on Life Sciences of the National Research Council (1993) concludes that science and engineering provide many "tools to address environmental problems of enormous consequence to our social and economic well-being. But we are not using those tools most effectively."

THE PROBLEM OF BIOTIC IMPOVERISHMENT

These organizations and the constituencies they represent recognize that all is not well on planet Earth; planetary life-support systems critical to human society are threatened. The threat is loss of biological integrity, or biotic impoverishment--the systematic reduction in the earth's ability to support living systems. Important aspects of biotic impoverishment include the following (Karr, 1995a):

- Soil depletion, decertification, and salinization
- Depletion of renewable natural resources (e.g., forests and fisheries)
- Depletion and contamination of water supplies
- Extinction of species
- Habitat destruction and fragmentation

- Alteration of global biogeochemical cycles
- Epidemics and pest outbreaks
- Introduction of exotic species
- Chemical contamination
- Global climate change; ozone depletion
- Reduction in human cultural diversity
- Reduced quality of human life and economic deprivation
- Environmental injustice and racism

Collectively, this broad sweep of issues illustrates the magnitude of the environmental challenge facing all members of the human community. It also reminds us of the close association and common underpinning of environmental and social concerns. The loss of species, the destruction of agricultural lands, and the differential exposure of economically disadvantaged people to environmental hazards degrade the quality of human life. As human influence expands, the limits of technology, especially unintended consequences of technology, become more obvious. Depletion of water supplies cannot be "fixed" by science's making water to refill aquifers. Citizens and political leaders, engineers and ecologists must work together to develop creative solutions; failure to do that will relegate the world to continued biotic impoverishment and threaten the sustainability of human society.

ECOLOGICAL INTEGRITY AND ECOLOGICAL HEALTH

If biotic impoverishment is the problem, then protecting the integrity of biological systems must be the goal. But how do we define *biological integrity* in a world that is increasingly altered by the actions of humans? How do we reconcile the inevitable changes required to accommodate a growing human population and the proliferation of modern technology while guarding the planet from irrevocable biotic impoverishment? Answering these questions in clear and explicit terms is especially important as we seek to bring scholars from diverse disciplines together to focus on common problems.

What do *health and integrity* mean? What kind of health or integrity do we seek? Are we seeking "environmental health," or is that phrase too narrowly associated with human health? As a societal goal, *biological integrity* suggests a meaning beyond human health. The sum of physical, chemical, and biological integrity is *ecological integrity* (Karr and Dudley, 1981). Restoring and maintaining the "physical, chemical, and biological integrity of the nation's waters" has been a goal of the Clean Water Act in the United States since 1972 and of the International Joint Commission (U.S. and Canada) on the Great Lakes. "Maintenance of ecological integrity" is the first priority of the amendment to Canada's National Park Act passed by Parliament in 1988.

Integrity implies an unimpaired condition or the quality or state of being complete or undivided; it implies correspondence with some original condition. Biological integrity (Angermeier and Karr, 1994; Frey, 1975; Karr and Dudley, 1981; Karr et al., 1986) refers to the capacity to support and maintain a balanced, integrated, adaptive biological system having the full range of elements (genes, species, assemblages) and processes (mutation, demography, biotic interactions, nutrient and energy dynamics, and metapopulation processes) expected in the natural habitat of a region. Although somewhat long-winded, this definition carries the message that (1) biology acts over a variety of scales from individuals to landscapes, (2) biology includes items one can count (the elements of biodiversity) plus the processes that generate and maintain them, and (3) biology is embedded in dynamic evolutionary and biogeographic contexts.

An evolutionary foundation ties the concept of integrity to a benchmark against which society can evaluate sites altered by human actions. The complex biological systems that evolved at a site have already demonstrated their ability to persist in, even modify, the region's physical and chemical environment. Their very presence means that they are resilient to the normal variation in that environment. Species abundance, for example, changes as a function of changes in the physical environment and in interactions among species in a local assemblage. But the bounds over which systems change as a result of most natural events are limited when compared with the changes imposed by human activities such as row-crop agriculture, urbanization, or dam construction.

Human society sets aside extensive areas as parks and reserves to protect their natural state or integrity. Those areas deserve protection because of the diverse values they provide to society. Water bodies, including both surface and groundwaters, deserve special protection as well, because they provide water to society and support recreational and other values. Further, they are the lifelines of a continent, reflecting the condition of surrounding landscapes, linking landscapes across great distances.

Few places maintain a biota with evolutionary and biogeographic integrity because of the demands of feeding, clothing, and housing more than 5.7 billion people. The growth of human populations in the last few centuries has made the human species the principal driver of change on Earth. Humans appropriate the equivalent of 40 percent of Earth's annual terrestrial production (Vitousek et al., 1986). Providing for that human population requires massive alteration of the planet in ways that preclude a return to the pristine environments of the pre-industrial era. Thus, biological integrity is lost on a large share of the planet and is unlikely to be regained. Yet loss of ecological integrity for all lands and waters in all regions of the world is unacceptable on scientific, economic, aesthetic, and ethical grounds.

Health, on the other hand, implies a flourishing condition, well-being, vitality, or prosperity. An organism is healthy when it performs all its vital functions normally and properly; a healthy organism is resilient, able to recover from many stresses; a healthy organism requires minimal outside care. The concept of health applies to individual organisms as well as to national or regional economies, industries, and natural resources such as fisheries.

Ecological health describes the goal for the condition at a site that is cultivated for crops, managed for tree harvest, stocked for fish, urbanized, or otherwise intensively used. At these sites, integrity in an evolutionary sense cannot be the goal. Healthy land use, with or without active management, should not degrade the site for future use or degrade areas beyond the site. Soils, for example, should not be eroded or otherwise transformed to reduce future productivity (see Pimentel, 1993). Groundwater should not be depleted.

Land use should not have deleterious effects beyond a site; atmospheric contamination should not result in downwind effects, such as increased greenhouse gases or ozone depletion. Healthy sites should not release contaminants or eroded soils that degrade sites elsewhere. Using these two criteria--no degradation of the site for future use and no degradation of areas beyond the site--most modem agricultural and urban land use, for example, is not sustainable. Recognition of that reality is the foundation for recent initiatives for sustainable communities and sustainable agriculture.

Failure to protect the ecological health of intensively used lands is also unacceptable on scientific, economic, aesthetic, and ethical grounds. We have no choice but to develop a conceptual framework to define acceptable and sustainable uses.

These concepts are easily applied to small parcels of land. Scaling up to large landscapes presents a serious challenge. What proportion of a landscape should be protected under a biological integrity goal? The World Commission on Environment and Development (1987) recommended 12 percent, but that seems inadequate. Does that proportion vary among regional ecosystem types (e.g., desert, forest, or grassland)? Do water bodies, fragile sites, or sites with the highest biodiversity deserve the highest priority for protection?

MEASURING HEALTH AND INTEGRITY

Neither ecologists nor engineers have been especially adept at defining or measuring either ecological health or ecological integrity. The track record of freshwater management provides an instructive example. Human society depends on freshwater as well as the resources associated with freshwater and marine systems. Yet 55 countries now have populations that equal or exceed the ability of their national territory to provide an adequate supply of freshwater (Ozturk, 1995). Improved water conservation, treatment and recycling programs can delay the crisis, but growing human populations will keep society on a treadmill trying to keep up with expanding demand. Even where the supply of water remains adequate, resource degradation continues because society chronically undervalues the products and services provided by aquatic ecosystems.

Although rivers are in many ways the lifeblood of society, prevalent attitudes toward rivers reflect disdain for their value and arrogance about our ability to replace or repair them. Despite the mandate in the Clean Water Act for protecting the integrity of the nation's waters, for example, it took nearly two decades to begin to incorporate that concept into water resource protection, largely because appropriate benchmarks were not defined for evaluating success in attaining those goals. That failure leads to six "realities" about the condition of water resources (Karr, 1995b).

1. **Water resources, especially their biological components, are in steep decline**. The proportion of aquatic organisms at risk of extinction is considerably higher than that of terrestrial organisms (Angermeier and Karr, 1994; Masters, 1990). The spread of exotics and the decline of native species are common to waters throughout the United States. Fish consumption advisories are issued each year in more than 40 states, and riparian corridors along U.S. streams have been destroyed in most areas. Despite strong mandates and massive expenditures to protect "the physical, chemical, and biological integrity" of the nation's waters, signs of continuing degradation are pervasive within individual rivers, the continent, and the globe.
2. **Degradation stems from more than chemical contamination, the primary focus of conventional water-quality programs**. The assumption that monitoring for chemical contaminants ensures chemical, physical, and biological integrity is flawed. Society wastes money and degrades resources because decisions based on chemical criteria do not adequately protect water quality. Priority lists of chemicals do not accurately reflect ecological risks; point-source approaches do not effectively control the influence of nonpoint sources or the cumulative effects of numerous contaminants; and the chemical-contaminant approach fails to diagnose and correct water resource problems caused by other human influences, such as degradation of physical habitat or alteration in flow (Karr, 1991).
3. **Long-term success in protecting water resources requires careful thought about goals, or benchmarks, Including development and uses of criteria for protecting ecological Integrity**. Water resources are not simply water; their quality and value to society depend on more than water quality and quantity alone. We must begin to track the condition of our waters as we track the status of local and national economies. Biological monitoring and biological criteria provide the most robust approach. Waterways that cannot support healthy biological communities are unlikely to support human society for long.
4. **The legal and regulatory framework in place today does not respond soon enough to continued degradation**. Government agencies have been weak, inappropriately focused, and therefore largely ineffective at reversing resource declines, especially those not associated with point sources of chemical contamination. This observation is Consistent with the observation that major environmental legislation derives from the effectiveness of grassroots organizations, not

from the leadership of government agencies. The effectiveness of that legislation is diminished because regulations to enforce it often compromise legislative goals (Greider, 1992; Karr, 1990).

Underfunding--the chronic complaint from all bureaucracies and scientists--is not, however, the most important problem. Failure to set a clear societal goal and develop a comprehensive assessment and planning effort to accomplish that goal is unacceptable. Too often, as in the implementation of the Clean Water Act, a least-cost option to reduce water discharge is selected on the basis of available technology, a political need for equity, and narrow medium-specific goals. Environmental protection should emphasize the need to minimize insults to the total environment--land, water, and atmosphere. We can no longer afford to implement the Clean Water Act as if crystal-clear, distilled water running down concrete conduits were the objective.

5. **The quantitative expectations that constitute biological integrity vary geographically**. Criteria developed for chemical contaminants have been applied uniformly for diverse water bodies. But the idea that the same chemical criteria should apply to all waters is ludicrous, for the underlying physical and chemical properties of streams vary regionally. Evolutionary and biogeographic variation are key components of biological integrity.
6. **Because biological systems are complex, multiple components of biology should be protected**. Measurement of all components is logistically impossible. Thus, we must define a reasonable set of biological attributes that reliably track biological condition. Extensive experience in aquatic and terrestrial systems suggests that four key biological features should be tracked: species richness, species composition, individual health, and trophic (food web) structure. Collectively, these attributes detect (1) changes in species, including the identity and number of species present in the regional biota (elements); (2) ecological processes such as nutrient dynamics and energy flow through food webs; and (3) health of individuals, which is likely to influence demographic processes.

Several approaches have been developed in the past decade to integrate complex biological data. The development of a multimetric approach (multiple biological attributes are evaluated to assess resource condition) for use in freshwater streams in the United States (Fausch et al., 1984; Karr, 1981, 1991; Karr et al., 1986) stimulated researchers and agency staff to adopt a similar method in water resource evaluations over a wider geographic area (Crumby et al., 1990; Deegan et al., 1993; Fausch and Schrader, 1987; Hughes and Gammon, 1987; Leonard and Orth, 1986; Lyons, 1992; Oberdorff and Hughes, 1992; Steedman, 1988) and with a variety of taxa (Kerans and Karr, 1994; Ohio EPA, 1988; Plafkin et al., 1989).

The multimetric approach works because it recognizes biology as fundamentally important, selects only biologically meaningful and reliable measures, and is easy to communicate to policymakers and citizens. The multimetric approach provides a structure for knowledge that uses the common sense of biologists familiar with a regional biota, much as economic indices use common sense about economic conditions (e.g., Dow-Jones Average, Index of Leading Economic Indicators). Properly conceived and used, multimetric approaches based in sound biology are statistically rigorous (Fore et al., 1994). They provide a way to summarize complex information in a single quantitative expression while preserving information about each biological attribute. Properly selected measures of biological integrity can be used to determine whether life-support systems are degraded and identify the factors responsible for degradation. They may even be used to track the success of restoration programs.

DEVELOPING INTEGRATED SOLUTIONS

If we are to stem biotic impoverishment and reverse environmental degradation, we must

- Set societal goals based on broad concepts of ecological integrity and ecological health.
- Forge partnerships among scientists, engineers, policymakers, resource managers, and citizens to develop approaches for attaining those goals.
- Revise the legal framework guiding environmental policy to ensure that both ecological risks and threats to human health are minimized.
- Protect existing resources.
- Restore resources that are degraded.

BRINGING ENGINEERS AND ECOLOGISTS TOGETHER

Two disciplines of fundamental importance to human society, engineering and ecology, have expanded at unprecedented rates during the twentieth century. Most practitioners of one of these disciplines have only limited knowledge about the other, and fundamental conceptual differences have limited their interaction. Engineering developed to improve the lot of humans; most engineering incorporates only the chemical and physical dimensions of the natural world. The failure of engineering to recognize the importance of biological limits and connectivity within biological systems is matched by the failure of ecology to contribute to the resolution of important societal problems.

Engineers and ecologists fail to address the right problem at the right time. Engineers are accustomed to others defining problems for them to solve, or they propose inappropriate solutions to perceived problems. Ecologists spend too much time trying to understand problems before they take action. They may be incapable of contributing useful solutions because they get lost in the details of natural environmental variation.

Today societal realities compel both disciplines to improve their craft by expanding their interactions in the service of society. Those interactions must be based on mutual respect and understanding and on actions to avert the consequences of continued biotic impoverishment.

Traditionally, human actions have not been evaluated so that their influence on ecological health or integrity was identified. When human populations were small, resources were abundant, technological skills were less advanced, and environmental degradation was less extreme. As a result, society did not notice or understand ecological integrity or health because degradation was local and usually transitory. An undeveloped frontier was always available. But the frontier is gone; supplies of many renewable resources have been depleted; chemical pollution is pervasive; and the global atmosphere is changing under the onslaught of human actions.

We cannot avoid the use of technology, but we can no longer adopt technology without careful evaluation of its ecological effects. Most technology has been directed toward important, but narrow and typically short-term goals, such as protecting human health, achieving economic "efficiency," or replacing lost natural resources. Rarely have careful evaluations of the long-term consequences of a technology been completed before the technology was adopted. We must change our approach. We must ensure that protection of ecological health and integrity plays a central role in decisions about consumer goods and development of technologies, including when, where, and how to apply technology. Failure to protect ecological integrity and ecological health across all landscapes is probably the most serious threat to the security of individuals, nations, and global human society.

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Ecological Engineering: A New Paradigm for Engineers and Ecologists

William J. Mitsch

A NEW COLLABORATION

The engineering profession is now in the position to make a substantial contribution to the "greening" of the planet through ideas such as ecological engineering. In this retrospective period of human history, it is important to determine, without necessarily questioning all that has been built and engineered to date, (1) whether to continue practices as usual (and whether we can afford to do so), and (2) what new approaches are available to engineers for restoring the "bodily functions" of nature on which we depend. Many signs indicate that a shift is taking place both within and outside the engineering profession to accommodate ecological approaches to what was formerly done through rigid engineering and a general avoidance of any reliance on natural systems. For example, engineers, resource managers, and ecologists are rethinking whether to restore the upper Mississippi River levees to their state before the 1993 floods or to take a more ecologically friendly approach. The U.S. Army Corps of Engineers is now "greening" and some in that organization see themselves as the nation's ecological engineers. Agricultural engineers, known for the efficiency with which they drained the landscape, are retooling in many locations to rebuild wetlands. The Kissimmee River in Florida is being "restored"--at enormous cost--to something resembling its former self before it was straightened 20 years ago.

This paper presents the most recent definition of ecological engineering, examines the new field in its historical context, contrasts it with other fields, presents a classification system for ecological engineering projects, and summarizes recent events related to the development of the field.

DEVELOPMENT AND DEFINITION OF ECOLOGICAL ENGINEERING

Ecological Engineering as an Extension of Ecology

Ecological engineering is a new field with its roots in the science of ecology. It can be viewed as designing or restoring ecosystems according to ecological principles learned over the past century (Figure 1). Ecology, as a field often designated as a discipline within the biological sciences, has had a strong history of development over the past century, dating back to the coining of the term *ecology* by the German biologist Ernst Haeckel (1866). The principles of the field have been developed by scientists such as Cowles, Shelford, Clements, Gleason, Lotka, Elton, Thienemann, Forel, Lindeman, Likens, Hutchinson, the Odum brothers, and others. As with any science, much discussion centers on which theories are correct, particularly with ecological energetics and concepts such as succession, but a strong science has developed at the population, community, and ecosystem levels.

Applied ecology, as an extension of these ecological theories, has become popular since the 1960s, particularly in light of public concern for environmental matters. But it has usually been limited to monitoring and assessing environmental impacts or managing natural resources; that is, it has principally remained descriptive. Good examples of recent applied fields in ecology are ecotoxicology and landscape ecology, both of which are *descriptive* of humanity's effects on the environment. But description alone is not sufficient to deal with many of today's environmental issues. The solution to some of these seemingly unsolvable problems requires a *prescriptive* discipline (Odum, 1989a), that is, one that depends on the environmental problems being defined and then prescribes a solution to those problems. One recently proposed prescriptive discipline is called ecological engineering (Mitsch and Jørgensen, 1989a; Mitsch, 1993).

Both basic and applied ecology provide fundamental concepts to ecological engineering but do not define it completely. Ecological engineering should have its roots in the science of ecology, just as *chemical* engineering is close to chemistry and biochemical engineering is close to biochemistry. It logically should be considered a branch of ecology as well as a new field of engineering.

Definition and Goals

At a May 1993 workshop on ecological engineering sponsored by the National Research Council (see New Discipline, 1993), in a slight variation of the definition given in the Mitsch and Jørgensen (1989b), ecological engineering was defined as

> the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both.

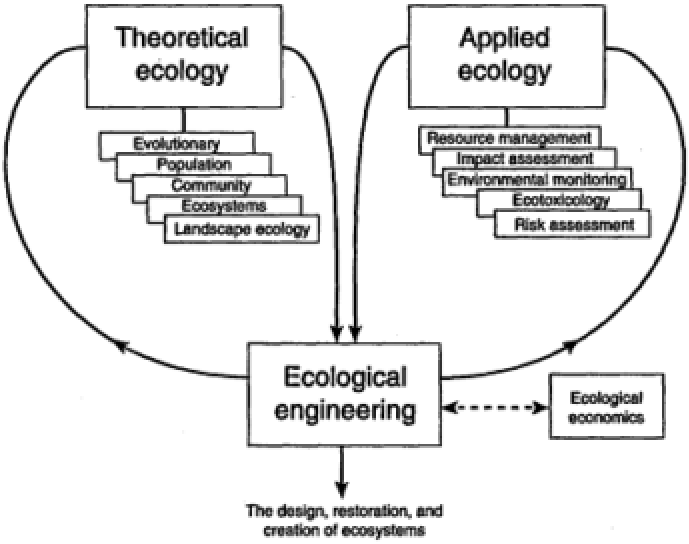

FIGURE 1 The relationships among ecology, applied ecology, and ecological engineering. Ecological engineering depends on the theories developed by traditional ecology (theoretical and applied), but knowledge gained from successes and failures of ecological engineering systems will feed back to substantiate or refute many ecological theories (from Mitsch, 1993, copyright 1993 American Chemical Society, adapted with permission).

In short, it involves the building of ecosystems that have value to both humans and nature. Ecological engineering combines basic and applied science for the restoration, design, and construction of aquatic and terrestrial ecosystems. The goals of ecological engineering and ecotechnology are as follows:

1. The restoration of ecosystems that have been substantially disturbed by human activities such as environmental pollution or land disturbance.
2. The development of new sustainable ecosystems that have human and ecological value.

History of Ecological Engineering

The term *ecological engineering* was coined by H. T. Odum in the 1960s (Odum, 1962, 1971; Odum et al., 1963) and has since been used extensively in North America, Europe, and especially China. Ecological engineering was first defined in terms of energy flow as "those cases in which the energy supplied by man is small relative to the natural sources, but sufficient to produce large effects in the resulting patterns and processes" (Odum, 1962) and as "environmental manipulation by man using small amounts of supplementary energy to control systems in which the main energy drives are still coming from natural sources" (Odum et al., 1963). Odum (1971) elaborated on the breadth of ecological engineering by stating that "the management of nature is ecological engineering, an endeavor with singular aspects supplementary to those of traditional engineering." In his view, "partnership with nature is a better term." *Ecotechnology*, which is sometimes used synonymously with ecological engineering, has been described as "the use of technological means for ecosystem management, based on deep ecological understanding, to minimize the costs of measures and their harm to the environment" (Straskraba, 1993; Straskraba and Gnauck, 1985). Combining ecosystem function with human needs is the emphasis of ecological engineering, defined by Mitsch and Jørgensen (1989b) as "the design of human society with its natural environment for the benefit of both." That definition amplifies Odum's points by illustrating that if society used the energy flows of nature as opposed to the fossil fuel-based energy of conventional technology, two issues could be addressed: (1) an environmental problem might be solved, and (2) precious nonrenewable resources would not be expended in great amounts to accomplish this solution. Ecological engineering provides approaches for conserving our natural environment while at the same time adapting to and sometimes solving difficult environmental pollution problems.

