



Investing in Research for Sustainability

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an assessment is awkward using standard frequentist statistical methods, since they are concerned with the properties of functions of the data (such as means and standard errors) if data are sampled repeatedly. In ecological decision problems, data are not sampled repeatedly: we must work with what we have. Frequentist methods cannot answer questions concerning the relative probabilities of various parameter values since parameters are fixed, not random. Similarly, hypotheses are either true or false: one cannot assign a probability to a hypothesis using frequentist methods. The result of statistical hypothesis testing methods is typically a single favored hypothesis. This leads to decision making that ignores uncertainty in our knowledge and consequently neglects the consequences of unlikely events with bad outcomes. Often economic optimization models (such as the maximum sustained yield for fisheries) are applied to attempt to maximize yields even though the data provide little information about biological characteristics of the exploited stocks. The consequence of such decision making is a continual series of surprises and failures.

In contrast, the modern theory of decision (Chernoff and Moses 1959, Berger 1985, Lindley 1985, Mangel 1985) is based upon the subjective interpretation of probability. Probabilities are used to quantify degrees of belief in a variety of hypotheses. The main tool is Bayes' theorem, which enables one to update estimates as new data are available. The first product of such an analysis is a probability distribution for the various hypotheses, calculated from the data that are currently available. On the basis of this distribution one can assess the probable consequences of a variety of actions. The action that is recommended can be chosen on its aggregated performance under a variety of plausible hypotheses. An important component of this process is the careful description of uncertainties in our present knowledge. One can often design experiments that will reduce such uncertainties in the future. There is no substitute for informative data and careful experiments. The advantage of decision-theoretic meth-

ods is that uncertainty is handled in a consistent and systematic way rather than being ignored as a consequence of an hypothesis test.

None of the above discussion suggests we should not do ecological research. Rather it suggests that ecological research on large-scale systems of interest in most discussions of sustainability has limitations. Ecology has made a lot of progress and we are not embarrassed to say that we are ecologists to our colleagues in physics and chemistry. Rather we take pride in the intrinsic difficulty of the field and tell them "Rocket scientists have it easy!" However, when providing society with advice about the sustainability of natural resource use, we keep in mind the explosion of the space shuttle Challenger. If rocket scientists can make such a big mistake, we ecologists, working in a much harder field, need to be aware of the limitations of our understanding.

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INVESTING IN RESEARCH FOR SUSTAINABILITY^{1,2}

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Is sustainable use of a living resource impossible, sustainable development an oxymoron, and scientific research of limited utility in designing policies and

managing resource exploitation? That is what Ludwig et al. (1993) seem to suggest in their article on the history of exploitation of renewable resources. They are probably correct if sustainable use or sustainable development is defined as the first phase of exploitation of a single species and science as small-scale reduc-

¹ Manuscript received 2 June 1993.

² For reprints of this Forum, see footnote 1, p. 545.

tionist biology. But is the issue usefully defined in that way?

Their article really has two schizoid parts. The first, and longest, articulates a deeply held and pessimistic personal belief supported by selected anecdotes, largely drawn from fisheries. It is a belief that says human greed and shortsightedness almost always lead to over-exploitation and often to collapse of the resource. Anticipation and management using scientific data is confounded by the large spatial scale of the natural processes, by the high degree of natural variability, and the inherently unpredictable behaviors common to complex ecological systems and to human behavior.

At the minimum, that view is a refreshing antidote to the cornucopian beliefs of the Julian Simons of the world (Simon and Kahn 1984), who see an infinite capacity for human learning, a limitless ability for people to adapt and substitute, and a set of problems that unfold fast enough to be perceived, yet slowly enough for response to be effective and timely. It assumes that the time stream of natural and human events is smooth and continuous and that the behaviors of natural systems are constrained to a narrow range of temporal and spatial variability.

But both are beliefs, and since both have partial elements of truth within them, bright people have the ability to mobilize compelling examples and causal arguments that convincingly support those diametrically opposite views. Great intellectual fun, but hardly the sort of game that the politician, the public, or the media can easily use to base confident evaluations of recommendations for investment or for action.

In contrast, the second part of their article draws on the results of their extensive research and practical experience in analyzing and participating in the science, designs, and management of natural resources, where they have created major innovations and made significant contributions in the past to systems and mathematical modelling, population dynamics, large-scale experimental and management designs, and adaptive methods of management that focus on the interaction among renewable resources, management agencies, developers, and exploiters.

Once they base their remarks on this rigorous body of analysis, synthesis and experience, the message is entirely different. They turn from the conclusion that management is impossible to a set of tested prescriptions for management that are sustainable. The prescriptions arise from a recognition of the integrated nature of ecological and environmental problems that links the dynamics in space and time of natural processes at the scales relevant to the issue, with the motivations of exploiters, managers, and scientists. The bite in their article, both in the first bad news and the second good news part, is in the implication that sustainability is neither a realistic goal nor a useful concept, and that investments in scientific research for sustainability are not wise. But that is only made con-

vincing by assuming there is only one kind of science and one exploitive definition of sustainability. I shall deal with each in turn.