The term *ecological engineering* has been applied to the treatment of wastewater and septage in ecologically based "green machines," with indoor greenhouse applications built both in Sweden and the United States in the late 1980s (Guterstam and Todd, 1990; Teal and Peterson, 1991, 1993). Here the applications are described as "environmentally responsible technology [which] would provide little or no sludge, generate useful by-products, use no hazardous chemicals in the process chain, and remove synthetic chemicals from the wastewater" (Guterstam and Todd, 1990). All applications within this subset of ecological engineering use ecosystems for treatment of human wastes, with an emphasis on truly solving problems with an ecological system rather than simply shifting the problem to another medium.

Concurrent with, but separate from, development of ecological engineering concepts in the West was the emergence of a similar development of the term *ecological engineering* in China (see Mitsch et al., 1993a, for an entire issue of a journal dedicated to ecological engineering in China). Much of the approach to environmental management in China has remained an art, but in the past decade there has been explicit use of the term *ecological engineering* in China to describe a formal "design with nature" philosophy of the late Professor Ma Shijun (Ma, 1985, 1988; Ma et al., 1988; Ma and Yan, 1989). Ma (1988) defined ecological engineering as "a specially designed system of production processes in which the principles of the species symbiosis and the cycling and regeneration of substances in an ecological system are applied while adopting the systems engineering technology and introducing new technologies and excellent traditional production measures to make a multi-step use of substance." He suggested that ecological engineering was first proposed in China in 1978 and is now used throughout the country, with about 500 sites that practice agro-ecological engineering, defined as an "application of ecological engineering in agriculture" (Ma, 1988). That number has since been updated to about 2,000 applications of ecological engineering in China (Yan and Zhang, 1992; Yan et al., 1993). At a Symposium on Agro-ecological Engineering in Beijing (Ma et al., 1988), Qi and Tian (1988) suggested that "the objective of ecological research [in China] is being transformed from systems analysis to system design and construction," stating that ecology now has a great knowledge base from observational and experimental ecology and is in the position to meet global environmental problems through ecosystem design, the main task of ecological engineering. Yan and Yao (1989) describe integrated fish culture management as it is practiced in China as ecological engineering because of its attention to waste recycling and use

PRINCIPLES IN ECOLOGICAL ENGINEERING

A few basic concepts collectively distinguish ecological engineering from more conventional engineering approaches to solving environmental problems:

1. Application of self-design.
2. Ecosystem building as the acid test of ecological theories.
3. Reliance on system approaches.
4. Conservation of nonrenewable energy sources.
5. Conservation of nature.

Self-design

Ecotechnology is dependent on the self-designing capability of ecosystems and nature. When changes occur, natural systems shift, species are substituted for each other, and food chains reorganize. As individual species sort, as some arc selected and others are not, a new system ultimately emerges that is well suited to the environment superimposed on it. Humans participate in self-design by providing choices of initial species, matching species with the environment. Nature does the rest. For example, in designing a wetland, we may want to introduce dozens of different plants at different water depths because of our inability to predict exactly where certain plants will survive and even if they will survive at all. Nature then takes over and chooses the plants that will thrive at certain water depths, soil conditions, and grazing pressures. Odum (1989a) refers to this capability of self-design as *self-organization*, which "designs a mix of man-made and ecological components [in a] pattern that maximizes performance, because it reinforces the strongest of alternative pathways that are provided by the variety of species and human initiatives." Multiple seeding of species into ecologically engineered systems is one way to speed the selection process in this self-organization, or self-design (Odum, 1989b). As described by Mitsch and Jørgensen (1989b):

> [Ecological engineering] is engineering in the sense that it involves the design of this natural environment using quantitative approaches and basing our approaches on basic science. It is technology with the primary tool being self-designing ecosystems. The components are all of the biological species of the world.

This focus on, and use of, biological species, communities, and ecosystems with a reliance on self-design is one feature that distinguishes ecotechnology from the traditional engineering technologies, which rely on devices and facilities to remove, transform, or contain pollutants, but which do not consider direct manipulation of ecosystems.

The Acid Test

The ecological theories that have been put forward in scholarly ecological publications over the past 100 years need to serve as the basis of the language and the practice of ecological engineering. But just as there is the possibility of these theories providing the basis for engineering design of ecosystems, there is a high probability of advancing the understanding of ecological systems in ecological engineering because of the unique research approach that reconstructing ecosystems provides to scientists. Bradshaw (1987) has described the restoration of a disturbed ecosystem as the "acid test of our understanding of that system." Restoration ecologists have made a clear connection between basic research and ecosystem restoration through the analogy that the best way to understand a system, whether a car or a watch, is to "attempt to reassemble it, to repair it, and to adjust it so that it works properly" (Jordan et al., 1987). Thus, ecotechnology is really a technique for doing fundamental ecological research and applying it.

A Synthesis, not Reductionism

Ecological engineering emphasizes, as does systems modeling for ecologists, the need to consider the entire ecosystem, compartment by compartment, but ultimately to make a whole. Odum (1989a) has stated that the practice of ecological engineering cannot be supported completely by reductive, analytic, experimental testing and relating. Approaches such as modeling and benefit-cost analysis are more important, as ecosystem design and prognosis cannot be predicted by summing parts to make a whole. We must learn to work with whole ecosystems rather than one species at a time. We must be able to synthesize a great number of disciplines to understand and deal with the design of ecosystems. Restoration ecology, a subfield of ecological engineering, has been described as a field in which the investigator is forced to study the entire system rather than components of the system in isolation from each other (Cairns, 1988b). Cairns goes on to state that "One of the most compelling reasons for the failure of theoretical ecologists to spend more time on restoration ecology is the exposure of serious weaknesses in many of the widely accepted theories and concepts of ecology" (Cairns, 1988b).

Nonrenewable Resource Conservation

Because most ecosystems are primarily solar-based systems, they are self-sustaining. Once an ecosystem is constructed, it should be able to sustain itself indefinitely through self-design with only a modest amount of intervention. This means that the ecosystem, running on solar energy or the products of solar energy, should not need to depend on technological fossil energies as much as it would if a traditional technological solution to the same problem were implemented. If the system does not sustain itself, it does not mean that the ecosystem has failed us (its behavior is ultimately predictable). It means that the ecological engineering has not facilitated the proper interface between nature and the environment. Modem environmental technology, for the most part, is based on an economy supported by nonrenewable (fossil fuel) energy; ecotechnology is based on the use of some nonrenewable energy at the start (the design and construction work by the ecological engineer) followed by dependence on solar energy.

Ecosystem Conservation

Ecological engineering involves identifying those biological systems that are most adaptable to human needs and those human needs that are most adaptable to existing ecosystems. Ecological engineers have in their toolboxes all of the ecosystems, communities, populations, and organisms that the world has to offer. Therefore, a direct consequence of ecological engineering is that it would be counterproductive to eliminate or even disturb natural ecosystems unless absolutely necessary. This is analogous to the conservation ethic that is shared by many farmers even though they may till the landscape. This suggests that the ecotechnology approach could lead to a greater environmental conservation ethic than has been realized up to now. For example, when wetlands were recognized for their ecosystem values of flood control and water quality enhancement, wetland protection efforts gained a much wider degree of acceptance and even enthusiasm than they had before, despite their long-understood values as habitat for fish and wildlife (Mitsch and Gosselink, 1993). In short, recognition of ecosystem values provides greater justification for the conservation of ecosystems. A corollary of this observation is the point made by Aldo Leopold that the first rule of a tinkerer is to not throw away any of the parts. The ecological engineer is nature's tinkerer.

COMPARISONS WITH EXISTING FIELDS

Environmental Engineering

Ecological engineering is not the same as environmental engineering, a respected field that has been well established in universities and the workplace since the early 1960s and was called sanitary engineering before that. Environmental engineers are certainly involved in the application of scientific principles to solve pollution problems, but the concepts usually involve energy and re-source-intensive operations such as settling tanks, scrubbers, filters, and chemical precipitators. Certainly, some techniques such as trickling falters could be considered ecological engineered approaches when they were conceived, but the field has gone far beyond designing ecosystems. It is certainly possible that ecological engineering will develop in a partnership with environmental engineering, but the two fields remain distinct today. For interesting discussions of the differences and similarities between these two fields, see McCutcheon and Walski (1994), Mitsch (1994), and Odum (1994).

Biotechnology

Ecological engineering and its synonym "ecotechnology" should also not be confused with biotechnology, which involves genetic manipulation to produce new strains and organisms to carry out specific functions. Some of the differences between ecotechnology and biotechnology relate to their basic principles, control, design, and ultimate possible costs to society (see Mitsch and Jørgensen, 1989b). Nevertheless, a comparison can be made between the development of ecotechnology and biotechnology. Ecotechnology is almost at the stage where biotechnology was 20 years ago. Molecular biology was just beginning then to establish the basic science and techniques for the yet unborn field of biotechnology. Today, ecology is recognized as a fundamental science and is now developing the ecosystem-level tools to develop the field of ecotechnology. Despite the progress made in biotechnology (usually involving genetic manipulation of species), many researchers and environmental managers believe that it will not be a major factor in solving the world's environmental problems and that there may be some adverse environmental consequences from its development. Ecotechnology, which uses the existing array of species, communities, and ecosystems of the earth, may receive more attention as limitations of biotechnology are experienced.

Restoration Fields

Restoration ecology has been described as "the full or partial replacement of structural or functional characteristics that have been extinguished or diminished and the substitution of alternative qualities or characteristics than the ones originally present with the proviso that they have more social, economic, or ecological value than existed in the disturbed or displaced state" (Cairns, 1988b). Several restoration fields have developed somewhat independently, and all appear to have the design of ecosystems as their theme. Although related to ecological engineering or even a part of it, several of these approaches seem to lack one of the two major criteria of ecological engineering, namely (1) recognizing the self-designing ability of ecosystems or (2) basing the approaches on a theoretical base, not just empiricism. Early work in Europe was based on the concept of bioengineering, the use of plants as engineering materials (Schiechtl, 1980). More recently, much has been written on restoration ecology (Aber and Jordan, 1985; Buckley, 1989; Jordan et al., 1987) and ecosystem rehabilitation (Cairns, 1988a; Wali, 1992). This approach has also been applied to river and stream restoration (Gore, 1985) and to agriculture as agroecosystems (Lowrance et al., 1984).

CLASSIFICATIONS OF ECOLOGICALITY ENGINEERED SYSTEMS

Classification According to Function

Ecological engineering, or ecotechnology, involves several approaches or applications to the design of landscapes (Table 1). These applications range from constructing new ecosystems for solving environmental problems to ecologically sound harvesting of existing ecosystems.

Classification According to Structure

Early development of ecological engineering in the West has stressed a partnership with nature and has been investigated primarily in experimental ecosystems rather than in full-scale applications. Some of the more significant experiments that have been conducted or are currently under way in ecological engineering relate to aquatic systems, particularly shallow ponds and wetlands. Ecological engineering as practiced in China has been applied to a wide variety of natural resource and environmental problems, ranging from fisheries and agriculture to wastewater control and coastline protection. The emphasis in the Chinese systems has been on applications rather than experimentation and on the production of food and fiber more than environmental protection (Mitsch, 1991; Mitsch et al., 1993b). To simplify the variety of approaches and systems used in ecological engineering, Mitsch (1993) divided ecological engineering case studies into three categories:

TABLE 1 Classification and Examples of Ecological Engineering According to Types of Applications

Application	Examples
Ecosystems are used to reduce or solve a pollution problem that otherwise would be harmful to other ecosystems.	Wastewater recycling in wetlands; sludge recycling
Ecosystems are imitated or copied to reduce or solve a resource problem.	Reconstructed wetlands; integrated fishponds
The recovery of an ecosystem is supported after significant disturbance.	Surface coal mine restoration; lake and river restoration; restoration of hazardous waste sites
Existing ecosystems are modified in an ecologically sound way to solve an environmental problem.	Biomanipulation of fish in reservoirs; biological control of eutrophication symptoms
Ecosystems are used for the benefit of humans without destroying the ecological balance.	Sustainable agroecosystems; sound renewable resource harvesting

SOURCE: From Jørgensen and Mitsch (1989).

1. Mesocosms
2. Ecosystems
3. Regional systems

Examples of systems in each of these categories are given in Table 2. Mesocosms are generally artificially enclosed systems (sometimes called closed systems) but can range in size from laboratory bench-size systems to Biosphere 2 in Arizona. Much of our understanding of ecosystem behavior can come from the construction of scale-model ecosystems. Scale models of ecosystems (microcosms and mesocosms) have been built around the world (Beyers and Odum, 1993), including scale models of both the Everglades and Chesapeake Bay (Adey and Loveland, 1991) and experimental mesocosms to investigate the role of hydroperiods (the fluctuation in water level over time) on nutrient and metal retention in marshes (Busnardo et al., 1992; Sinicrope et al., 1992). Ecosystem applications have been dominated by wetlands and water pollution control ecosystems; the ecosystem is probably the scale for which we have the most examples of ecological engineering today. Regional systems involve the construction or restoration of a multiplicity of ecosystems that are all interconnected in reinforcing patterns and pathways. Many examples of this type of system are found in China where human nutrition is tied into a functional ecosystem or set of ecosystems.

TABLE 2 Classification and Examples of Ecological Engineering Case Studies at Mesocosm, Ecosystem, and Regional Scales

Ecological Engineering Project	Location	Purpose	References
Mesocosm (Closed System)			
Treatment of septage wastes	Harwich, Massachusetts	Produce clean water (drinking water standards) from septage from an unlined landfill lagoon	Teal and Peterson (1991, 1993)
Biosphere 2	Oracle, Arizona	Simulate planet earth and investigate possible space habitation	Nelson et al. (1993)
Ecosystem			
Experimental estuarine ponds	Morehead City, North Carolina	Investigate estuarine ponds receiving a mixture of wastewater and salt water	Odum (1989b)
Forested wetlands for recycling	Gainesville, Florida	Experimentally investigate forested cypress domes for wastewater recycling and conservation	Odum et al. (1977); Ewel and Odum (1984)
Root-zone wetlands for wastewater treatment	Throughout Europe	Investigate use of root-zone wetlands to provide tertiary treatment of wastewater	Brix (1987); Gumbricht (1992)
Renovation of coal mine drainage	Coshocton County, Ohio	Study iron retention from coal mine drainage with *Typha* wetland	Fennessy and Mitsch (1989)
River pollution control	Suzhou, China	Use water hyacinths (*Eichhornia crassipes*) for water pollution control and production of fodder	Ma and Yan (1989)
Heavy metal removal from soils	Copenhagen, Denmark	Use plants and EDTA to remove metals	Jørgensen (1993)
Forest reconstruction	Throughout Japan	Develop dense stands of woody vegetation to hide industrial complexes, control visual, noise, and chemical pollution, stabilize soil, and provide urban green space	Miyawaki and Galley (1993)

Ecological Engineering Project	Location	Purpose	References
Region			
Restoration of riparian landscape	Lake County, Illinois	Restore midwestern U.S. river floodplain and determine design procedures for restored wetlands	Hey et al. (1989)
Phosphate mine restoration	Central Florida	Reconstruct wetland/upland landscape at phosphate mine	Brown et al. (1992)
Agro-Ecological Engineering	Several hundred sites in China	Incorporate multiple-product farming with extensive recycling	Ma et al. (1988); Yan et al. (1993)
Fish production/wetland systems	Yixing County, Jiangsu Province, China	Produce fisheries synchronized to *Phragmites* wetland production and harvesting	Mitsch (1991)
Salt marsh restoration	China's east coast, esp. Wenling, Zhejiang Province	Develop *Spartina* marshes on former barren coastline for shoreline protection and food and fuel production	Chung (1993)
Integrated tree-livestock system	Somalia	Develop *Acacia albida* crop-livestock system	Unruh (1993)

IMPORTANCE TO ECOLOGY AND ENVIRONMENTAL MANAGEMENT

The need for ecological engineering is evident in the following arguments:

1. The state of the environment, combined with a dwindling of nonrenewable natural resources available to solve environmental problems, suggests that the time has come for a new paradigm in engineering that deals with questions and solutions on the scale of ecosystems and landscapes. There are a great number of environmental and resource problems that need an ecosystem approach, not just a standard technological solution. Ecotechnology will play a significant role in a sustainable society. Since we cannot solve all of our environmental problems with technological solutions alone and since our energy future is clouded, we need to investigate alternative means of cleaning the environment.
2. Many current solutions to environmental problems are part of a "shell game." We control one kind of pollution, such as water pollution, to find that we have another kind of problem, such as a waste disposal problem on land. Little attention is paid to ecologically sound approaches that consider both direct and indirect effects.
3. Ecological engineering is currently being practiced by many professions under a great variety of names, including ecotechnology, ecosystem restoration, artificial ecology, biomanipulation, ecosystem rehabilitation, nature engineering (in Holland), and bioengineering (originated in Germany) but with little theory to back the practices. Engineers are building wetlands, lakes, and rivers with little understanding of the biological integrity of these systems. Ecologists and landscape architects now design ecosystems with homespun methodologies that must be relearned each time. Engineers who design ecosystems relearn the approaches each time and do not generally publish their successes in the open literature. The theory has not yet connected with the practice.
4. Engineering and ecology are ripe for integration into one field and should not remain separate approaches that are often adversarial. Ecology as a science is not routinely integrated into engineering curricula, even in environmental engineering programs. Engineers are missing the one science that could help them the most in environmental matters. Likewise, environmental scientists and managers are missing the tremendously effective engineering approach in their problem solving. The basic science of ecological engineering is ecology, a field that has now matured to the point that it needs to have a prescriptive—rather than just a descriptive—aspect.
5. Engineers now need, more than ever, a better understanding of ecological concepts and limitations in their daily practice, particularly if they deal with natural systems. For example, an important aspect of ecological engineering, the application of self-design (i.e., Mother Nature as the general contractor and chief engineer), is a decided departure from most traditional engineering. Engineering

to this point in history has been interested in designing totally predictable systems with little left to chance or the vagaries of nature.

6. The idea of nature conservation is so important that it needs to become a goal of engineering, not just one of its possible outcomes.

Short- and Long-Term Impact of Ecological Engineering

In the short-term, ecotechnology could bring immediate attention to the importance of "designing and building ecosystems" as a logical extension of the field of ecology as it applies directly to solving environmental problems. In the long-term, ecotechnology will provide the basic and applied scientific results needed by environmental regulators and managers to control some types of pollution while reconstructing the landscape in an ecologically sound way. The formalization of the idea that natural ecosystems have values for humans, other than directly commercial ones, is also a benefit of ecotechnology and will go a long way toward promoting an environmental conservation ethic and preserving biodiversity.

Specifically, ecotechnology will contribute to an improved environment in the long-term in several ways:

1. In the future we will be faced with climate changes, disappearing wetlands, degraded forests, and polluted lakes and coastal waters. A combination of adaptation and prevention may be the most appropriate strategy. Ecotechnology will provide environmental managers with the tools needed to facilitate adaptation of natural and human systems to these changes.
2. Major land use changes such as surface mining and the draining of wetlands continue to alter the landscape. Wetland mitigation and surface mine reclamation are generally approached empirically, with little bridging to the theory of ecosystem function. The emphasis on fundamental work as a basis of ecological engineering will provide ecological theory to support and refine current empirical approaches.
3. Ecotechnology will be needed as environmental agencies begin to clean up the environment through conventional approaches. The restoration of dumps for solid and hazardous waste, the reintroduction of fish and other aquatic organisms in recently improved streams, rivers, lakes, and reservoirs, and the recovery of forests with the reduction in acid precipitation all require ecological engineers who know which species to reintroduce.

Recent Developments

There are some signs that ecotechnology will become prominent in research communities in the near future and may well serve as the newest frontier of ecological science. Research support is generally increasing for fields related to ecological engineering, including ecosystem restoration and biomanipulation (Department of Energy, Department of Defense, National Science Foundation), wetland design and experimentation (Environmental Protection Agency [EPA], U.S. Army Corps of Engineers, Department of Transportation), reservoir and lake restoration (U.S. Fish and Wildlife Service, state agencies), nonpoint source water pollution control (EPA and Department of Agriculture [USDA]), forest recovery (USDA Forest Service), and sustainable agroecosystems (USDA).

The first known international ecological engineering conference, held in Trosa, Sweden (Etnier and Guterstam, 1991), highlighted many of the applications of indoor and outdoor ecological engineering wastewater systems. This was followed by a workshop in May 1993 sponsored by the National Research Council of the National Academy of Sciences in Washington, D.C. Two new *journals—Ecological Engineering* and *The Journal of Ecotechnology and Ecological Restoration*—have been launched in the past three years. SCOPE (Scientific Committee on Problems of the Environment), with the encouragement of the U.S. National Academy of Sciences, has approved a multiyear, three-continent workshop project entitled Ecological Engineering and Ecosystem Restoration. A society for ecological engineers is beginning to form in Europe. The dialogue between environmental engineers and ecological engineers has begun with joint editorials in 1994 in the *Journal of Environmental Engineering and Ecological Engineering* (see McCutcheon and Walski, 1994; Mitsch, 1994; Odum, 1994).

Ecological engineering programs in academia are being discussed in a variety of departments and programs at the Ohio State University, University of Illinois, University of Maryland, and University of Florida. Students have read the new literature on the field and are eager to find universities that have integrated programs in this new field. Professional certification issues must be addressed, but ecologists, noticing the professional stature of engineering, have developed at least one certification program for professional ecologists (Ecological Society of America Professional Certification) and at least two for wetland specialists (Society of Wetland Ecologists and U.S. Army Corps of Engineers).

CONCLUSIONS

The integration of ecology into an application that some ecologists have chosen to call ecological engineering, or ecotechnology, has not yet taken place to as great a degree as might be expected, given the great public concern for major environmental problems. Compared with graduates in engineering, graduates in ecology remain near the start of the learning curve when confronted with real-life issues of wetland construction, river restoration, habitat reconstruction, or mine land rehabilitation. They often rise to the occasion quickly with homespun ecotechnology and novel approaches, but they must continually relearn techniques that work. Engineers, on the other hand, know hydrology, physical sciences, and design principles, but are not well versed in the ecology necessary to understand, predict, and build ecosystems. While ecological theory may be mentioned, it has usually not been integrated into a framework that could be provided by ecological engineering. Furthermore, ecotechnology is, by definition, a combination of basic and applied research and requires interdisciplinary teams for its proper application. The development of such a discipline will require cooperative efforts from many related fields, and the fruitful integration of these efforts will need a new administrative structure in universities and research laboratories for this cross-fertilization of fields to prosper. The development of the field requires more discussion and interdisciplinary interaction among both engineers and ecologists.

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Why Aren't All Engineers Ecologists?

Albert H. Wurth, JR.

> *"What is Engineering? The control of nature by man. Its motto is the primal one —'Replenish the earth and subdue it'.... Is there a barren desert—irrigate it; is there a mountain barrier—pierce it; is there a rushing torrent—harness it. Bridge the rivers; sail the seas; apply the force by which all things fall, so that it shall lift things.... Nay, be 'more than conqueror' as he is more who does not merely slay or capture, but makes loyal allies of those whom he has overcome! Appropriate, annex, absorb, the powers of physical nature into human nature!"*
>
> *Rossiter W. Raymond*[1] *— 1913*

ECOLOGY AND ENGINEERING

The modifications made to the environment by human activity have been anthropocentric, directed at adapting natural systems to human needs and wants. The scale and scope of human intervention in natural systems have increased with growing capacity for engineering, but it is difficult to argue that this increase has been pursued for its own sake. Put another way, though we have relentlessly attempted to "improve" on nature, the undesirable effects of this effort have been caused not so much by hostility toward natural systems as by a lack of careful attention to them.[2] Pollution, resource depletion, and environmental degradation have not been desired outcomes. Rather, such impacts have increased as "side-effects" of improved production. Engineers have sought faster transportation, better shelter, improved communication, and more efficient processes, not more pollution or development pressure on natural areas.

The almost inadvertent character of the impact of engineering on natural systems has made it difficult for the engineering discipline to recognize and address issues like sustainability. In fact the source of the concern about the sustainability of natural systems in the face of ongoing human modifications has emerged primarily from another quarter, the work of the ecologists.

Current concern for ecological sustainability focuses especially on the long-term and less-apparent costs of human modifications, on the counterproductive effects or "unintended consequences" of human activity, on paying attention to the "by-products" (costs to natural systems) as well as the products (benefits to humans) of our technological system. These concerns have been brought to the fore by the work of ecologists, who attempt to analyze ecosystems as wholes and investigate interactions and other effects in natural systems not immediately apparent to humans. From the ecologists' perspective, which unlike the engineers' does not begin with human wants and needs, concepts like "side-effects" or distinctions between products and by-products are difficult to incorporate into ecosystem analyses. Natural systems or ecosystems are studied, at least in theory, in terms of their overall operation, not their productivity for human wants and needs. Thus, the different attitudes of engineering and ecology toward natural systems can be attributed to their different starting points.

Steven L. Goldman has underscored these differences in approach between engineering and science. He contrasts engineering's *theoria*, that is, "its characteristic world-view and rationality" with the *theoria* of the physical sciences (1990, p. 125). Engineering is distinguished by its grounding in context and valuation, with its emphasis on design; science seeks to understand universal and independent natural systems, with a focus on discovery. As Goldman notes, "the problems addressed by the sciences are ... supposed to be given to them by 'Nature'.... Within the practice of science, scientific problems are commonly conceived of as discovered; they are not arbitrary human inventions" (p. 129). On the other hand, "engineering problems are overtly invented.... given to engineers not by a supposed independently existing Nature, but by people who have, for a variety of generally obvious ulterior motives, invented them" (p. 130).[3]

These differences, however, can be overstated. The emphasis on design in engineering, while perhaps distinct from the focus of analytic physical sciences, is less incompatible with ecological science. This paper is offered as an argument that ecologists and engineers have a great deal in common, and that recognition of that common ground offers significant opportunity for a new twenty-first century synthesis that could give energy and direction to the quest for sustain-ability.

ENGINEERING STUDENTS AND ECOLOGY

The impetus for this paper came from a recognition of a recurring phenomenon in my course in environmental politics. It seemed that every time the course, a political science course in the College of Arts and Sciences, has been offered, some of the best and most engaged students have been engineering students. While part of this phenomenon can, no doubt, be attributed to the fact that many of these individuals have been excellent students who have performed well in all their classes, it has always seemed that these students not only have done well in all aspects of class performance, but also have exhibited genuine interest in ecology and environmental issues. In short, it has been my impression that these engineering students seem to display a particular attraction to, or affinity for, the course material.[4]

While the historical and philosophical writings in the course are also popular with the students, the readings and arguments that seem to have the most impact on the engineers tend to be the ones that deal with ecology and resource use. In particular, classic environmental analyses that use concepts familiar to engineers like entropy and systems (e.g., Boulding, 1993; Georgescu-Roegen, 1993), studies using models (Meadows et al., 1992), and energy analyses emphasizing efficiency (especially Lovins et al., 1986) seem to have particular appeal with the engineering students.

The enthusiasm of the engineering students suggests that there are aspects of ecological and environmental analyses that have an inherent attractiveness to students of engineering. A quick analysis suggests where this appeal might lie.

ENGINEERING AND ECOLOGICAL SYSTEMS

A discipline like engineering, focused on material balances, production efficiency, and waste minimization will very likely be attuned to the inputs (resources) and outputs (product and waste) of the systems it engineers. Indeed, an emphasis on efficiency of resource use and waste reduction is inherent to the engineering project. Ecologists seem to have a strikingly similar focus in the necessary inputs, efficiencies, production, maintenance, and waste handling of *the ecosystems* they study.[5] Despite their differences in *theoria*, their pursuits and subject matters have marked similarities. Both ecology and engineering seek to understand the integration of components of systems to produce functional wholes. This approach actually equips the engineer to be receptive to ecosystem models, because ecosystems, like artifacts, have to *work*; their parts have to fit together.[6]

If the engineers and ecologists share an interest in working systems, why is it that the two disciplines often assume conflicting positions on issues? Indeed, one primary force that has contributed to the intrusion of human activity on the ecological systems of the natural environment has been the growth of engineering. Despite their affinities, the directions taken in the real world by the two disciplines have tended to place practitioners at odds rather than to emphasize their common practice.

Given their similarities in orientation, the divergence of the two disciplines seems to be artificially constructed by the professional, educational, and social influences on the two fields. Despite their shared concerns with systems, the ecologist's definition is an expansive one, attempting to explore and understand a complex network, while the engineer's has been much more susceptible to constraints on both the size and character of the particular system and on the relevant inputs and outputs. Here, Goldman's argument about engineering's distinct *theoria* again helps explain the engineering approach.

Nevertheless, despite the differences in the two disciplines' treatments of relevant or important components and limits of the system being studied, the understanding of the nature of a system, and thereby of an ecosystem, should be much more familiar terrain for an engineer than, say, for an economist or a politician.

Indeed, engineers are well equipped to understand impacts of human activity on ecosystems; any reasonably complete materials balance analysis of a manufacturing process reflects the fact that car manufacturers produce more than cars, that steelmakers make more than steel, and that nuclear plants generate more than electricity. The profession we would most likely charge with determining the impact of a year's production of automobiles on air and fuel resources would be engineers.

This basic understanding of physical processes and materials balances clearly equips engineers to identify stresses to ecosystems. Their grounding in real-world inputs and outputs makes engineers less susceptible, at least on a theoretical level, to ignoring real costs of the industrial system (like pollution). The externalities, or uncounted costs of production, that economists quibble over have real measurability to engineers (valuation is another issue—see below); no engineer believes that smoke goes "away."

ENGINEERING AND POLITICS

Still, it would be a mistake to overestimate the capacity of engineers to apply ecological models to the systems they design. There is a reason that the engineer's attention is not turned toward the same overall analysis of a system that an ecologist might perform. While Goldman (1991) has called this the "social captivity of engineering," I would prefer to use a language that might be even less familiar, namely, that *political* decisions determine the approach taken to the technical analysis made by an engineer. Here, the definition of politics is much broader than the conventional "activity of the government" that so often defines American images of politics. The politics is the capacity to make decisions that shape or constrain the lives of others, the possibility to exert power over others. To the extent that, as Goldman argues, the decisions about which systems to investigate and which to avoid, or which variables must be carefully monitored and which can be ignored, are made by "managers," these managers inform, or hold captive, the engineering practice.

This captivity is an undeniably political (in the broadest sense) constraint. Goldman sees these "managers" as employers, government agencies, other institutional authorities who define the practice of engineering in context, making it "a decision-dominated, rather than a (technical) knowledge-dominated process" (1991, p. 122). So rather than finding the natural boundaries of the ecosystem, the engineer is trained to accept the project or system as defined by the manager. Which costs count and which do not is a decision made in terms of social values determined by the culture, the economic system, and the preferences of the decision makers. Inputs and outputs are not measured in terms of their impact on natural systems or their sustainability unless those values are included in the constraints imposed by the managers.

Thus, the environmental impacts and side-effects of engineering practice have occurred not because of engineering's *inherent* tendency to ignore ecological constraints. Sustainability is not necessarily at odds with engineers' efforts. Engineers work under the conditions set by the political decision makers, those with the power to define the engineer's problem and to set the constraints on its solution. Much as the political scientist E. E. Schattschneider (1975) has argued about political agendas, the questions asked delimit and determine the answers provided.

The political constraints that limit engineers' attention to ecosystem effects are many and various. The most obvious are economic—in market systems, services of nature are underpriced, and all externalities or social costs are, by definition, misvalued. Monetary, not ecological, cost drives engineering design. In practice, the bulk of this power lies in the hands of the economic decision makers in the business world.[7]

But the design parameters for engineers can be ecologically wrongheaded for a variety of other reasons besides inaccurate estimate of environmental externalities. As Herman Daly and John Cobb have argued, the sheer scale of the impact of the engineered world has a cumulative effect in relation to the ecosystem, so it is not simply a matter of better estimating the conditions imposed on engineering to reflect more accurately costs that had previously been ignored. As Daly and Cobb note, "the price system, with marginal Pigovian adjustments [for externalities], leads to an optimal allocation of a given resource flow, whatever its scale happens to be. But the price system does not lead to the optimal scale" (1989, p. 144). New scale constraints must be acknowledged.[8] The relative size of the industrial and engineered world in relation to the ecosystem that supports it must be recognized. "Continuous growth in the scale of the aggregate economy could only make sense in the context of an unlimited environment" (Daly and Cobb, 1989, p. 145).

Similarly, even accurate pricing does not deter certain kinds of politically popular engineering enterprises, like nuclear weapons, space programs, defense systems, and other governmental programs criticized by detractors as pork barrel projects. All such undertakings typically have benefits that are difficult to estimate, high costs and, most important, a strong political constituency.

Similar tales are told outside of government regarding pet projects for corporations, universities, and other bureaucracies. All such institutions can fund large pie-in-the-sky projects with little "bottom-line" justification. It would be difficult to explain either the Empire State Building or the Sears Tower on the basis of real estate market analyses. All these real-world political decisions shape the character and scope of engineering practice, and often direct it away from ecological sustainability.

Perhaps then, the "prepolitical" state of their engineering training explains the interest of the engineering students in my environmental politics classes. These young people who are attracted to engineering haven't yet learned the conventional levels of analysis, the appropriate and inappropriate systems to analyze. The questions they ask have not yet been delimited by the political forces that define standard engineering practice. Indeed, the reason, arguably, that I find the interests in ecology in my engineering students is precisely that they have a naive or, dare I say, pure attraction for the elegance and complexity of ecological systems. Their interest in design and models, which underpins their pursuit of engineering, easily translates into an appreciation of ecosystems.

In a sense this argues that despite engineers' "captivity," there is an essential element of engineering and the engineering approach that is very likely shared by engineers long before their capture by social or professional or economic forces. It is something more primal—maybe a problem-solving mentality, perhaps an instinct to make things work, or an urge to build something —that distinguishes the interest of the engineers (and presumably makes them likely candidates for captivity) and is the element evinced by those students in my environmental politics class.

TOWARD A SYNTHESIS

Investigating the sources of their differences, then, reveals the underlying affinities between engineers and ecologists and suggests a potential for fruitful communication and synthesis. Such a synthesis would require not so much a change in technical methods or training, but rather what I have called a political change. One obvious possibility is a redefinition of the scope of engineering practice, with an emphasis on expansion of system boundaries to extend to the impacts on natural systems on both input and output sides. As indicated, this is necessarily a political undertaking, one which, while not partisan in the traditional sense, does require some managerial or leadership effort to redefine engineering practice.

While in one sense this might seem threatening to standard engineering practice, it would be a fundamental misunderstanding of the argument to perceive such change as problematic for engineering. Engineering in essence, with its intuitive problem-solving and system orientation, might need to change very little. Engineering as practice, for whom and for what, might have to change a great deal and adopt an additional set of constraints.

Recent efforts to bring ecology and engineering closer together have taken many forms ranging from industrial ecology (Frosch, 1993) to ecological engineering (Mitsch, 1993). While all these initiatives reflect the spirit of the argument presented here, they tend to fall short of what might be the ideal long-run perspective. If the ecology of natural systems identifies significant earthly limits in terms of which sustainability must be expressed, then the devotion of a branch of engineering to this area of research and development represents another boundary that limits the potential integration of the disciplines. The systematic understanding of ecosystems can hardly be a branch of engineering independent of, and parallel to, other engineering fields. Rather, it would seem that all engineering fields should redefine their disciplinary specializations in terms of their respective systems' places in ecosystems. Rather than a new subfield or discipline destined to take its place alongside existing specialties, the ecological model really is better understood as informing all subfields. It is this same ubiquity or inescapability that, I think, catches the attention of engineering students. The impact of ecology looks more like the constraints of thermodynamics than like the opportunity for a new branch of the profession.

If we accept the need to face ecological constraints, the fundamental recognition must be that the economy and the industrial system exist within and depend on the ecosystem. Accordingly, twenty-first-century engineering and development must challenge industrial gigantism and expanding control and scale with a commitment to reengineer the developed world to have less impact on ecosystems.

In practical terms, engineering within ecological constraints means turning engineering away from natural systems and back onto previously engineered systems. Two easy suggestions would be to follow Amory Lovins's recommendation to "wring more efficiency" out of existing technologies and Herman Daly's recommendation to substitute development for growth.

Finally, a metaphor might serve better than a list of recommendations. The treatment of wildlife by civilized societies has seen two conflicting models, the zoo and the wildlife refuge. In the former, wild natural creatures are brought into civilized, developed settings; in the latter, wild areas are set aside to be protected and undeveloped, and civilization makes small unobtrusive outposts that (at least in theory) do not upset the ecosystem that supports the wild area. The lesson for future engineering is obvious. Wild creatures don't survive in zoos. The zoo model must be displaced by the wildlife refuge. In place of specimens from the wild transplanted into our engineered world (which we don't do well), we need to reengineer our artificial world and tidily insert it into an otherwise protected and undisturbed global ecosystem.

NOTES

1. From "The New Age," an address delivered at the Perkin Medal Meeting, Society of Chemical Industry, Chemists' Club, New York, January 24, 1913, by Rossiter W. Raymond, quoting "a statement uttered by me ten years ago, in an address on the Dynamics and Ethics of Engineering. It is so delightful to be able to reiterate without change an opinion ten years old." [That is the reason for the quotation marks in the text above—quoting himself.] In *The Journal of Industrial and Engineering Chemistry*, March 1913, pp. 249-251.
2. One obvious exception might be the view of natural systems as "unproductive," which generated a kind of restless urge to improve them, whether by irrigating arid lands or draining wetlands.

This perspective assumed that river, grassland, and forest *ecosystems* didn't do anything, that they were wasted or unproductive resources. John Wesley Powell's account of his journey through the American West portrayed the land as potentially useful through reclamation.
In contrast, a current concern of ecologists is with the productivity of unengineered or natural systems, and especially with unrecognized productivity.

3. Goldman offers a series of contrasts between the two disciplines:

> ... the distinctive world outlook of engineering,... its *theoria,*... would be to the *theoria* of the physical sciences as induction is to deduction, as the pragmatic is to the rational, as nondeterministic design is to deterministic law, as the contextual is to the universal, as the pluralistic and contingent is to the unique and necessary, as the open- ended is to the once-and-for-all, as Ciceronian rhetoric is to Platonic philosophy, as the skeptical is to the certain, as the Principle of Insufficient Reason is to the Principle of Sufficient Reason (1990, p. 135).

4. While most students find the material from a course on such issues to be obviously timely and relevant to current events, the dedication exhibited by the engineering students seems to reveal a special affinity between the interest they have in engineering and the logic or character of ecological science.
Though my impressions are just that, impressions, and not based on a systematic review, I feel that this same enthusiasm and interest on the part of engineering students is much less pronounced in the other political science classes I teach.

5. Both fields, arguably, also seek a kind of internal elegance in the processes they investigate.

6. See James Karr's discussion of ecosystem "integrity" and "health" (in this volume), and C. S. Holling's investigation of ecological "resilience" (in this volume). Eugene P. Odum has argued that the "holism" of ecology distinguishes it from the "reductionism" of analytic science and should be a model for broader syntheses of the natural and social sciences (1977).

7. If monetary constraints are the only costs considered, the only design parameters, then engineering, which might be good in terms of the specified constraints, could mean potential disaster for the broader ecosystem. Illustrations of "well-engineered" products like lead paint, chlorofluorocarbons, and 8-mile-per-gallon cars indicate the nature of the problem.
A similar point put in a slightly different way, as I suggest to the engineers in my classes, is that designing a better car for an insane traffic system is not necessarily a design for an improved transportation system.

8. This scale issue is especially *critical* in a world that regards bigger as better. See Bryan Norton's argument that all environmental problems are essentially problems of scale (in this volume).
Daly and Cobb recommend sustainability quotas for resources, both sources and sinks, to regulate the scale of the industrial economy.

> Instead of beginning with the impossible task of calculating full-cost prices [prices including externalities] and then letting the market determine the right quantities on the basis of these prices, we could begin with the 'right' quantities and let the market calculate the corresponding prices. But what do we mean by the 'right' quantities? Only that the economy is constrained to operate with volumes of resource flows that are within the renewable biospheric capacities of regeneration and waste absorption (1989, p. 142-143).

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CASE STUDIES

Engineering for Development in Environmentally Sensitive Areas: Oil Operations in a Rain Forest

June Lindstedt-Siva, Lou C. Soileau IV,
Dilworth W. Chamberlain, and Martin L. Wouch

THE DILEMMA OF DEVELOPMENT IN NATURAL HABITATS

Human populations and their support systems have expanded to the point that they can potentially affect global ecology. Perhaps the most significant impacts are the long-term ecological effects that result from anthropogenic disturbance, modification, and conversion of natural habitats. The result is that native plant and animal populations are reduced, confined to small areas, or lost altogether. At some point the survival of species themselves may be in jeopardy. Most species become endangered or threatened not for genetic or physiological reasons, but because their habitat is modified or eliminated, or they are overharvested.

Rapid human population increases are occurring in less developed, tropical countries where biological diversity is greatest. Here, deforestation is resulting in the rapid loss of rain forest habitat, potentially eliminating species about which little is known. Pressure on natural systems comes from basic survival needs for food and fuel and from the desire of the people and their governments to raise the country's standard of living, provide housing, and promote industrialization and modem agricultural development. The problem is not confined to the developing world; industrialized countries are also losing natural habitats.