ONE KIND OF SCIENCE?

Ludwig et al. (1993) highlight the inadequate and diversionary nature of traditional science, science that is disciplinary, reductionist, and detached from people, policies, and politics. But there is another stream of science that is often in conflict with this traditional caricature.

This other stream is represented within biology by evolutionary biology and by systems approaches that extend to include the analysis of populations, ecosystems, landscape structures and dynamics, and more recently, further extend to include biotic and human interactions with planetary dynamics. The applied form of this stream has emerged regionally in new forms of resource and environmental management where uncertainty and surprises become an integral part of an anticipated set of adaptive responses (Walters 1986). It is fundamentally interdisciplinary and combines historical, comparative, and experimental approaches at scales appropriate to the issues. It is a stream of inquiry that is fundamentally concerned with integrative modes of inquiry and multiple sources of evidence.

It is this stream that has the most natural connection to related ones in the social sciences that are historical, analytical, and integrative. It is also the stream that is most relevant for the needs of policy and politics.

The first stream is a science of parts that emerges from traditions of experimental science where a narrow enough focus is chosen in order to pose hypotheses, collect data, and design critical tests in order to reject invalid hypotheses. The goal is to narrow uncertainty to the point where acceptance of an argument among scientific peers ultimately can become essentially unanimous. It is appropriately conservative and unambiguous, but it achieves that by being incomplete and fragmentary.

The other is a science of the integration of parts. It uses the results and technologies of the first, but identifies gaps, develops alternative hypotheses and multivariate models, and evaluates the integrated consequence of each alternative by using information from planned and unplanned interventions in the whole system that occur in or are designed to be implemented in nature. Typically, the goal is to reveal the simple causation that often underlies the complexity of time and space behavior of complex systems. Often, there is more concern that a useful hypothesis might be rejected than a false one accepted—"don't throw out the baby with the bath water." Since uncertainty is high, the analysis of uncertainty becomes a topic in itself.

The premise of this second stream is that knowledge of the system we deal with is always incomplete. Surprise is inevitable. Not only is the science incomplete, the system itself is a moving target, evolving because

of the impacts of management and the progressive expansion of the scale of human influences on the planet.

In principle, therefore, there is an inherent unknowability, as well as unpredictability, concerning these evolving managed ecosystems and the societies with which they are linked. There is therefore an inherent unknowability and unpredictability to sustainable development. The essential point is that evolving systems require policies and actions that not only satisfy social objectives but, at the same time, also achieve continually modified understanding of the evolving conditions and provide flexibility for adaptation to surprises. Science, policy, and management then become inextricably linked.

It is this science of integration and synthesis that has been ill served by funding agencies and universities. It is where the priority should lie for investments in research and education.

ONE KIND OF SUSTAINABILITY?

In many cases of renewable resource management, success in managing a target variable for sustained production of food or fiber leads to an ultimate pathology of more brittle and vulnerable ecosystems, more rigid and unresponsive management agencies, and more dependent societies, just as Ludwig et al. (1993) claim. But there seems to be something inherently wrong with that conclusion, implying, as it does, that the only solution is a radical return of humanity to being "children of nature."

That pathology seems to confirm the opinion that sustainable development is an oxymoron. Moreover, those pathologies occur not only in examples of renewable resource management but also in examples of rigid policies of regulation of toxic materials by the U.S. Environmental Protection Agency or in examples of narrow implementation of the Endangered Species Act by the U.S. Fish and Wildlife Service.

But if we examine that pathology over a longer and larger span, examples appear where external and internal crises, amplified by the pathology, trigger a sudden lurch in understanding, a redesign and expansion of policy, and a return of flexibility and innovation. That pattern of discontinuous learning might still be rare in the frontier stage of resource development of British Columbia, the province where the pessimism of Ludwig et al. (1993) was shaped, but it is not at all uncommon elsewhere, where there has been a longer history of development or a faster dynamic of the system. There have been enough examples to prompt an exploration of examples of those lurching phases of pathological exploitation, followed by crises and learning ranging from the Everglades of Florida, the forests of New Brunswick, the estuary of Chesapeake Bay, the Great Lakes, and the Baltic Sea (Gunderson et al., *in press*).

In New Brunswick, for example, the intensifying gridlock in forest management, combined with slowly

accumulated and communicated scientific, economic, and social understanding, led to an abrupt transformation of forest policy that became regionalized, freed from local constraints, and set in an adaptive framework designed to achieve both ecological and economic benefits (Baskerville, *in press*). It is a policy that functions for a whole region by transforming and monitoring the smaller scale stand architecture of the landscape and by releasing the productive and innovative capacities of industry.