There is little hope of stopping natural habitat losses in the near term. This is as true in the Santa Monica Mountains of southern California as in the forests of Brazil. Some important habitats can be protected in parks or reserves, but this strategy saves only habitat "islands" and, alone, cannot ensure maintenance of biodiversity over time. Solutions for the long-term must emphasize finding ways to maintain the ecological integrity and functions of "developed" areas. This approach is consistent with the concept of sustainable development (Lovejoy, 1994).

DEVELOPMENT THAT PRESERVES ECOLOGICAL INTEGRITY

The following are examples of development that has resulted in preservation of ecological or biological integrity as defined by Angermeier and Karr (1994). In each of these examples, most of the land is maintained in open space, and "facilities" occupy only a small portion. In addition, public access is restricted.

Camp Pendleton Marine Base in San Diego County, California, contains many small wetlands that would have been converted to marinas and condominiums long ago had they not been on the military base. Because so many acres of wetlands have been lost to development in southern California, the small remaining wetlands at Camp Pendleton are increasingly important to coastal ecology.

Point Mugu Naval Air Station in Ventura County, California, also supports many acres of wetlands, and some endangered species. In addition, because it is protected from disturbance, this is one of the few parts of the southern California mainland coast where seals and sea lions regularly haul out to rest.

Vandenberg Air Force Base in Santa Barbara County has some of the best rocky intertidal habitat in California, supporting the biodiversity that was lost from more populated areas of the coast many years ago.

The Guadalupe Dunes oil field in Santa Barbara County consists of oil wells, pipelines, roads, and oil storage and treatment facilities. Because most of this coastal property is maintained in open space and public access is restricted, it is one of the last places in the region where native dune vegetation survives, including some endangered species. Because of public use (dune buggies, dirt bikes), dunes adjacent to the oil field are damaged so that they no longer support native vegetation.

Similarly, in Kern County, California, oil fields are some of the only remaining large tracts of land that have not been converted to agriculture or urbanization. Here, too, native plants and animals are present, including several endangered species. One working oil field was recently designated an ecological preserve and is being managed as such, in cooperation with state agencies. This management will continue beyond the life of the oil field (Loll and Steinhauer, 1993).

For these examples, protection of natural ecosystems was often an unforeseen by-product of the type of development that occurred. However, today these environments are protected by design, as part of managing the facilities. It is the latter, environmental protection by design, that must be encouraged and supported both domestically and internationally.

ENVIRONMENTAL PLANNING AND MANAGEMENT PROCESS

The goals of environmental planning and management are to minimize the adverse environmental impacts of development and to maintain or enhance the ecological integrity and functions of the natural system. The principles can be applied to development as diverse as an agricultural crop, housing tract, power plant, or oil production. The interdisciplinary process of environmental planning and management requires interaction of the environmental sciences, engineering, and operations. It can be applied to ongoing operations or new projects, though it has its greatest effect when applied to new projects early in their development, when siting, design, and engineering options are still open.

Figure 1 illustrates the process. The process begins when a project proposal is developed, including siting and design alternatives. An environmental reconnaissance study is conducted to identify the major ecological features of each site.

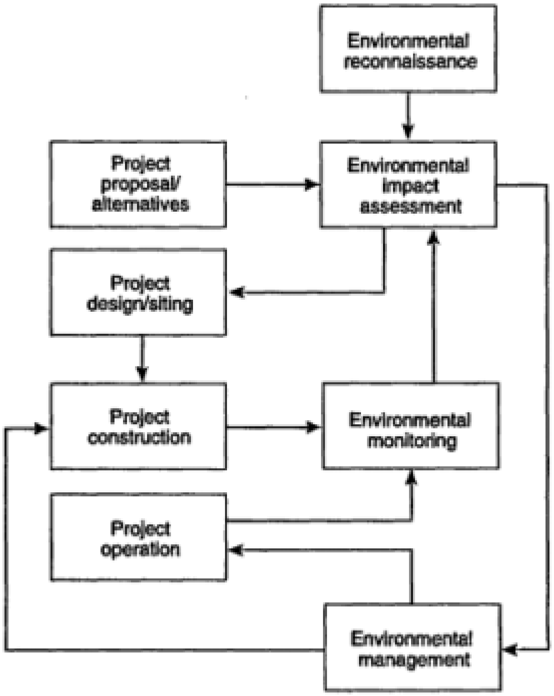

FIGURE 1 Environmental planning and management process.

This need not be, and in most cases cannot be, a lengthy and expensive study. Much can be learned by knowledgeable scientists from a literature review, site visit, and study of topographic maps and aerial or satellite photos. On the basis of this information, an environmental impact assessment is prepared. This includes an analysis of the potential impacts of the various alternatives as well as recommendations of alternatives and mitigation measures. This information is fed back into an environmental management plan for the project siting and design process. The site and project design alternatives are selected and permits and other approvals are obtained.

During the construction phase of the project, environmental monitoring begins. Monitoring may begin before construction if additional, site-specific environmental data are needed. Monitoring to establish a baseline against which to measure future impacts is usually not feasible because of the time, scope, and cost of a study required to define natural variation. Therefore, the monitoring program must focus on environmental parameters and populations likely to be affected during the construction and operations phases of the project. Environmental impacts are assessed and the information is fed back into an environmental management plan that becomes part of the operations plan for the project. Monitoring continues to some degree during operations so that impacts can be assessed continually and the management and operations plan can be modified as necessary.

Once this process is completed, the environmental and engineering information generated becomes extremely valuable to those planning similar developments or different projects in similar habitats. Therefore, dissemination of the results—including both successes and failures—is critical.

OIL DEVELOPMENT IN AN ECUADOR RAIN FOREST

Tropical forests are complex environments that support a greater diversity of plant and animal species than any other terrestrial habitat. Most of these species (e.g., insects) have not been named, described, or studied by scientists. Raven (1994) estimates that there are 8-10 million species on earth, though only 1.4 million have been named. Tropical forests are also rich in substances, both medicinal and industrial, that are useful to their indigenous residents as well as society at large (Lewis, 1990).

Tropical rain forests receive 80-300 inches of rainfall a year (Holdridge, 1967). They typically consist of a relatively tight canopy of broad-leafed evergreen trees and two or more underlying layers of trees and shrubs. Undergrowth vegetation is usually sparse because little sunlight reaches the forest floor. Soils are typically acidic and poor in nutrients. Nutrient cycling depends on degradation of leaf litter, fallen trees, and shrubs on the forest floor. Because this cycle is so easily altered by disturbance, tropical forests are among the world's most sensitive environments (Wilson, 1988). The largest remaining contiguous tracts of tropical forests are in the Amazon drainage of South America and in central Africa.

The scientific community has recognized the problem of deforestation in the tropics for a long time. In 1980 a National Research Council panel predicted that most forests would not exist as they were at that time by the close of the century (National Research Council, 1980). Deforestation in the tropics is also thought to influence local climate and contribute toward global climate *change* (Wilson, 1988). The ecology of humid tropical systems is poorly understood. Substantial research is needed to develop sustainable uses in these systems as well as methods to reduce impacts of development and restore damaged systems (National Research Council, 1982; National Science Board, 1989).

The environmental impacts of development in the tropics are closely linked to socioeconomic effects. Bringing development of any kind to semi-isolated indigenous populations generally brings profound changes to those cultures. Contact alone may expose communities to diseases for which no immunity has been developed. Alteration of the natural habitat may deplete or alter traditional food and water sources. When two cultures come into contact, the dominant culture will, in the long run, submerge the other culture unless preventive steps are taken.

Major Environmental and Social Issues

Deforestation and habitat alteration are occurring rapidly in the tropics worldwide. Historically, the primary cause of deforestation in South America has been invasion by colonists who clear the forest to raise cattle or grow crops. Governments have also "opened" new areas, encouraging colonization and other types of development. Roads are probably the major contributing factor in deforestation. Wherever roads have been built into previously isolated areas, the result has been encroachment by "outsiders," followed by deforestation and environmental degradation as well as profound social impacts. Oil development in the tropics has often also included major road construction.

Compared with deforestation and habitat loss, environmental pollution from oil operations using contemporary technologies and practices is a lesser, though potentially significant issue in the tropics. When vegetation is removed and heavy equipment used, there is a high potential for soil erosion and contamination of streams used for drinking water as well as fishing. Garbage and sanitation wastes as well as oil exploration and production wastes are potentially significant sources of contamination in these sensitive environments. Air pollution associated with operations may be locally significant.

In the past, when areas of tropical forest were "developed," the results were often also detrimental to indigenous people. Uncontrolled, spontaneous colonization by outsiders often displaced the local populations and introduced diseases. Colonists in all parts of the world have been tenacious and relentless. Stopping or slowing colonization is extremely difficult, especially when there are roads into an area and when colonization is an attractive option for improving the lives of settlers. Social consequences may include displacement of indigenous people and degradation or depletion of resources needed for survival (drinking water and native plants and animals), erosion of culture, alcoholism and other ills, and the possibility of making communities dependent on the outside world with no way to maintain or return to traditional ways if outside support systems are removed.

ARCO Project

It is in this context that ARCO Oriente Inc. (a subsidiary of Atlantic Richfield Company [ARCO] based in Quito) is exploring for oil in Ecuador. ARCO International Oil and Gas Company (AIOGC), a division of ARCO, has oversight responsibility for ARCO Oriente. The site is Block 10, a forested area on the eastern slopes of the Andes and part of the Amazon drainage basin (Figure 2). The remainder of this paper describes the major environmental and social issues relevant to the project (Lindstedt-Siva and Chamberlain, 1991), and discusses some of the ARCO programs in place during the exploration phase, as well as plans for the development phase of the project. These plans will be finalized and implemented if ARCO and the government of Ecuador agree to proceed with the development project. The following discussion outlines an approach to oil development that, in many respects, represents a major departure from conventional operations and, in our view, a significant advance in environmental protection.

Exploration Phase

Oil exploration and production in Ecuador began early in the 1900s, first along the Pacific coast and later in the interior. ARCO Oriente Inc. began exploring for petroleum in Ecuador in November 1988. ARCO and its partner, AGIP (Overseas) Ltd., are service contractors for the Ecuador state petroleum company, PETROECUADOR, by an agreement signed in June 1988. Block 10 covers 200,000 hectares (494,000 acres) in Pastaza Province. PETROECUADOR and other oil companies produce approximately 390,000 barrels of oil a day from fields north of Block 10.

Between November 1988 and July 1989, seismic exploration was conducted throughout the block (Figure 3) except in the extreme southwest corner, where operations were discontinued in deference to the wishes of indigenous people living in the area. Seismic lines (narrow paths to aid deployment of seismic exploration equipment) as well as footpaths and helipads needed to support the seismic operations were cleared by hand (chain saw and machete) and occupied an estimated 341 acres. A subsequent seismic operation conducted between August 26 and September 29, 1991, resulted in hand-clearing an additional 14.4 acres.

FIGURE 2 ARCO International Oil and Gas Co., ARCO Oriente, Block 10, Pastaza Province, Ecuador.

Three exploratory oil wells were drilled at two roughly 4.5-acre sites, Moretecocha and Villano, named for nearby villages and chosen with assistance from the villagers. One well was drilled near Moretecocha and two near Villano. Oil has been found at both locations, but the Villano wells appear to have standalone commercial potential. Possible pipeline routes have been surveyed from the Villano discovery area.

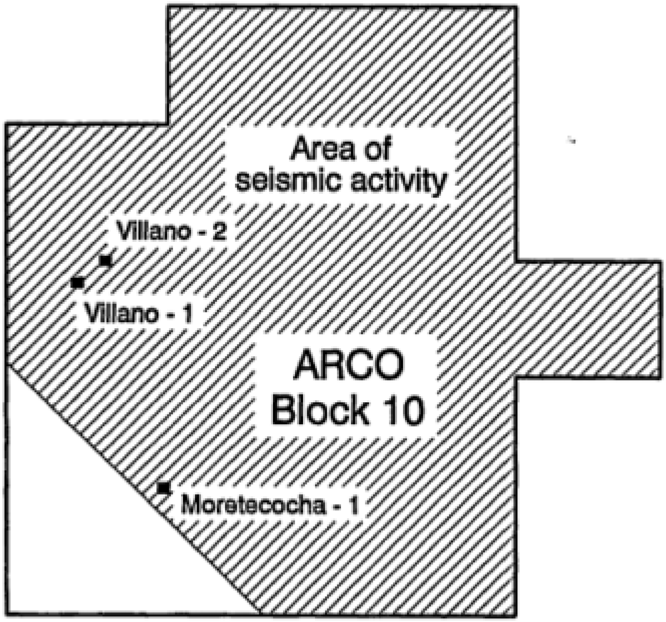

FIGURE 3 Seismic operations and exploratory well sites, Block 10.

Environmental and Social Strategies

A major goal of the company is to minimize adverse environmental and social effects of the project. Environmental guidelines for rain forest exploration operations were developed by ARCO before drilling the first exploratory well (AIOGC, 1990). Major elements include the following:

1. Build no new roads—move all equipment and personnel using existing out-of-forest roads, aircraft, or on foot.
2. Minimize the "footprint" of all operations (seismic lines, helipads, campsites, drill sites)—the smallest feasible footprint minimizes vegetation removal and reduces all other environmental impacts accordingly.
3. Minimize the use of heavy equipment (tractors)—use hand methods (machete, chain saw) when vegetation must be removed. Natural restoration of disturbed areas is much faster if the topsoil is not disturbed.
4. Consult with local communities—informing and involving residents of villages nearest to, and most affected by, the project is vital. For example, local

villagers help select trees to be used in construction, participate in cutting lumber, and advise ARCO on other environmental and social issues, such as identification of wildlife and plant species, and on the locations of cultural significance to villages. Although primary emphasis has been at the "grass roots," it is also important to encourage dialogue with all indigenous groups that express an interest in such dialogue.

5. Restore disturbed sites.

Lumber Harvesting and Transport

Drill sites were designed to be smaller (4.5 acres) than those commonly constructed in the area (about 12 acres). Some lumber was required for construction at drill sites and campsites. Indigenous residents, in cooperation with Ecuadorian foresters, selected trees for harvest on the basis that they were fast-growing and not used to make canoes or otherwise significant to the community (e.g., special use or meaning). Trees were cut by hand using chain saws at remote locations, taking care to minimize canopy gaps. Boards were cut at the remote site, then transported to the construction site by helicopter or footpath. This method of harvesting and transporting lumber is unconventional and greatly reduced the ecological impacts of the project over what it would have been expected if lumber were harvested and transported through the forest in the conventional way using heavy equipment (McMeekin, 1991; McMeekin and Zak, 1990).

This method of selective harvesting closely mimics natural treefall in that only single trees are cut in a given area; there is no "clearing." Gaps in the canopy due to natural treefall create light gaps of up to 360 square meters. Light can penetrate to ground level in these gaps, creating microhabitats and stimulating plant growth (Brokaw, 1982; Connell, 1979). For ARCO operations, trees were selected and harvested at unevenly spaced intervals, depending on the location of trees meeting the selection criteria. After six months, gaps created from timber harvesting displayed vegetation regeneration similar in genetic diversity and structure to that found in natural treefall gaps, although trampling and a thick layer of sawdust slowed recovery of some areas (Woodward-Clyde, 1992). Recovery in exposed areas begins with the growth of sun-tolerant species as the first stage of the succession process that leads to natural restoration of the forest (Brown and Press, 1992).

Construction and Heavy Equipment

Construction of drill sites for exploratory wells was the only part of the project that required the use of heavy equipment in remote areas. The drilling rig and supporting heavy equipment were brought to the site in sections by helicopter and assembled at the site. Heavy equipment use was permitted only within the confines of the drill site. After construction and drilling were completed, all equipment was disassembled and removed by helicopter.

Reclamation

Natural recovery of helipads, seismic lines, and campsites was rapid because vegetation was cut by hand (using chain saws and machetes) and top soil was not disturbed. Where heavy equipment was used to construct drill sites, recovery has taken more time. Reclamation programs were implemented to enhance the recovery process. Topsoil removed to construct drill sites was retained and protected on-site. Nurseries were established at each drill site to provide native plant seedlings. Monitoring of the initial phase of reclamation at the Moretecocha-1 well site indicated that additional work was appropriate; this work has been recently completed. A reclamation program incorporating what was learned at Moretecocha was implemented at the site where the Villano-2 and Villano-3 wells were drilled. This site was occupied for about two and one-half years and may be used in the future if the oil discovery is developed. The plans for both the Moretecocha (most recent phase) and Villano sites included contractual terms for local indigenous monitoring and maintenance to tend the vegetation and replace any plants failing to survive, as well as to report problems at the sites requiring attention from ARCO.

Social Issues

The situation with regard to indigenous communities in Ecuador is complex. There are three major groups living in Block 10—Quichua, Huaorani, and Schuar. These indigenous groups, the colonists, provincial leaders, and the Ecuadorian government are involved in an ongoing controversy over land fights and development issues. However, Ecuador has made progress in resolving land fights issues by granting such fights to various communities in 1992. Several organizations claim to represent the various indigenous communities, and it has been a challenge for ARCO to cooperate with any one organization without alienating another. In attempting to minimize such controversy and keep the consultation and decision making close to the communities that are nearest to, and likely to be most affected by, oil operations, ARCO has focused more attention on communities than on the larger, representative organizations. ARCO Oriente personnel meet regularly with communities to maintain communication, exchange information, and resolve issues. ARCO Oriente has developed partnerships with communities in the vicinity of operations by negotiating agreements with them for the use of their land, rather than merely assuming the fight to use the land according to agreements with the Ecuadorian government. As a result of consultation and negotiation, ARCO has provided support to the communities in the form of medical assistance, training, educational supplies, school structures, and airship improvements. The goal of this support is that it result in positive changes in the community that will last beyond the life of the project.

Development Phase

As of this writing, ARCO and AGIP are preparing a field development plan that the government of Ecuador will use to decide whether or not the project should proceed to the development phase. In anticipation of development, a number of environmental studies and planning exercises were completed. Whether or not the project proceeds, the ideas and strategies that emerged from this process have broken new ground and provided what may be a model for development in environmentally sensitive areas.

Conventional Technology and Approaches

Conventional development of an oil field requires construction of drill sites, pipelines, gathering and processing facilities, and pump stations. Technology and construction methods for these facilities are well established and accepted in the industry and are currently common practice in Ecuador and elsewhere. Drill sites in this region have historically occupied about 12 acres. They are connected to one another and to support facilities by roads. Pipelines are used to transport oil from wells to gathering and treatment facilities and for shipment out of the area. Pipeline construction requires road construction first, so that equipment can be moved to the site. Roads are also required for access to the oil fields and pipeline for routine operations. Pipelines are typically monitored from aircraft, requiring that pipeline corridors be cleared of vegetation so that leaks or other problems can be detected from the air.

In addition, remote operations complicate the problem of transporting workers to and from the oil fields. Normally, workers are housed in the field for shifts of 7 to 14 days. Oil field operations continue 24 hours a day; therefore, a contingent of 40 to 50 personnel is not unusual.

Environmentally Based Technology

During planning, all conventional approaches to drilling, operations, and logistics were challenged. Can alternative approaches be developed that will reduce environmental and social impacts of the project over conventional approaches? Is it possible to develop an oil field in a remote forest without roads? Can alternative methods be found to construct and monitor a pipeline without roads and without breaking the forest canopy?

When we first asked these questions, the nearly universal response was that it is not possible to develop a project without roads. At a minimum, an unconventional, roadless project was expected to be costly. The more the questions were studied, however, the more likely it looked that at least some of the challenges could be met. The following concepts emerged from these studies.

The Offshore Model

The goals of a roadless operation with a small footprint caused the project team to search for an alternative model to conventional oil field development technology. The key breakthrough in our thinking came when the project leader (L. C. Soileau) visualized oil production in a rain forest using the only current example of oil production without roads, an offshore operation (Figure 4a). The setting of a remote, tropical rain forest is directly analogous to an offshore site. If the offshore model is applied to this onshore situation, many of the same practices and development techniques used by ARCO in open waters could be applied cost-effectively to the rain forest environment. ARCO had already gained experience developing small-footprint operations as part of the large oil production project on the North Slope of Alaska. The goal there was to minimize impacts on tundra.

Refining the Offshore Model

Conventional contemporary onshore development with a road was evaluated to give baselines for development and construction time, cost, and risk as well as the socioenvironmental impacts. This approach was evaluated against conventional offshore development as well as variations of the offshore model.

The conventional offshore approach is to house personnel on platforms, along with processing facilities for oil, gas, and water. Logistical support for the platforms (e.g., crew and equipment transport) is provided by boat or helicopter. The rain forest version of this approach would be to locate processing facilities and personnel quarters in a compact design at the drill site with logistical support by air.

The second alternative evaluated is production processing in the field while housing personnel at the nearest community with support facilities (water, electricity, housing, roads). This hybrid concept allows for location of oil, gas, and water processing at the oil field as in a conventional development combined with the offshore approach to logistics and support.