Hence it is not useful, except as a debating position, to define sustainable use or development as exploitation of a single species during an initial phase of development. It begins to be useful as a guide to science, investment, and action when the definition of sustainability focuses on the social and economic development of a region with the goals to invest in the maintenance and restoration of critical ecosystem functions, to synthesize and make accessible knowledge and understanding for economies, and to develop and communicate the understanding that provides a foundation of trust for citizens.

A PROFILE FOR RESEARCH AND ACTION

Citizens and politicians are frustrated because they are not hearing simple and consistent answers to the following key questions concerning present environmental and renewable resource issues: what is going to happen under what conditions, when will it happen, where will it happen, who will be affected, and how uncertain are we?

The answers are not simple or consistent because we have just begun to develop the concepts, technology, and methods that can deal with the generic nature of the problems. Those generic features can be described in various ways, but here is my overly academic attempt.

- 1) The problems are essentially systems problems where aspects of behavior are complex and unpredictable and where causes, while at times simple (when finally understood), are always multiple. *Therefore interdisciplinary and integrated modes of inquiry are needed for understanding. And understanding (not complete explanation) is needed to form policies.*
- 2) They are fundamentally nonlinear in causation. They demonstrate multistable states and discontinuous behavior in both time and space. *Therefore the concepts that are useful come from nonlinear dynamics and theories of complex systems. Policies that rely exclusively on social or economic adaptation to smoothly changing and reversible conditions lead to reduced options, limited potential, and perpetual surprise.*
- 3) They are increasingly caused by slow changes reflecting decadal accumulations of human influences on air and oceans and decadal to centuries trans-

formations of landscapes. Those slow changes cause sudden changes in fast environmental variables that directly affect the health of people, productivity of renewable resources, and vitality of societies. *Therefore analysis should focus on the interactions between slow phenomena and fast ones and monitoring should focus on long-term, slow changes in structural variables. The political window that drives quick fixes for quick solutions simply leads to more unforgiving conditions for decisions, more fragile natural systems, and more dependent and distrustful citizens.*

- 4) The spatial span of connections are intensifying so that the problems are now fundamentally cross scale in space as well as time. National environmental problems can now more and more frequently have their source both at home and half a world away, witness greenhouse gas accumulations, ozone hole, AIDS, deterioration of biodiversity. Natural planetary processes mediating these issues are coupling with the human, economic, and trade linkages that have evolved among nations since WW II. *Therefore, the science needed is not only interdisciplinary, it is cross scale. And yet the very best of environmental and ecological research and models have achieved their success by being either scale independent or constrained to a narrow range of scales. Hierarchical theory, spatial dynamics, event models, satellite imagery, and parallel processing perhaps open new ways to violate, successfully, the hard-won experience of the best ecosystem modellers, i.e., never include more than two orders of magnitude or the models will be smothered by detail.*
- 5) Both the ecological and social components of these

problems have an evolutionary character. That is why the phrase sustainable development is not an oxymoron. The problems are therefore not amenable to solutions based on knowledge of small parts of the whole, nor on assumptions of constancy or stability of fundamental relationships, ecological, economic, or social. Assumptions that such constancy is the rule might give a comfortable sense of certainty, but it is spurious. Such assumptions produce policies and science that contribute to a pathology of rigid and unseeing institutions, increasingly brittle natural systems and public dependencies. *Therefore, the focus best suited for the natural science components is evolutionary, for economics and organizational theory is learning and innovation, and for policies is actively adaptive designs that yield understanding as much as they do product.*

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ENVIRONMENTAL SUSTAINABILITY: MAGIC, SCIENCE, AND RELIGION IN NATURAL RESOURCE MANAGEMENT^{1,2} -

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Resource management is a discipline whose history is replete with spectacular failures, but whose practitioners seldom change their policies in response to past experience (Ludwig et al. 1993). This institutional pattern of stereotypic response to repeated failure is itself worthy of study (Hilborn 1992). Such failure is an inevitable consequence of a contradiction between human desires and human capabilities. The usual result is a magical theory that purports to satisfy unlimited

human populations and unlimited per capita consumption with limited resources; the miracle of the loaves and fishes has become an objective of policy. The Sustainable Biosphere Initiative is in that tradition.

SUSTAINABILITY IN THEORY AND IN PRACTICE

Faustmann (1968, originally published in 1849) used the concept of sustainability to calculate a forest rotation period that would maximize economic benefits. Since that time, sustained yield has been a goal of theoretical treatments of forest management, which have developed associated concepts of a "regulated

¹ Manuscript received 2 June 1993.

² For reprints of this Forum, see footnote 1, p. 545.