A third alternative, locating processing facilities as well as worker housing at the nearest urban community along the oil pipeline route, is the current preferred model (Figure 4b). Here there is access to electric power, roads to other areas, and existing support systems for oil field workers, including housing and telecommunications. The equipment and systems at the oil field are minimized and as simple, reliable, and durable as possible. This approach concentrates people at the population center and reduces the number of people required in the field. The

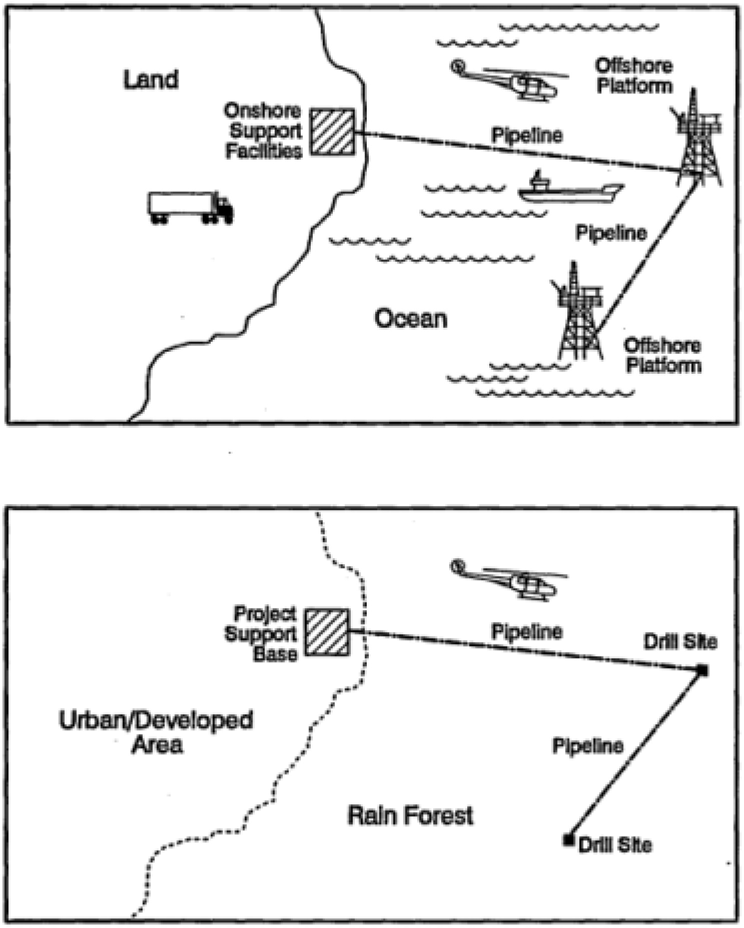

FIGURE 4 (a) Conventional offshore oil development. (b) Offshore development model applied to rain forest.

complication of this approach is the isolation of producing wells from field supervisors and work crews.

Production Processing Technology

Conventional contemporary oil field technology used to separate and treat produced oil, gas, and water is complex, requiring close monitoring and maintenance (Figure 5a, conventional technology). Project engineers studied various alternatives and finally developed a simpler, low-maintenance approach (Figure 5b, alternative technology). This alternative minimizes the acreage required for equipment as well as numbers of workers required to support it. This minimizes environmental impact and also reduces the opportunity for social interaction between indigenous communities and oil workers. The lack of road access gives protection from colonization by outsiders and maintains local control. The indigenous communities will continue to manage their lands and resources and can make the deliberate decision to discourage or encourage entry of colonists, other industries, or agriculture. In addition, since company and contractor personnel will visit the field only as needed, greater control of cultural "evolution" will be exercised by the indigenous people themselves. There are possibilities for long-term employment of local people, if desired. Further, with flexibility designed into the pipeline, power, and processing systems, future discoveries can be integrated into this plan with continued minimal impact.

Costs

Costs for a remote operation are higher than costs for conventional operations during the construction phase. However, the offshore model approach will reduce costs over the long-term because of the smaller number of personnel that must be maintained at remote locations, the simplicity and lower maintenance required for production equipment, and the lack of road construction and maintenance.

Pipeline Options

Many pipeline options were evaluated. Only three constraints were placed on engineering teams: (1) the capability of transporting 30,000 barrels a day, (2) no permanent roads leading to developed areas, and (3) a cleared right-of-way less than 20 feet wide, rather than the conventional 60 feet. Numerous innovative techniques for constructing and monitoring the pipeline have emerged.

One of the more unusual concepts was to design a *land pipelay barge* . Constructing a pipeline offshore requires a specially made barge that transports the pipe to the offshore location and contains equipment needed to weld, wrap, inspect, and lay the pipeline on the seafloor. The ARCO team thought that tree

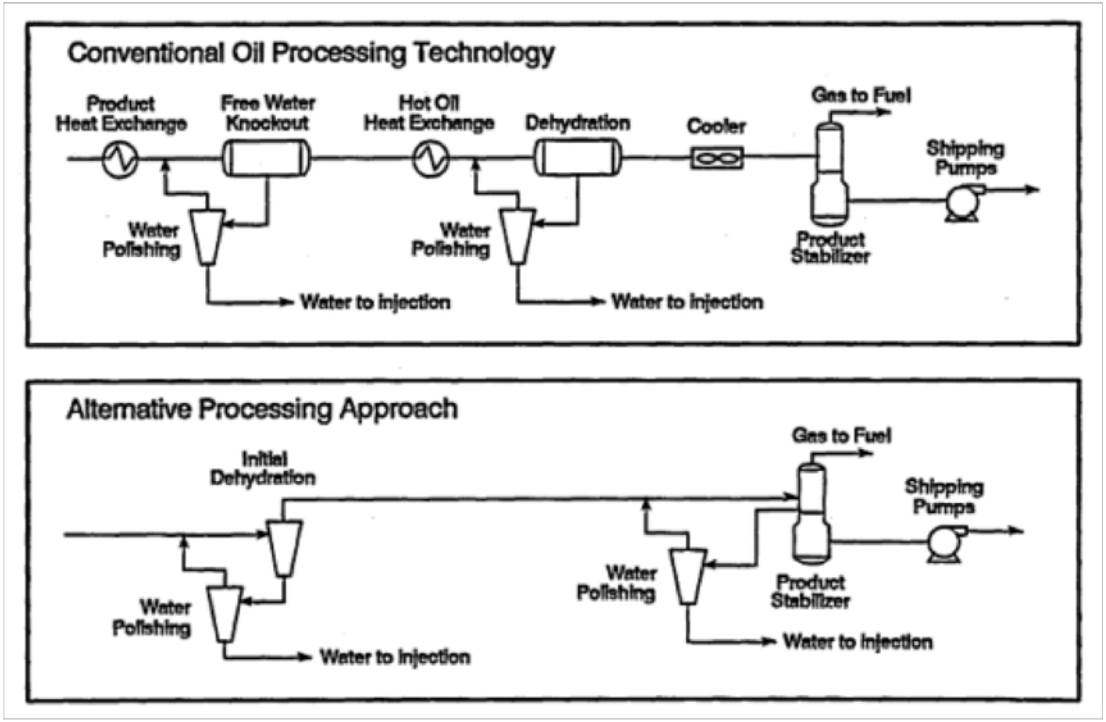

FIGURE 5 Conventional and alternative oil field technology.

removal could be minimized by designing a land barge of multiple, wheeled platforms linked together. The right-of-way for the pipeline would be slightly wider than the barge since each platform would straddle the pipeline ditch. Each platform would serve a separate function. The lead unit would trench the ditch. The second unit would carry the sections of pipe and feed them one by one into the automatic welding machine. The third unit would quench and wrap the pipe. The fourth unit would inspect and drop the pipeline into the ditch. The fifth unit would refill the ditch. Using retired military-tracked heavy vehicles, this concept may yet be viable.

Using *manual labor* to construct the pipeline would reduce the need for heavy equipment and roads. This approach would require either laying the pipeline on the surface or digging the ditch by hand. A surface line would minimize tree loss and corridor width. However, conventional 15- to 24-inch-diameter pipe is difficult or impossible to move by hand. In addition, welding machines are required to connect the 40-foot sections. This problem could be solved by using high-pressure plastic pipe that could be fused together with machines that can be carried by humans over rough terrain. Alternatively, two smaller parallel pipelines could be installed rather than one larger one. The smaller pipe would be easier to handle in the field.

Another approach is to use *flexible, armored pipe* such as is used offshore. This pipe is reinforced, high-pressure rubber hose wrapped in a metal sheath. Long sections of coiled pipe could be flown along the pipeline route, uncoiled and connected by hand, and laid around the larger trees.

Consideration was given to a *double pipeline* with oil flowing through the center pipe and monitoring equipment in the space between the small and large pipe. Such a double-walled pipe could be laid in the Villano River. Although there would be temporary disruption to the river, this technique would minimize vegetation removal and soil disturbance during pipeline construction as well as the need for roads to transport equipment.

To avoid constructing a permanent road along the pipeline, it may be possible to build *temporary roads* that would be dismantled after pipeline construction. Temporary roads could be surfaced with reusable materials, such as surplus steel plating from military aircraft runways or "lumber" made from recycled plastic waste. This material could be moved along the pipeline route and used as road surface for the heavy ditching and pipe-moving equipment. In many places, temporary bridges could be used and then removed to eliminate permanent river crossings.

The terrain may require *tunneling* through small hills, under streams, or from the top to the bottom of escarpments. Sections of the pipeline could be laid in these small-diameter tunnels to eliminate permanent bridges and impede the crossing of any of these natural barriers by off-road vehicles or horse-drawn carts.

Using these concepts, it may be possible to design the pipeline so that the right-of-way is 20 feet or less. With a *corridor* of this size, the natural forest canopy may be preserved or easily restored.

Pipeline Monitoring and Maintenance

Once the pipeline is laid, it must be monitored for breaks, corrosion, and leaks. Normally, a pipeline route is observed by periodic overflights using a small airplane or a helicopter. If this pipeline is constructed using techniques that allow the forest canopy to remain unbroken, airborne observation will not be possible. Again using the offshore model, flow meters could be used to monitor the volume of oil in the pipe at various points. Pressure monitors can be used to detect leaks. As is the case in all major pipelines, instruments are placed in the pipe to clear the line of extraneous fluids and monitor corrosion. To take the place of aerial observation, indigenous people who live along the route could be hired to walk the line and report any leaks or damage.

Selecting an Approach

Some of these concepts may be viable and find their way into the project. Availability of materials such as superhigh-pressure plastic pipe or the feasibility of "land barges" will be considerations. Cost will also be a major consideration. Reinforced flexible pipe, for example, would be extremely expensive and may not even be available in the large diameter required. However, exploring ideas such as these has enabled project personnel to completely rethink the process of constructing, maintaining, and monitoring a pipeline.

Current Status of Environmental Planning and Management

The type of environmental planning and management described here is not widely practiced, even in developed countries. Yet, if we hope to conserve natural ecosystems and reduce the rate of loss of biological diversity, sound environmental planning and management are critical. The process need not be lengthy or expensive. The key for the long-term is adequately trained environmental scientists, engineers, and operating personnel working together. These teams must be challenged to "break the mold" and depart from conventional thinking.

SCIENCE AND ENGINEERING NEEDS

Environmental planning and management is based on getting information from the environment and feeding it back into the management plan of the project. We must find better, less expensive, and less time-consuming ways to obtain this information. We need scientifically sound, rapid assessment and monitoring methods that are affordable. Neither industries nor government regulatory agencies have the resources to do long-term, baseline studies to inventory species and document natural variation of populations. Yet, accurate environmental data, useful in the project management process, are needed. For most development projects around the world, in both developing and industrialized countries, resources will not be available to support the type of environmental studies that have been required in North America and western Europe, and these fall short of a real baseline. More effective, less costly methods are needed everywhere.

Since it will not be possible to study everything, we need to develop methods that focus on those parameters that will tell us most about the environment at least cost. Are there different or better ways to make use of satellite-generated data and aerial photography? Can some populations be used as indicators of environmental quality to eliminate the need to monitor all populations (e.g., birds, ants, butterflies)? Are there some stages of the life cycle more appropriate to monitor than others (e.g., larvae)? What physical parameters would yield the most appropriate information about the environment in the least time at the least cost? Under the auspices of Conservation International, two biologists, Al Gentry and Ted Parker, developed the Rapid Assessment Program, which uses satellite imagery, aerial reconnaissance, and field surveys to develop an inventory of species in just a few weeks (Roberts, 1991). In addition, a panel of tropical scientists recommended that specific key plant and animal populations be surveyed prior to development activities in the tropics (National Research Council, 1982). These are good examples of approaches to this problem.

Durable, low-cost instrumentation is needed for environmental monitoring from temperature probes to current meters to animal collars that use satellite telemetry for tracking. The extent to which monitoring can be automated and equipment made durable and easy to use will determine its applicability in project management.

One way to reduce the loss of natural ecosystems is by restoring damaged systems, creating new systems, and enhancing existing systems. There have been several projects to create or restore wetlands. Others have successfully restored natural forest habitats. Experiments have been conducted on enhancement of marine ecosystems by building "artificial reefs." There is a great need to develop methods to restore, create, and enhance ecosystems and to strengthen the science base underlying them. This includes careful monitoring of projects and dissemination of the information, whether they succeed or fail. In some cases, such as wetlands, regulations are ahead of science. To support the national goal of "No Net Loss" of wetlands, regulators may require wetlands creation or restoration as a condition of permitting activities in wetlands. However, issuing a permit does not necessarily make it possible to create a functioning wetlands ecosystem. Generally, more funding agency support and more attention from the academic community are needed to support the emerging field of restoration ecology.

Environmental planning and management are not emphasized in academic curricula in ecology or engineering, the two major disciplines required to practice them. Courses in this subject should be available for majors in both of these disciplines. Few universities require classes in ecology for engineering students or engineering for ecologists. To achieve an environmentally compatible development, engineers must have a basic understanding of the environments in which they will be working and environmental scientists must learn some of the language and constraints of engineering. Sound environmental planning and management require the cooperative interaction of these disciplines. It would aid the process if this interaction began during the training of its practitioners. It is important to build a base of environmental planners and managers in all countries.

Industries and government agencies participating in the environmental planning and management process should also disseminate the information gained from development projects. The possibility of a central bibliographic database should be explored.

MOVING TOWARD SUSTAINABLE DEVELOPMENT

If there is a chance to preserve natural habitats and the biodiversity they support, it will not be enough to focus on creating parks and refuges and conducting biological Surveys. Parks and refuges are of value in that they preserve samples of diversity. Inventories are essential, but they document what is being lost while doing little to reverse the trend. A long-term solution to the problem requires that more attention be given to land that will be "used," that is, to develop methods that allow use of the land while maintaining its ecological integrity and functions. This area has not received much attention from the academic community or national funding agencies. Few "developers" (from slash-and-burn colonists in the rain forest to housing developers in the United States) have the resources to conduct the long-term studies required even to inventory the species that are Present, much less to gain a complete understanding of the systems in which the development will take Place. Yet ecologically based management methods must be applied if natural systems are to be maintained outside parks and preserves.

The following are examples of questions that need the attention of the research community and funding agencies.

Will undisturbed corridors in the midst of a development maintain the overall ecological integrity of the system? How large should corridors be? What configurations?

Which has less ecological impact overall, high-density or low-density housing? What are the ecological and social trade-offs?

What kinds of monitoring can best and most cost-effectively indicate when an activity is damaging an ecosystem? When is a damaged system "recovered?" Is it possible to determine when a "restored" system is self-sustaining?

How clean is "clean" in the ecological sense? For example, in cleaning up an oil spill, is ecological recovery faster if some oil is left in the environment rather than using extreme measures, such as high-pressure hot water, to remove it?

Are there methods to restore damaged or degraded habitats more effectively than natural recovery? Which methods are ineffective or actually increase damage or prolong recovery?

These questions identify areas of research and reporting that have "fallen through the cracks." They are not seen as part of the mission of any agency or funding group. Yet there is a great need to develop the science base in these areas that have practical and immediate application. To develop the methods requires the collaboration of environmental scientists and engineers, much the way in which AIOGC developed unconventional strategies for its Ecuador development project. One further element is required for implementation of sound environmental planning and management practices, a supportive regulatory framework.

DISCUSSION

The Villano Field oil discovery in Ecuador is requiring ARCO to become innovative in designing an exploration and development plan with the goal of minimizing environmental and social impacts. A key feature of ARCO's work in the area is that oil exploration was conducted and a plan was developed for oil production and transportation without construction of new roads and with a significantly reduced "footprint." Although operations have been conducted elsewhere without constructing roads to remote areas, the ARCO concept is a significant departure from conventional operations, with clear environmental and social benefits. By applying lessons learned from oil operations around the world and encouraging creative technical thinking, a plan is being developed which is operationally sound, cost-effective, and proven by application in an offshore environment. The plan is consistent with the environmental and cultural objectives of the company and the indigenous people in the area.

There is the broader question of whether to develop oil resources in Ecuador or in other rain forests. The fact is that oil development will occur in Ecuador; the country's economy depends on oil revenues. If ARCO does not produce the oil, some other company probably will do so by making use of conventional technology and practices now common in the area. The approach described in this paper is, in ARCO's view, a major advance in environmental protection that has application beyond the single project.

A major effort is needed to strengthen the science base as well as train and encourage scientists and engineers to practice the innovative thinking and collaboration required to implement sound environmental planning and management. Environmental scientists and engineers in the academic community must develop programs to promote this field. Industry scientists and engineers must be empowered to take risks and think unconventionally, since it is through them that most new ideas will be generated and applied in the field. Governments need to develop regulatory frameworks that support, rather than impede, this process. Supporting and encouraging sound environmental planning and management offers some hope that the ecological integrity and functions of natural systems may be maintained when development occurs.

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Lessons in Water Resource and Ecosystem Regulation from Florida's Everglades and California's Bay/Delta Estuary

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THE VALUE OF NEGOTIATED FLEXIBILITY

Secretary of the Interior Bruce Babbitt stated recently that the two most perplexing issues in water management in the United States were in Florida and California. He was referring to environmental controversies in the Everglades in southern Florida and California's San Francisco Bay/Sacramento-San Joaquin Delta (Bay/Delta).

Two main lessons emerge from events surrounding the Everglades and the Bay/Delta. First, regulations aimed at improving water quality and habitat are most effective when they embody an incremental approach with frequent evaluation and updates. Conversely, large-scale, irreversible, and sweeping programs tie the hands of resource managers and prevent new programs that can elicit the broad-based support necessary to sustain any long-term management strategy.

Second, negotiated understandings and agreements involving state and federal resource agencies and local stakeholder groups are effective ways to develop mutually acceptable solutions. Once resolution of such complex environmental matters becomes embroiled in litigation, it becomes extremely difficult to realize an adequate solution.

This paper first compares the geography and history of the Everglades and the Bay/Delta. It then examines the political and legal events surrounding the Everglades controversy and the lessons of those events for the Bay/Delta crisis and other resource management cases.

SIMILARITIES BETWEEN THE EVERGLADES AND THE BAY/DELTA

The Everglades and the Bay/Delta are strikingly similar in physical geography and social importance.

Florida's Everglades

The Everglades are a wetland ecosystem significantly altered by human development. In this ecosystem's natural state, water flowed southward from the Kissimmee chain of lakes along the meandering Kissimmee River into Lake Okeechobee, an expansive shallow-water lake in the south-central part of the Florida peninsula (Figure 1). When heavy summer rains occurred, Lake Okeechobee flooded, and the water drained southward in a "river of grass," 50 miles wide and 6 inches deep through the region called the Everglades. Weather-related changes in the water level of the lake created a complex ecosystem dependent on varying water flows (Mairson, 1994).

These naturally variant conditions, in part, created the need to pursue development projects in the Everglades from the early 1900s to the 1960s. Hurricane-induced flooding caused losses in human life and property, and extended droughts caused overdrafting of groundwater basins that provided water for cities and agriculture. In response, the state and federal government created an extensive flood control and water conveyance system (Light et al., 1989). They confined the Kissimmee River into a straight canal, diked Lake Okeechobee to prevent flooding, and reclaimed some 6 million acres of wetlands south of the lake, mostly for agriculture, by building canals and levees to funnel water toward the coast. After completion of the projects, all flows into Lake Okeechobee and the Everglades were controlled by gates and pumps. By 1953 five major canals totaling 440 miles existed in the area. The canals took water from the marshlands and diverted it for agricultural use or for groundwater recharge for later urban and agricultural pumping. The fertile, dark peat soils of the Everglades are prone to subsidence, and levees are required to protect the reclaimed land from flooding.

These projects, however, came at a high environmental cost. The reduced and confined flows into the Everglades and the high phosphorus levels in agricultural drainage degraded the natural ecosystem. Increased nutrient levels and modified water levels caused a monoculture of cattails to overcome native saw-grass in many areas. Water bird abundance has declined dramatically because of diminished habitat and the effect of reduced flow on the fish populations that provide the birds' food source (Light et al., 1989).

The importance of the Everglades in Florida's economy underscores the importance of maintaining the ecosystem in a condition that can satisfy the competing uses of its waters. Agricultural areas rely on canals for direct diversions and for recharging groundwater. Cities also draw their water supplies from

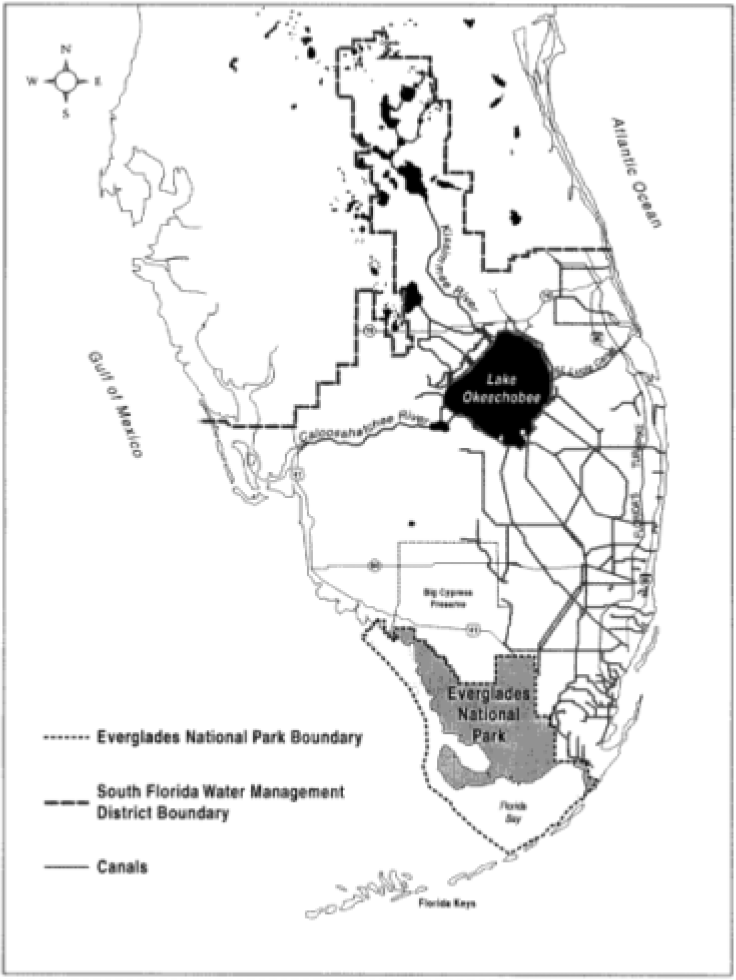

FIGURE 1 The Everglades. SOURCE: South Florida Water Management District.

aquifers fed by the canals, and the fish and wildlife of the Everglades depend on sufficient flows to sustain their critical habitats.

The San Francisco Bay/Sacramento-San Joaquin Delta

Like Florida's Everglades, the Bay/Delta in California is a stressed ecosystem that plays a vital role in the state's water resource and economic infrastructure (Figure 2). The Bay/Delta also is a complex water system altered significantly by human development.

Before development the confluence of the Sacramento and San Joaquin Rivers, along with numerous mountain tributaries, formed a massive inland marsh of 750,000 acres. Freshwater from upstream mixed with seawater entering with the tides from San Francisco Bay and the Pacific Ocean. Spanish explorers in the eighteenth century described the delta as a "sea of reeds." The shallow waters, foliage, and brackish quality of the water nurtured a rich fishery.

After the gold rush, settlers began reclamation projects to drain the marshlands for farming. They built canals to divert water from the reclaimed lands and levees to prevent flooding. By the tune this massive reclamation effort was completed in 1930, the landscape of the delta had completely changed. More than 500,000 acres had been enveloped by 1,100 miles of levees. The sea of reeds had become an island archipelago of some 70 islands encircled by more than 700 miles of rivers, sloughs, and channels. Most of these islands have supported agriculture, with corn as the most important crop, along with safflower, sugar beets, alfalfa, wheat, and others. The peat soils, similar to those in the Everglades, were susceptible to subsidence and flooding, so agriculture was and still is a risky enterprise (Schwarz, 1991).

Conditions in the delta required development of other water projects. Salinity levels in the delta historically varied greatly according to weather patterns, and during the severe drought years of the early 1930s, salt water reached all the way upstream to Sacramento and Stockton. Beginning in the late 1800s and throughout this century, water projects were built to control flooding, divert water from upstream tributaries, and export water for agricultural and urban use. The two largest reservoirs, Oroville and Shasta, retain water throughout the year, providing higher flows during the dry season and enabling water managers to control salinity intrusion into the delta. The State Water Project and federal Central Valley Project (two of the largest public works projects in the nation) include diversion facilities in the southern end of the delta to export water southward through the Delta Mendota Canal and California Aqueduct (Figure 3).

Today the Bay/Delta serves as the hub of California's water supply system. The federal and state water projects divert water from the delta into aqueducts that convey water southward into the San Joaquin Valley agricultural areas and then pump it 2,000 vertical feet over the Tehachapi Mountains into the urban communities and farms of southern California. The North Bay and South Bay

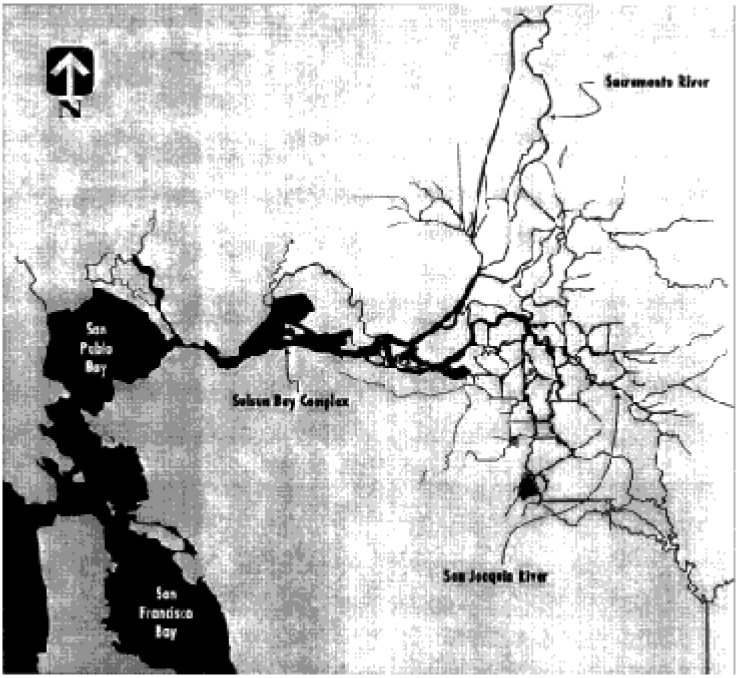

FIGURE 2 Delta waterways. SOURCE: California Department of Water Resources.

aqueducts serve urban users in the San Francisco Bay Area. In addition, riparian farmers in the delta divert water for irrigation, agricultural water districts in the Sacramento and San Joaquin river basins take water from the system, and the City of San Francisco and East Bay Municipal Utility District (serving Oakland and Berkeley) store and divert water upstream of the delta for urban use.

Like the Everglades, the Bay/Delta has experienced environmental problems in recent decades. Exports from the delta and upstream diversion primarily for agricultural use have reduced the amount of freshwater flowing through the delta and altered flow patterns through the channels, with negative effects on fish populations. Introduction of nonnative species, polluted agricultural runoff, poaching, local land-use changes, and droughts also contributed to the widespread decline of fish species in the Bay/Delta. The winter-run chinook salmon and delta smelt have been listed as endangered and threatened, respectively,

FIGURE 3 Major features of state water project and Central Valley project.

under the federal Endangered Species Act (ESA). These listings significantly constrain operation of the pumping facilities in the southern delta, as the pumps must shut down for significant periods to prevent entrainment of these fish. These periodic shutdowns have significantly decreased the reliability of supplies from the delta, jeopardizing water plans of agencies throughout California.[1]

California's water supply infrastructure is the backbone of the state's economy. Factors diminishing the reliability of the water supply, such as the environmental problems in the Bay/Delta, threaten California's economic future.[2] Therefore, there can be no distinction between protecting the environment and promoting California's economy in the case of the Bay/Delta. The two goals are inextricably linked, and developing an acceptable solution to the conflict will sustain both the resources and future economic activity.

THE EVERGLADES CONTROVERSY

Concerns over the ecological health of the Everglades led in 1970 to congressional legislation mandating minimum flows into Everglades National Park.[3] Although the park was unquestionably affected by the canals, levees, pumps, and water control structures that regulate flows into the area, it was unusual for Congress to micromanage such a complex ecosystem by legislatively mandating specific flow requirements. The results of this program were clearly detrimental to the environment. The timing and magnitude of flows were inappropriate, exaggerating natural extremes (Light et al., 1989). The ecosystem continued to decline, prompting an emotional public reaction that set the tone for future political and legal developments.

In retrospect, the inflexibility and sweeping character of the congressional requirements doomed the flow standards from the beginning. There were no built-in mechanisms for monitoring environmental effects of the standards or for modifying them to meet the demands of changing natural hydrologic conditions. This omission tied the hands of resource managers in the Everglades' highly dynamic, variable, and unpredictable ecosystem. In short, the program embodied the characteristics of ineffective environmental regulatory schemes—rigid standards that precluded appropriate ecological decision making.

The Role of the South Florida Water Management District

In 1983 severe high-water conditions in Everglades National Park eliminated the wading-bird nesting season, and the Everglades Research Center (part of the National Park Service) told the South Florida Water Management District (SFWMD) that an "ecological emergency" threatened the park. Later the Park Service asked for a comprehensive restoration plan including changes in flow distribution and intentional breaching of levees and filling in of canals to return flows to the approximate levels that existed before widespread development.

The Florida legislature had expanded SFWMD's duties from traditional flood control and water supply to include issuance of permits for certain types of water use, surface water and stormwater management, land acquisition for riverine habitat restoration, and water quality protection.[4] This new mission made SFWMD stewards of environmental uses, as well as water uses, and expanded its role in resolving the Everglades crisis.

In response to its new role in the controversy, SFWMD developed a two-pronged program to resolve the issue. The first part involved alternative dispute resolution (ADR), an approach to consensus building that seeks to identify common ground among various parties and to build agreements based on mutual interests. The other aspect of the program was SFWMD's iterative testing process (ITP), a progressive approach to resource management emphasizing incremental testing and evaluation of the effects of environmental regulation and active integration of ecological forces into the regulatory decision making process (Light et al., 1989).

Alternative Dispute Resolution

To break the gridlock that had precluded a mutually acceptable solution, SFWMD developed an approach involving negotiation and consensus building among groups having historically disparate interests, such as environmentalists and sugarcane growers. The District found that even amidst long-standing disputes with deeply entrenched positions, small but meaningful steps toward collaborative problem solving could take place. Good-faith negotiations, in turn, unlocked doors for much bolder and meaningful strategies based on increased understanding and attention to safeguards (Light et al., 1989).

The District's commitment to ADR required expenditure of much energy on outreach and required that technical findings be made available for scrutiny by others. In the long run, this fostered greater trust and respect for the District's abilities and intentions. For example, SFWMD avoided litigation with farmers who, contending that the risk of flooding was too great, protested SFWMD's plan to modify flow patterns around Everglades National Park. Using ADR methods, the District negotiated an agreement with the farmers whereby the District operated short-term test-diversions to monitor effects on flood risk. This experience suggests that taking small steps, such as experimental testing, can pave the way for more ambitious future programs by minimizing the perceived risk to interested parties who might feel threatened by new and innovative approaches.

Iterative Testing Process

The District recognized that water management interventions in the Everglades over the past 80 years (for both development and environmental purposes) had been too sweeping and rigid and failed to integrate ecological processes. As a result, these decisions contributed to the degradation of the Everglades' resources. The District sought an alternative to the traditional water planning approach, which had few built-in mechanisms for remedial action. The Everglades case needed an approach to water management that fostered testing of policies and technical measures on a scale sufficient to be highly informative, while limiting environmental risks.

The District developed ITP as a new approach to water management (Light et al., 1989). The key to this new approach was incremental changes followed by systematic testing and analysis to gauge environmental responses to those changes. This feedback would guide the next resource management decision, permitting the modifications necessary to achieve the ecological objective. One salient feature of this approach is the integration of ecological processes into decision making. Making incremental changes and modifications enables scientists to see how natural processes affect and react to environmental modifications. By permitting natural response mechanisms to guide and calibrate the water management measures in this way, latent and healthy ecological patterns can emerge.[5] Unfortunately, the District's ITP programs were not able to come into full effect because of litigation that drastically affected the water management process in the Everglades.

Litigation Developments

Beginning in October 1988, a major lawsuit and associated settlement negotiations dominated the Everglades debate. In that month, the U.S. Justice Department sued SFWMD to enforce state water quality standards. The Justice Department filed suit in federal court under state law rather than federal law, because the Federal Clean Water Act did not apply to polluted runoff from farming operations that were discharging phosphorus into the Everglades through a federal water project facility.

The water quality standards that SFWMD was responsible for enforcing were narrative, or nonnumeric. The law stated that concentrations of nutrients, such as phosphorus, must cause "no imbalance in the flora or fauna" of the region. There always had been controversy surrounding how to translate this narrative standard into numerical ones and whether the standards were working.

After the lawsuit was initiated, Florida's new governor, Lawton Chiles, entered federal court and declared, "We want to surrender. I am here. I have brought my sword. Who do I give it to?" (Palm Beach Post, 1994). In July 1991 the state and federal governments reached a settlement agreement that included conversion of some farmlands into marshes to filter out phosphorus and establishment of phosphorus reduction targets. The estimated cost of the program was $465 million.

Certain aspects of the agreement embodied principles of the iterative testing process, as discussed above. The agreement stipulated that a panel of scientists would determine numerical interpretations of the narrative phosphorus criteria. This interpretation would become the temporary "numerical standard." The panel would evaluate the results and suggest adjustments based on the monitoring data. The agreement attempted to represent the incremental, flexible, and systematic approach SFWMD had been advocating.

Again, however, litigation delayed implementation of the new approach. Sugarcane growers challenged the legality of the agreement, contending that the federal government was illegally interfering with the state's sovereignty over water issues. In the summer of 1993, Secretary Babbitt announced a framework agreement between two of the three major sugar firms regarding the allocation of restoration costs. One of those firms broke off talks with the Interior Department in December 1993.

Recent Developments

In May 1994 the Florida Supreme Court overturned a ballot initiative that sought to levy a one-cent-per-pound tax on raw sugar and to use the proceeds for an Everglades restoration trust. The court ruled that the initiative violated the "single-subject rule" because the restoration trust would have performed functions of legislative, executive, and judicial branches, in violation of the Florida constitution. In addition, the court ruled that the title and summary of the measure were misleading.[6]

At the time of this writing, the Florida legislature had just passed the Everglades Forever Act, a comprehensive program for restoring the Everglades ecosystem.[7] While the timing of the passage of the act prevents detailed treatment here, it is possible to summarize some of the more important provisions. The act will generate more than $700 million over 20 years (more than $300 million from agriculture) for various activities aimed at improving water quality and water supply throughout the historic Everglades, including Lake Okeechobee, the agricultural areas in the region, Everglades National Park, and urbanized areas of the southeast coast.

The Everglades Forever Act seeks to improve water quality through increased inflows to the "protected areas" of the Everglades, an ambitious research and monitoring program, directions to the state Department of Environmental Protection to establish new phosphorus criteria before the year 2003, and establishing time lines for construction of new stormwater treatment areas. The financing for these programs will come primarily from a tax on agricultural lands (ranging from about $25 per acre annually in 1994 to $35 in 2013) and an increase in property taxes in the 15 counties that make up the Everglades region.[8]

Lessons from the Everglades Controversy

The Everglades controversy provides several lessons in the institutional aspects of water resource management. The unique geography of the Everglades and its history of human modifications suggest that regulatory programs should adopt an incremental, flexible, and monitored approach as embodied by SFWMD's iterative testing process. The Everglades controversy also demonstrates that ambitious negotiation programs provide the best hope for finding a workable solution that is acceptable, at least in part, to all interests. After the litigation process began to drive the Everglades dispute, resource managers and others lost the ability to fashion creative solutions.

THE BAY/DELTA CRISIS

In California, the State Water Resources Control Board (State Board) is the agency with primary authority over water quality and water allocation. As such, the State Board is responsible for formulating water quality plans and for regulating rights to the use of waters of the Bay/Delta. The State Board also has the duty to protect uses of water for agriculture, cities, and fish and wildlife.

Two key regulatory parameters for protection of the Bay/Delta's beneficial uses are flow and salinity. The two are interrelated, because the timing and magnitude of freshwater flows can affect salinity levels at various locations in the Delta. In 1978 the State Board adopted a Water Quality Control Plan as required by the federal Clean Water Act (CWA) and also adopted a water rights decision under state law to implement the plan. The State Board's water rights decision (Decision 1485) included flow and salinity requirements and focused regulations solely on the State Water Project and the federal Central Valley Project.

As generally required by the CWA, the U.S. Environmental Protection Agency (EPA) reviewed the Water Quality Control Plan for approval and conditioned its approval on commitments from the State Board to improve aspects of Decision 1485 for fish and wildlife if fishery declines indicated a necessity. When the striped bass population declined in the late 1970s and early 1980s, the State Board took no significant actions in response to EPA's request.

The Water Quality Control Plan and Decision 1485 also received intense scrutiny under state law in state court. The *Racanelli* decision in 1986 by a state appellate court declared parts of the State Board's 1978 plan invalid, ruling among other things, that the plan failed to consider the role of all Bay/Delta watershed diverters, focusing instead only on the State Water Project and the Central Valley Project.[9] The State Board adopted a revised Water Quality Control Plan in 1991, but EPA disapproved it, claiming that changes made from the 1978 plan were inadequate.

In the fall of 1992, President Bush signed into law the Central Valley Project Improvement Act, which requires a significant portion (800,000 acre-feet per year from the project's approximate annual yield of 7 million acre-feet) of the Central Valley Project's water supply yield to go toward fisheries restoration, possibly including increased flows through the delta.[10] The act also levies fees on users within the project's service area, with the proceeds used to finance an ambitious fisheries habitat restoration program.[11]

In response to a request from Governor Pete Wilson, the State Board in December 1992 released draft water rights Decision 1630, which was intended to provide "interim" standards for protection of the beneficial uses of the Bay/Delta, with particular attention to fisheries protection. Draft Decision 1630, if adopted, would have affected most Bay/Delta watershed users and included extensive flow and salinity requirements designed to protect fish and their habitats. In a historic shift of positions, urban water agencies throughout northern and southern California supported the environmental objectives of the proposal, while suggesting modifications in the proposed regulations. This change was significant because prior to that time, water agencies in northern and southern California rarely adopted the same positions on issues such as Bay/Delta standards. To the contrary, southern California water agencies along with San Joaquin Valley agricultural water districts had traditionally fought with agencies in northern California.

Governor Wilson requested the State Board on April 1, 1993, to stop work on draft Decision 1630, claiming that federal involvement in the Bay/Delta through enforcement of the Endangered Species Act made state action "irrelevant."[12]

EPA's Proposed Standards

In response to the State Board's action on draft Decision 1630, the EPA proposed a set of standards in January 1994, claiming federal authority under the CWA.[13] The EPA proposal contained a salinity intrusion standard mandating a fixed number of days for meeting a 2 part-per-thousand salinity level at various locations in the Bay/Delta estuary from February through June. EPA reached this formula from statistical analysis of past hydrologic conditions, intending to recreate conditions as they existed in the late 1960s and early 1970s (before significant levels of State Water Project exports from the southern delta and a period that EPA believes had good habitat conditions for fisheries).

Although generally supportive of Bay/Delta standards that are more protective of fisheries, urban water agencies in northern and southern California objected to EPA's specific proposal on several grounds: (1) the standard was unduly rigid and failed to include mechanisms for properly responding to changes in precipitation and runoff within the year; (2) the plan, at times, would have placed the optimum salinity conditions for fisheries too far downstream from the most productive habitat zones; (3) the proposal lacked mechanisms for biological evaluation to accommodate adjustments to the standard based on measured re-suits; and (4) legal questions existed regarding EPA's authority to adopt and implement the type of standards proposed.

Urban agencies invested substantial resources in analyzing EPA's proposal, and attempted to produce an alternative that could better meet environmental objectives of the EPA proposal. As a result of extensive studies by technical consultants and others, the urban agencies concluded that environmental objectives of the proposal could be met at a lower water cost. These studies formed the basis of an "Urban Alternative" to EPA's proposal, sponsored by a coalition of northern and southern California urban water agencies.

"The Urban Alternative"

The alternative proposed by urban water agencies improves on EPA's proposal by providing flexibility, monitoring, and a foundation for realizing long-term solutions to the Bay/Delta problem. EPA's proposed salinity standard failed to account adequately for changing runoff patterns within the year. In contrast, the Urban Alternative contains a sliding-scale methodology to permit the standard to update itself periodically within the year to ensure that the regulation responds to natural variations of hydrologic conditions. This approach is similar to the iterative testing process in Florida in that the standard would incorporate natural ecological functions to guide regulatory decision making.

The Urban Alternative also includes biological monitoring and evaluation, which EPA's proposal lacked. As discussed earlier, a systematic, incremental plan for resource management requires monitoring to gauge effects of the standard on the environment. The Urban Alternative would require extensive biological evaluation so that the standards could be updated periodically.

Long-Term Solutions

Immediate standards for the Bay/Delta are only the first step in resolving the larger Bay/Delta issues, and the urban group advocates establishing a process for determining these long-term solutions. The preferred approach would include consideration of the ecosystem as a whole, using multispecies, habitat-wide approaches instead of the single-species approach under the Endangered Species Act, which lacks flexibility and balance. Long-term analysis and solutions also would take into account factors other than delta exports and diversions that have contributed to fisheries declines, including drought, agricultural runoff, introduced nonnative species, and poaching. Finally, an environmental decision making process must take place to evaluate water management alternatives to improve methods by which water is conveyed through and diverted from the delta.

CONCLUSION

Experiences in the Everglades have much to teach resource managers about institutional aspects of water regulation in a complex ecosystem. Flexible and incremental approaches are far superior to rigid regulatory schemes that too often have prevailed. Negotiated agreements, which require creativity and scientific determinations that the judicial system often cannot deliver, are far superior to court battles for making resource management decisions.

These principles apply equally to the current controversy in California's Bay/Delta. A group of urban water agencies from northern and southern California has proposed an approach that incorporates characteristics of effective regulatory processes. Because of the logical and scientific bases of this alternative and the urban agencies' efforts to consult with political leaders and technical staff of the regulatory agencies, there is hope that mistakes made in the Everglades will not repeat themselves in California.

Notes

1. See "Joint Effort Holds Out Hope for California Water," Standard & Poor's Creditweek Municipal, March 21, 1994, p. 112: "Probably the most far reaching action affecting water resources management in California in the past decade was the listing of the winter-run Chinook Salmon and the Delta Smelt, combined with the biological opinions that followed. The restrictions placed on water project operations contained in the biological opinions have immediate and future consequences on delta water export capability."

2. *Idem*: "The allocation of water supplies for consumption in California remains in gridlock as both federal and state legislators try to achieve a workable solution to the conflicting interests in the delta.... Problems faced by California water suppliers will have a generally negative impact on credit quality for years to come due to the economic impact and rising costs associated with water supply and reliability."

3. Public Law 91-28, River Basin Monetary Authorization and Miscellaneous Civil Works Amendments, Section 2: "[D]elivery of water from the central and southern Florida project to the Everglades National Park shall be not less than 315,000 acre-feet annually ... or 16.5 per centum of total deliveries from the project for all purposes including the park, whichever is less."

4. Water Resources Act of 1972, Chapter 72-299, Florida Statutes, 1972.

5. The Domenigoni Valley Reservoir Project in Southern California is another example of iterative processes for environmental management. The Metropolitan Water District of Southern California, in conjunction with several state and federal agencies, manages a 9,000-acre ecological reserve in conjunction with the Project. Biological managers evaluate incremental changes in habitat conditions, and make adjustments to protect the ecosystem supporting sixteen species that are candidates for listing under the Endangered Species Act.

6. In re. Advisory Opinion to the Attorney General—Save Our Everglades Trust Fund, 19 Florida Law Weekly S276, 1994.

7. Everglades Forever Act, 1994 Fla. Sess. Law Serv. 115 (West), amending Section 373.4592, Florida Statutes.

8. Section 373.4592(6), Florida Statutes.

9. See United States v. State Water Resources Control Board, 182 Cal. App. 3d 82 (1986). The popular name for the case derives from the appeals court jurist who wrote the opinion, Judge John T. Racanelli.

10. See Public Law 102-575, Title XXXIV, Section 3406(b)(2).

11. See Public Law 102-575, Title XXXIV, Section 3407(d)(2)(A).

12. See letter from Governor Pete Wilson to chairman of the State Water Resources Control Board, April 1, 1993 (Sacramento Bee, April 2, 1993).

13. Environmental Protection Agency, Proposed Rule: Water Quality Standards for Surface Waters of the Sacramento River, San Joaquin River, and San Francisco Bay and Delta of the State of California. *Federal Register* Vol. 59, No. 4, p. 810, January 6, 1994.

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Engineering Studies Based on Ecological Criteria

Hsieh Wen Shen

GOALS IN RIVER ENGINEERING

Decades ago, hydropower plants were considered the most environmentally sound means of generating electricity because they produce neither smoke nor nuclear waste. Gradually, however, the ecological consequences of dams and other river modifications have become appreciated. In particular, the environmental impact of the Aswan Dam in Egypt raised many concerns with regard to hydropower development. Gradually we learned the need to live in harmony with our environment. Streams are not just conduits for supplying water for human needs; they are also communities of species. This paper discusses the general goal of attempts to improve the ecological properties of rivers, describes alternative specific objectives, and reviews two Cases that provide insights into the potential for collaboration between ecologists and engineers.

The general goal for ecological development in a stream is to achieve a sustainable condition so that human beings can live in harmony with their environment. The World Commission on Environment and Development (known popularly as the Brundtland Commission) defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission, 1987). Many international and national organizations, including the United Nations, UNESCO, World Bank, and the Earth Council have held meetings to discuss various concepts of sustainable development and sustainability indicators. In general, ecologists treat "sustainability" as preservation of the natural function and status of the ecological system, whereas economists emphasize the maintenance and improvement of *human living standards* as indices for sustainability.

Two key questions arise:

1. How much should we emphasize human interests in defining ecological goals?
2. How do we define and achieve sustainability in the ecological aspects of stream systems?

No precise answer can be given for either of these questions. When human interests conflict with those of another species, one must judge the appropriate goal and approach for each problem. Sustainability with regard to stream ecology is also difficult to define. Maintenance may be required to sustain certain aspects of streams. The following examples may be instructive.

ALTERNATIVE OBJECTIVES

It is possible to distinguish four alternative objectives for projects intended to improve ecological conditions in streams and rivers.

1. *Restore to natural condition or a selected previous condition.* Ecological processes are dynamic. Some processes are known now and others may not be known now or ever. Ideally, one wishes to enhance ecological conditions to satisfy future needs, but unfortunately this is difficult to achieve, especially for diverse collections of species. A common approach is to attempt to restore a river basin to a natural or previous condition. It is assumed that if the future hydrological condition is the same as that of the selected previous condition, then the majority of the ecological criteria will be satisfied. It is generally not feasible to return a particular stream in the United States to its condition during pre-Columbian time. Rather one is more likely to achieve success by returning the stream to a more recent condition. This general approach is particularly attractive when directed at diverse biological communities. In this approach, one must investigate the previous conditions such as the frequency and the extent of flooding and the ranges of various flow parameters such as flow depths and flow velocity. The case study on the Kissimmee River is a good example of this approach.
2. *Achieve certain specific ecological criteria.* If the ecological criteria for certain species can be determined, then an alternative is to restore or maintain the river basin according to their specific needs, such as flow parameters required by different life stages, the magnitude and frequency of flooding, acceptable levels of sediment in the flow, and various water quality limits. A great deal of research is needed to understand the ecological criteria for many ecological elements under various hydrologic conditions. The case study of the Niobrara River (below) is a good example of this approach.
3. *Maintain stable streams*. The third, less satisfactory alternative is simply to design a stable stream system. This may or may not satisfy various ecological

criteria. A dynamic stream may be more suitable in a dynamic ecological evolution.

4. *Follow a combination approach*. Often, the restoration of a river basin to its natural condition must include considerations of both ecological criteria and the stability of the streams such that the three preceding approaches must be combined.

Regardless of the particular objective, successful enhancement of a stream will usually require integrated efforts by specialists from many fields. Public involvement is also critical. The following case studies demonstrate the importance of cross-disciplinary collaboration and public involvement.

Kissimmee River Restoration Studies

The channelization project in the Lower Kissimmee River Basin, Florida, resulted in severe losses of river floodplain wetlands and waterfowl populations throughout the river valley. An earthen channel, the C-38 canal, is the main element of this project. Immediately after project completion in 1971, a strong effort was initiated to restore this basin to its prechannelization status. This large Kissimmee River restoration project, when it is completed, will be a milestone in our journey toward ecological harmony because the only major goal of the project is ecological enhancement. In 1986 engineers and scientists from the University of California, Berkeley, working with the South Florida Water Management District, developed a set of restoration options. Ecological goals for the restoration plans were formulated. Alternative restoration plans were evaluated for their potential to satisfy the ecological goals. Analyses were based on a combination of field data, physical modeling, and numerical modeling. Finally, backfilling of certain reaches of canal C-38 was recommended. Details of this study are provided in Shen et al. (1994).

In most rivers, the ecological environment is the result of long-term adjustments by countless complex factors. Many of these factors and their interrelated processes are extremely difficult, if not impossible, to define. Thus, ecologists stress the need to restore a river basin to natural conditions after the occurrence of man-made changes. Unfortunately, in the Kissimmee River Basin, human activities have changed the upstream conditions so much that the level of Lake Kissimmee cannot be allowed to fluctuate as much as it did before channelization. Thus, it is necessary to establish a set of ecological criteria as the targets for restoration, rather than attempt to recreate prechannelization conditions. Alternative restoration plans must then be rated on the basis of their likelihood to achieve these criteria.

As in many other restoration projects, it is difficult to establish generally accepted ecological criteria because people representing various concerns stress different ecological goals. Conflicting requirements may even be proposed by the same group of people. Thus, the first task in our study of the Kissimmee River restoration was to search for a set of ecological criteria. These criteria must be ecologically justifiable and feasible, because if they are too restrictive then all feasible alternative measures can be eliminated. After many site visits, the principal investigator gradually satisfied the various interest groups that the study was sincerely searching for the most feasible plan for ecological restoration of the Kissimmee River. A symposium, suggested by the team and organized by the South Florida Water Management District, was held at Orlando in October 1988 to discuss various ecological and engineering concerns. This symposium was designed to focus on the restoration of the Kissimmee River ecosystem as a whole rather than individual species. A set of ecological restoration criteria was established. Their details will be discussed later. In essence, restoration requires that the floodplain receive flow relatively frequently to serve as a wetland. Also, floodwaters should return to the original river system slowly. These ecological criteria must be satisfied while simultaneously meeting independent constraints for flood control, navigation, and sedimentation. The main engineering approaches were to divert flows to the river's original course and its floodplain by blocking the C-38 canal with hydraulic structures such as weirs and earth plugs. Backfilling part of the canal was also considered.

The primary criterion for achieving environmental restoration goals is the reestablishment of prechannelization hydrology. Key characteristics of prechannelization hydrology were discussed in several papers presented at the Kissimmee River Symposium (Loftin et al., 1990). Critical hydrologic determinants of prechannelization ecological integrity were reduced to a form that could be used to compare alternative restoration plans. Key hydrologic criteria are given below.

1. *Continuous flow with duration and variability comparable to prechannelization records*. Historical data indicate that continuous discharge was a critical factor in the evolution and maintenance of biological communities in the prechannelization Kissimmee River ecosystem. Restoring the integrity of the Kissimmee River ecosystem depends on reestablishing the range of discharges of appropriate duration during representative (e.g., 10-year) postrestoration periods. Sheri et al. (1994) described the monthly discharge variations. The flow discharge characteristics thought to be necessary to restore biological communities that existed before channelization are (a) continuous flow from July through October, (b) highest discharges in September through November and lowest flows in March through May, and (c) a wide range of discharge variability. These features should maintain favorable levels of dissolved oxygen during summer and fall, provide nondisruptive flows for fish species during their spring reproductive period, and restore the temporal and spatial heterogeneity of river channel habitat.
2. *Average flow velocities between 0.24 and 0.55 meter per second (mps)*

when flows are contained within the river channel. Specifically, flow velocities within 60 percent of river channel cross sections must not fall below 0.24 mps for more than three consecutive days during July-September and 10 consecutive days during October-June. These velocities complement the discharge criteria by protecting river biota, because too little flow results in low concentrations of dissolved oxygen and excessive flow could interfere with important biological functions (e.g., feeding and reproduction of fish).

3. *Overbank flow along most of the floodplain when discharges exceed 40-57 cubic meters per second*. This criterion reinforces and will reestablish important physical, chemical, and biological interactions between the river and its floodplain.
4. *Slow flood recession rates*. A flood recession rate of less than 0.3 meter per month is required to restore the diversity and functional utility of floodplain/ wetlands, foster sustained river/floodplain interactions, and maintain river quality. Slow drainage is particularly important during biologically significant periods, such as the nesting season for wading birds. Rapid recession rates (e.g., rates that will drain most of the floodplain in less than a week) lead to fish kills and thus are not compatible with ecosystem restoration.
5. *Floodplain inundation frequencies comparable to prechannelization hydrology, including seasonal and long-term variability characteristics*. Shen et al. (1994) shows the prechannelization inundation frequencies for the floodplain adjacent to the Fort Kissimmee gauging station and provides guidelines for this criterion. For example, during a representative 10-year period, November stages should inundate 100 percent of the floodplain during 4 of the 10 years and 75 percent of the floodplain during 7 of the 10 years. When the entire floodplain is inundated, depths along the periphery of the floodplain should measure between 0.3 and 0.6 meter. These inundation levels will lead to redevelopment of floodplain structure and function and reestablish the floodplain as an integral component of the Kissimmee River ecosystem. Ecologically, the most important features of stage criteria are water level fluctuations that lead to seasonal wet-dry cycles along the Periphery of the floodplain, while the remainder (approximately 75 percent) of the floodplain is exposed to only intermittent drying periods that vary in timing, duration, and spatial extent. As stated in Loftin et al. (1990, p. 26):

> Reestablishment of ecological integrity requires that *all* restoration criteria are met *simultaneously*. A piecemeal restoration program in which some of the established restoration criteria are achieved in one segment of the system, and other criteria are met in another portion, will not accomplish restoration goals and may be of little or no value. Game fish populations, for example, may still be limited if appropriate flow characteristics are restored but production of potential food resources on the floodplain is limited by inadequate inundation, or inaccessibility to river fish because levees or berms block the connectivity (interaction) between the river and floodplain. Alternatively, restoration of

> floodplain inundation frequencies and the prechannelization stage-discharge relationship probably would not benefit game fish species unless enough flow is reestablished to improve dissolved oxygen regimes in the river during summer and fall. Similarly, water level fluctuations in broadleaf marshes on the floodplain will be of no value to wading birds if reestablishment of peripheral wet prairie habitat is restricted or precluded by rapid stage recession rates.

Three alternative restoration plans have been selected by the District for analysis. In the Fixed Weir Plan, 10 weirs would be installed along the canal to divert flows into the river oxbows adjacent to the weirs. In the Level I Backfill Plan, the same canal reaches in which weirs would be installed in the Weir Plan would be completely backfilled between the two junctions with the oxbows. In the Level II Backfill Plan a specific, long, continuous canal reach would be backfilled. New river reaches would be created to maintain a continuous river reach with the same canal backfill reach.

Fixed Weir Plan: The advantage of using weirs is their flexibility in operation. Gated weirs can be opened during floods to decrease the need for flood levees or additional flooding fights.

During high floods the oxbow flow velocities would be between 2 and 3 mps. These velocities would cause erosion and deposition of sediments in the river oxbow reaches and could interrupt navigation. Channel maintenance probably would be needed after major floods.

Approximately 40-50 percent of the oxbow length (revitalized river channels) adjacent to the weirs would have flow velocities within the ecologically acceptable range of 0.24 to 0.55 mps. These oxbows were part of the active river system before the construction of C-38 canal. However, many more reaches would have velocities greater than 0.55 mps (with maxima on the order of 1.5 mps) than below 0.24 mps. About 26 kilometers of banks (revitalized river channels) would be inundated at flow discharges of 40 cubic meters per second at the entrance of the river and 57 cubic meters per second at the downstream end of the river. About half of this inundation length would occur at oxbows. Several existing control structures in the river, together with their levees, can control the recession rates in the lower 40 percent of the pools. However, the stage recession rate after floods, in at least 60 percent of all upper reaches of pools, would far exceed 0.3 meter per month. These rates could even reach 0.3 meter in a six-hour period. Complex flow operation schemes might be devised to control both inflows and outflows from each pool to reduce the recession rate.

Level I Backfill Plan: For this plan, during high floods, the oxbow flow velocities would vary between 1.5 and 2.1 mps. These velocities would cause erosion and deposition in the oxbows. During normal flows, between 18 and 33 percent of the oxbow velocities would be in the range of 0.24 to 0.55 mps. Except for periods of low flows, more flow velocities would be above 0.55 mps (with maxima on the order of 1.5 mps) than below 0.24 mps. About 16 kilometers of banks (in revitalized river channels) would be inundated for flow discharges of 40 cubic meters per second at the entrance of the river and 57 cubic meters per second at the exit end of the river. All internal control structures together with their levees can only control the recession for the bottom 40 percent of the respective pools. At the upper 60 percent, the stage recession rate after floods would far exceed 0.3 meter per month. It is nearly impossible to design complex flow operation schemes to control both inflows and outflows from each pool to reduce the recession rate because the capacity for flood flow under this plan would be greatly reduced by the earth plugs blocking the canal. The amount of time that given proportions of the floodplain would be inundated under this plan is slightly less than would be inundated under the Fixed Weir Plan, and these values are far from meeting the requirements for ecological restoration.

Level II Backfill Plan: The Level II Backfill Plan should produce flow velocity ranges close to the ecological criteria if the future precipitation regime matches the precanal conditions and the flow regulation scheme can be properly designed. Historical data suggest that the flow properties of the Kissimmee River were similar in 1901 and 1958. In addition there was no detectable change in the river's course. During high floods, the oxbow flow velocities would vary between 1 and 1.3 mps and probably would not interrupt navigation. During normal flows, in 40 to 52 percent of the lengths of the oxbows, the flow velocities would be in the range from 0.24 to 0.55 mps, and in very few oxbows would the velocities exceed 0.55 mps. The flow velocity in all oxbows would be below 0.76 mps.

Upper lake level flood control capacity should be provided by leaving a portion of the Canal C-38 intact in the upper reach. Perhaps the best approach in this plan is to completely backfill part of the river reach. This should satisfy the flood criterion for Lake Kissimmee upstream from the Kissimmee River. Sedimentation problems can be investigated with a careful monitoring system. If significant movement of sediment occurs, appropriate actions should be taken. Construction would be carried out in several stages over several years. The extent of backfilling would be governed by the amount of available funding, available soil, the extent of the vegetation growth, and the possible relaxation of the water level constraint at Lake Kissimmee during flooding.

Field tests should be conducted at different times to monitor growth of vegetation. Knowledge of vegetation growth should be useful both to protect against erosion and to analyze hydraulic resistance. The data collected in the field during future years would determine the exact extent of backfilling.

A certain amount of dredging in the oxbows may be needed. In the Level II Backfill Plan, bank erosion and sediment deposition would be limited. Only a small amount of maintenance dredging in the oxbows may be needed after major flooding.

It is recommended that one type of plan be selected by the District from the three plans for final engineering design and construction analysis. Certain detailed engineering analyses such as the extent and sequence of the backfilling, as well as the number and location of earth plugs, or weirs, are still needed. The possible effects of each tributary (slough) during flooding should also be investigated. Currently sufficient data are not available to make these analyses.

In accordance with the study team's recommendations, the state of Florida has requested funding from the U.S. Congress. At the direction of Congress, the U.S. Army Corps of Engineers, Jacksonville District, has investigated the team's work and converted it into an engineering feasibility project, which is awaiting further federal funding.

Niobrara Whooping Crane Studies

The U.S. Bureau of Reclamation planned to construct a water supply dam on a braided section of the Niobrara River near Norden, Nebraska. The primary objective was to supply irrigation water for local farmers. This plan was stopped by the courts after the U.S. Fish and Wildlife Service pointed out that whooping cranes, an endangered species, stop at that reach of the Niobrara River during their migration seasons. I was asked to develop an engineering design compatible with the requirements of the cranes. Because there are only about 100 whooping cranes, it is difficult to determine their ecological requirements, but they are believed to be similar to those of the sandhill cranes. Sandhill cranes prefer to rest on sandbars that are submerged by less than 0.2 meter of slow-flowing water amid vegetation shorter than 0.9 meter, and away from riverbanks. These conditions are required to enable the birds to forage and evade predators. Based on these requirements, we determined that the braided feature (a river reach with multiple anastomosing channels) was critical to provide shallow, vegetated sandbars at sufficient distance from the riverbanks.

We identified the flushing flow requirements necessary to maintain the braided stream. Certain portions of the stream below the proposed Norden Dam would be unavoidably changed from braided to meandering by the release of flows with relatively small amounts of sediment particles from the reservoir. We planned to maintain the braided characteristic of the river farther downstream by regulating the flow, controlling vegetation growth, and even breaking the ice jams that form annually. We reported our conclusions to both the Bureau of Reclamation engineers and Fish and Wildlife Service biologists. After the conclusion of our study, we were pleased to learn that the Fish and Wildlife Service agreed to withdraw its objection to the construction of the dam if the Bureau of Reclamation would follow our recommended flow release plans. The Bureau of Reclamation agreed to follow our recommendations. In the end the dam was never built because of a lack of funding. Like the Kissimmee Restoration Project, this study indicated that engineers and biologists can work together, and engineers can provide plans to satisfy ecological needs.

FUTURE NEEDS

These two cases demonstrate the need for integrated efforts between engineers and ecologists to enhance our river management. We should seek to increase communication, conferences, and joint research across various disciplines. Every effort should be made for river engineers and stream ecologists to achieve a basic knowledge of each other's fields.

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"Do No Harm": A New Philosophy for Reconciling Engineering and Ecology

David J. Schaeffer

THE UPPER MISSISSIPPI RIVER AND ILLINOIS WATERWAY SYSTEM

The Upper Mississippi River (UMR) and the Illinois Waterway[1] (IWW) are important shipping arteries comprising 1,250 navigable miles that drain 697,000 square miles (Figure 1). Between 1960 and 1990, commerce on the UMR increased from 27 million to 91 million tons per year and IWW shipping doubled to 46 million tons per year. This navigation system (UMR-IWWS) includes 37 lock sites and more than 360 terminals. The projected average annual growth in shipping is between 1.7 and 3.1 percent for the UMR and between 1.2 and 2.5 percent for the IWW. However, most locks were designed to accommodate only a small fraction of the current traffic, and their 600-foot length is half that of many of the tows (U.S. Army Corps of Engineers, 1991), which requires that the barges be unlashed and sent through in smaller groups.

To ensure adequate navigation capacity on the UMR-IWWS through 2050, the U.S. Army Corps of Engineers proposes to spend several billion dollars renovating 27 locks on the UMR and 8 locks on the IWW. The proposed increases in navigation capacity are highly controversial.

OPPOSING PHILOSOPHIES

The controversy results from deep historical conflicts between the Corps with its production-based philosophy and various federal, state, and nongovernmental organizations with conservation-based philosophies (Leopold, 1949; Stone, 1974). The production-based philosophy is a short-term view (less than a

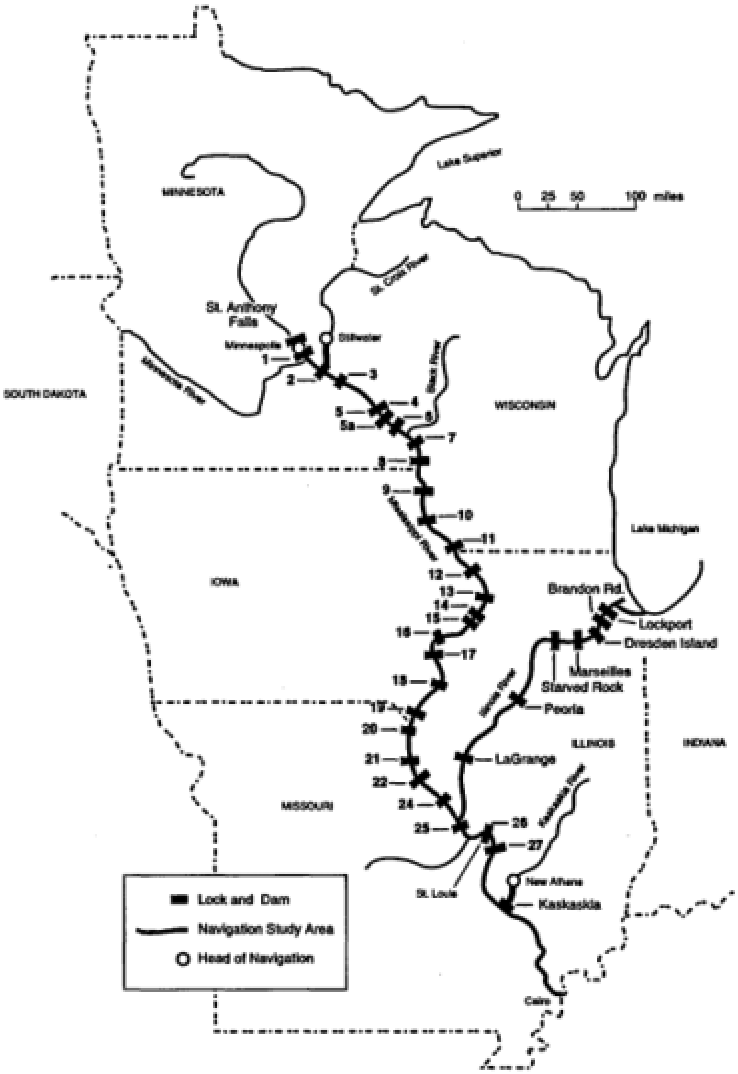

FIGURE 1 Upper Mississippi River and Illinois Waterway navigation system.

century): the *purpose of resources* is be used to their fullest by humans, with minimal regard to other users (i.e., species) or abiotic components of the ecological system. The conservation-based philosophy, as discussed in this paper, is a long-term view (centuries to millennia): the *purpose of ecosystems* is to provide numerous biological and abiotic resources on a sustainable basis. (The production-based philosophy has dominated for two centuries the statutes that govern resource use in the United States, but statutes are increasingly conservation-based.)

While Chief of Engineers, General Henry J. Hatch brought these philosophies together when he declared the U.S. Army Corps of Engineers to be the nation's *environmental* engineers. These philosophies are brought together *in law* by the National Environmental Policy Act (NEPA).[2] Disagreement regarding the appropriate philosophical balance in practice is at the heart of the conflict between conservationist decision makers outside the Corps of Engineers and decision makers in the Corps. The former believe that the Corps is not considering all significant effects of river navigation on the ecological systems.

Environmental management has a variety of objectives, including preservation, infrastructure maintenance, and biological diversity, and a variety of human uses, including income production, life support, recreation, and aesthetics. Achieving these objectives over the long-term requires sustainability of the underlying ecosystem (Costanza, in this volume; Costanza et al., 1992; Cox et al., 1993b; Rapport et al., 1985; Schaeffer, 1991; Schaeffer et al., 1988). Progress depends on striking an appropriate balance among the various goals, using environmental resources efficiently and only to the extent necessary (Herricks et al., 1988; Schaeffer et al., 1985). Incomplete ecological knowledge, or a balance weighted toward social perceptions that favor use, often results in ecological disasters such as occurred in the Florida Everglades after hydraulic modifications (Wodraska and yon Haam, in this volume).

The conventional production-based philosophy is based in a legal system that legitimizes exploitation of the ecosystem to accomplish short-term human-oriented goals at the expense of long-term ecosystem sustainability (McNeely, 1988). Because legislation is shaped by compromises among political, social, and economic forces, the law presents multiple, fragmented, and uncoordinated objectives for environmental management (Schaeffer et al., 1980). Specifically, the ecological goal of "sustainable" ecosystems is based on an emerging legal principle that the "right" of ecosystems to be sustainable is inherent (Stone, 1974). Conservation agencies do not at present operate under statutes that grant sustainability as an inherent ecosystem right, but these agencies do implement programs under statutes that regard sustainability as a goal. These statutes include NEPA, the Endangered Species Act, and the "health of the ecosystem" requirement in the 1990 Clean Air Act Amendments. The 1972 Federal Water Pollution Control Act established the goals that the nation's surface waters Were to be "fishable" and "swimmable." To achieve these goals required that standards be set for toxic effluents based on health effects (Section 307(a)(2)) and that surface water criteria be established based on the identifiable effects of each pollutant on the public health and welfare, aquatic life, and recreation (Section 304(a)).

Both philosophies consider interrelationships between ecosystems and human legal, social, political, and economic systems. However, their emphasis on dissimilar relationships results in fundamental differences between the two philosophy's valuations of ecosystem worth and protection.

Engineering Production Philosophy

Engineers' production-based philosophy is supported by existing legislation that subsumes economic, social, and political factors. Paradoxically, although this philosophy generally increases the use of ecosystems for short-term human purposes (e.g., mining, lumbering), it has resulted in explicit and implicit protections for ecosystems. For example, the "fishable" goal of the 1972 amendments to the Federal Water Pollution Control Act was (ostensibly) environmental.[3] However, a production-based philosophy dominated the EPA implementation regulations, which emphasized minimizing the danger to human health from consumption of contaminated water and aquatic organisms.

Generally, regulations developed using the production-based philosophy emphasize particular known and knowable components of ecosystems, such as specific "threatened" and "endangered" species, rather than the sustainability *of an entire ecosystem*. Although most regulations based on a production-based philosophy result in minimal legal protections to ensure ecosystem sustainability,[4] some implicitly limit adverse effects on the unknowable components of ecosystems, such as might result from climate changes and pollutants. One example is evidence that the sexual abnormalities, feminization, and marked declines in fertility and life span that are now being identified in many aquatic species of reptiles, fishes, and amphibians are due to binding of the estrogen receptor by pollutants present in the environment at levels defined in regulations as safe (Colborn et al., 1993; McLachlan, 1993). Though these effects were previously unappreciated, their magnitudes may be limited by existing regulations that were written in response to earlier understanding of effects of pollutants on reproductive systems.

The production-based philosophy also produces adverse consequences for management and protection efforts. Production-based goals make it difficult to determine whether an effect is adverse, because regulations, management aims, and protection programs are developed from assumptions that are not fully inclusive of the range of services provided by ecosystems. Some of these assumptions are given below.

1. Environmental management and protection efforts are based on "known"

science, with the presumption against adverse effects unless such effects can be demonstrated. For example, it has been known (i.e., assumed) that the discharge of very low concentrations of organic pollutants in waste waters causes no harm. But recent declines in numerous aquatic and amphibian species appear to be due to the estrogenic effects of low concentrations of highly potent compounds, for example, by binding to the estrogen receptor.

2. Environmental management and protection efforts are presumed to be comprehensive when they are actually only minimal. For example, water use policies in the western states have increased crop yields but have also continuously increased the salinity of the soil, destroyed the ecology of the Grand Canyon, and adversely altered rainfall patterns in the region (Maranto, 1985; Poster, 1984).
3. Environmental management and protection efforts are consumed by an inefficient process of administrative rule making and are perpetually open for challenge, review, and revision. For example, the U.S. Environmental Protection Agency (USEPA) spent several years developing separate regulations for the application of sewage sludge to agricultural and nonagricultural land, but changed its position at the last moment and promulgated a single standard (USEPA, 1993).
4. Statutes and regulations emphasize single stress agents or individual species and do not consider biological communities or, in the broad sense, their abiotic habitat. For example, the Clean Water Act's goal of "fishable" was translated by the Environmental Protection Agency as water quality criteria to ensure that fish were "consumable" by humans.

Conservation Philosophy

The conservation-based philosophy is directed toward enhancing and sustaining the known, knowable, and unknowable components of an ecosystem. A suitable legal framework would define and balance human long-term needs for sustainable ecosystems against short-term uses of ecological resources (McNeely, 1988).

Whereas the production-based philosophy uses multiple formulations of a sustainable ecosystem that depend on the proposed uses of resources, the conservation-based philosophy uses features common to all sustainable ecosystems[5] (Holling, in this volume; Odum, 1969; Rapport et al., 1985; Schaeffer et al., 1988). Many of these characteristics are familiar to engineers because they concern a system's thermodynamic and kinetic properties, including fluxes of energy and materials, regulation of fluxes through feedback processes, and establishment of pseudoequilibria, such as the capacity of an ecosystem to temper toxic effects. Like engineered materials, ecosystems fail when stresses exceed system limits (resistance failures), occur too frequently (resilience failures), or alter fundamental properties of the habitat (see Holling, in this volume). Engineers need to increase their understanding of ecological function. With this background, they can help ecologists develop standardized methods to measure ecosystem resistance and resilience, and quantify ecosystem tolerance limits, such as thresholds (Khan, 1992; Schaeffer and Cox, 1991).

Certain laws provide explicit protections for the known and knowable aspects of the domain encompassed in the term "ecosystem" in the conservation-based philosophy. For example, the Endangered Species Act affords protection to the spotted owl by ensuring the sustainability of the old-growth forest that is its habitat. This implicitly also protects the unknowable relationships among the owl, other species, and abiotic habitat components. The Endangered Species Act does not require balancing economic costs against the ecological benefits resulting from protection of a species. If the Endangered Species Act is an idealistic implementation of the conservation-based philosophy, the National Environmental Policy Act requires a pragmatic balancing of the production-based and conservation-based philosophies. Thus, if threatened and endangered species are not at risk, the National Environmental Policy Act will allow for an ecosystem to be exploited for some purposes, provided that efforts are made to avoid, minimize, or mitigate effects on other ecosystem components.

UPPER MISSISSIPPI RIVER NAVIGATION STUDIES

The UMR-IWW navigation system provides habitat for at least 485 species of birds, mammals, amphibians, reptiles, and fish, including many endangered or threatened species. It includes a national fish and wildlife refuge of more than 226,650 acres and provides drinking water, irrigation, and recreation services to hundreds of communities. To ensure that the natural resources and other services are not adversely affected by increases in barge traffic and the associated engineering efforts, the Corps has embarked on a $42 million program to assess the effects from increased navigation and recreational traffic. These studies will result in the preparation of a final environmental impact statement in 1999 by the Corps, with advice from state and federal natural resource agencies (U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency, Illinois Department of Conservation, Iowa Department of Natural Resources, Minnesota Department of Natural Resources, Missouri Department of Conservation, and Wisconsin Department of Natural Resources) and other organizations that can influence legal acceptability through the Courts (e.g., Izaak Walton League, Sierra Club, and Minnesota-Wisconsin Boundary Area Commission). However, the differences in the perspectives and goals of these various agencies, the Corps, and other organizations have resulted in a decade-long conflict in setting the goals for the ecological studies (Schaeffer et al., 1992; U.S. Army Corps of Engineers, 1991). As discussed below, the conflict reflects a clash of philosophies.

ASSESSING FUTURE EFFECTS: A CLASH OF PHILOSOPHIES

In response to requirements of the National Environmental Policy Act, the Corps is carrying out engineering and ecological studies to determine whether *incremental* increases in navigation traffic will cause significant, *incremental*, detrimental changes in ecological resources. Site-specific studies will be completed as structures are scheduled for renovation. The ecological studies will provide data the Corps needs to devise management plans for maintaining the best possible ecosystem conditions without constraining navigation. Thus, regarding the construction of the second lock at the Melvin Price Locks and Dam, an interagency team reported as follows:

> When [this study] was initiated, the objective was focused towards pursuing investigations which would identify and quantify impacts associated with the incremental traffic increase resulting from the second lock. However, recognizing that the basic study elements needed for this investigation will also be useful to future Corps studies that will require navigation impact information, the following ... objective was adopted by the interagency team:

The [Corps] will develop studies which identify and quantify navigation traffic impacts to significant [UMR-IWW] natural resources *where such impacts are currently poorly defined* due to lack of scientific data. *If possible*, studies will quantify the impacts associated with that increment of traffic caused by the second lock. *Where feasible* , studies will quantify secondary impacts (U.S. Army Corps of Engineers, 1991, p. 3; emphasis added).

In 1990 when this study plan was written, the Corps and representatives of the resource agencies had reached an accommodation that would allow the Corps to minimize the harm to the ecological system and satisfy demands for barge traffic capacity. Unfortunately, by the time the ecological studies were initiated in 1994, all the organizations had new representatives, who resurfaced the old conflicts that again polarized the philosophies. The problems appear to fall into three broad areas: personal beliefs that are not separated from agency policy (possibly because of the absence of enunciated policy); the Corps' focus on incremental effects and resource agencies' focus on total effects; and differences in reliance on mathematical models. Thus, the Corps' field and laboratory studies and mathematical models suggest that the effects will be small, possibly not measurable, and not ecologically significant. However, the conclusions drawn by the Corps were rejected by most resource agency representatives, who instead have concluded from general ecological considerations and field observations (e.g., habitat loss) that the effects will be significant and adverse. They want the Corps to provide absolute assurances that no harm will result from increases in navigation traffic.

The resource agency representatives have several beliefs stemming from their conservation-based philosophy. One belief is that the Corps must determine whether the *total* effect on ecological resources from *all* traffic will be appreciable, rather than limit the evaluation to the significance of *incremental* effects from *additional* traffic. Another belief is that the Corps should gather basic scientific and ecological data, even if such data cannot be used as a baseline for determining whether significant impacts occur or for the "avoid, minimize, mitigate" analyses the Corps has included in the environmental impact statement. The resource agencies' most important belief is that current traffic is *already* causing deleterious effects, so additional ecological effects due to increases in traffic can *not* be minimal. The resource agency representatives anticipate that engineering studies the Corps is carrying out using a 400-foot-long 1:25 scale model of the Mississippi River and barges will result in major revisions to the hydrodynamic and hydraulic models the Corps uses to estimate environmental effects (due to shear forces and sediment resuspension) from tows. The revised models would then confirm resource agency beliefs that increases in navigation traffic will cause significant adverse ecological effects. In contrast, most engineers expect small changes in model coefficients, confirming that forces, wave action, and sediment transport due to tows will be below ecologically relevant levels. Whatever balances are agreed to, all parties recognize that engineering changes must meet the navigation needs of society without compromising the ability of future generations to meet their own ecological needs.

CONCLUSION

In October 1994 the Cousteau society presented a "Bill of Rights for Future Generations" to the United Nations General Assembly. Articles 2 and 3 state:

> Each generation ... has a duty as trustee for future generations to prevent irreversible and irreparable harm to life on Earth....
> It is, therefore, the paramount responsibility of each generation to maintain a constantly vigilant and prudential assessment of technological disturbances and modifications adversely affecting life on Earth, the balance of nature, and the evolution of mankind in order to protect the rights of future generations.

Engineering profoundly affects the structure of life on Earth, so the engineers' ethic in carrying out technological modifications must be to "do no harm" to the environment. Thus, engineers cannot continue to develop and implement technology as if it occurred in a thermodynamically isolated system. Technological development takes place in an engineered system that has complex connections to multiple physical, chemical, biological, ecological, and social systems.

An environmental ethic can be included in engineering if production goals are defined within a conservation-based philosophy. This philosophic expansion can be summarized as a pair of goals:

> to *maximize engineering* to maximize ecosystem sustainability
> to *maximize engineering* by maximizing ecosystem sustainability

Effecting a change in philosophy to ensure the sustainability of ecosystems will require education, research, and changes in law.

NOTES

1. The Upper Mississippi River extends from River Mile (RM) 218.0 near St. Louis, Missouri, to RM 854.0 at Upper St. Anthony Falls Lock in Minneapolis-St. Paul, Minnesota. The Illinois Waterway extends from Grafton to Chicago, Illinois. The total Illinois and Mississippi River navigation system contains 37 locks (of which 35 are included in the proposed renovation program of the U.S. Army Corps of Engineers) and 360 terminals. Lock and Dam 26 (RM 202.9, Alton, Illinois) was replaced in 1989 by the Melvin Price Locks and Dam (RM 200.8); a second lock opened in 1994.

2. The National Environmental Policy Act (NEPA) was passed by Congress in 1969 in part to integrate environmental considerations into the decision making process for "every recommendation or report on proposals for legislation and other major federal actions significantly affecting the quality of the human environment" (§102[2][c]). NEPA put in place the requirement for impact analyses that have evolved from limited assessments that meet the letter of the law to comprehensive assessment programs that meet the spirit of the law. The role of NEPA in ensuring that the proposed changes in the UMR-IWW navigation capacity meet the *spirit* of the law has been discussed elsewhere (Cox et al., 1993a; Schaeffer et al., 1988, 1993).

3. Before 1972 the Federal Water Pollution Control Act (FWPCA) left it up to the states to develop ambient water quality standards to protect interstate and navigable waters for uses the state wanted to facilitate (e.g., agriculture, industry, recreation, human consumption, prevention of imminent health hazard). The 1972 amendments established a system of national standards, permits, and enforcement "goals" of "fishable and swimmable" waters by 1983 and *total elimination of pollutant discharges* into navigable waters by 1985. Following amendment of the FWPCA in 1977, it was designated the Clean Water Act.

4. Factors that alter an ecosystem from the conceptual image of that ecosystem embodied in a particular law (e.g., "fishable and swimmable") pose excess risk. The term *de minimis* risk is widely used in federal risk analysis (see Whipple, 1987) to mean a specific level below which a risk estimate is so small that it can be ignored i.e., a threshold (Schaeffer and Cox, 1991). A legal threshold for sustainability is the level of risk a given law accepts; for example, a game fish with a sustainable population but which is not edible due to contamination. An ecological threshold is the value of a relevant ecological parameter at the point at which the risk becomes adverse. For example, based on Karr's (1981) Index of Biotic Integrity, Khan (1992) found that the quality of Illinois fisheries usually was less than "good" if there were fewer than 17 species.

5. These include habitat for desired diversity and reproduction of organisms; phenotypic and genotypic diversity among the organisms; a robust food chain supporting the desired biota; an adequate nutrient pool for desired organisms; adequate nutrient cycling to perpetuate the ecosystem; adequate energy flux for maintaining the trophic structure; feedback mechanisms for damping undesirable oscillations; capacity to temper toxic effects, including the capacity to decompose, transfer, chelate or bind anthropogenic inputs to a degree that they are no longer toxic within the system.

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