ploitation. This is not a political position that is easily maintained, but so long as it can be, science has time to catch up.

Ludwig et al. (1993) are correct to insist that environmental problems are at heart human problems, for which scientific understanding may not be sufficient to bring about resolution. Science, both social and natural, remains necessary nonetheless.

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SCIENCE AND SUSTAINABLE USE[1,2]

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Ludwig et al. (1993) have written a very interesting and compelling paper on the difficulties of bringing scientific information to bear on the solution of environmental problems. Their contention is that resources are inevitably overexploited because of inherent problems that preclude scientists from achieving consensus. The objective of this paper is to demonstrate that the three features that according to Ludwig et al. (1993) prevent science from being the base of sustainable use are now being overcome.

One of three issues pointed out by Ludwig et al. (1993) is that lack of replicates and controls prevents us from achieving scientific understanding and consensus. The revealing lake experiments by Schindler have provided a compelling model of how ecosystem-level experiments can provide convincing demonstrations of whole-system responses to pollutants, and can lead to policy change (Schindler 1991). Experiments to assess whole-ecosystem response to perturbations are now being performed in a variety of terrestrial ecosystems (see Mooney et al. 1990). Moreover, experimental manipulation of factors such as atmospheric CO_2 are now underway at the whole-system level in a variety of ecosystems (Mooney and Koch, *in press*). Experiments that evaluate different management techniques at scales relevant to management are now performed in rangelands and forests (Walker et al. 1989). These experiments are aided by developments in remote sensing, computer science, and analytical techniques.

A second issue that Ludwig et al. (1993) highlight is that the complexity and the scale of resource management problems hamper scientific understanding and consensus because the normal reductionist approach cannot be utilized. There is reason to believe that science is now making important progress in understanding large-scale, complex, transdisciplinary problems. We give two examples of this. One has been in the development of the global change research program. The initial development of the global change research effort in the mid-1980s concentrated heavily on gaining

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new knowledge at the interface between physical and biological sciences. This has been a major effort since it involved scientists having to work across major disciplinary boundaries and in the process learning new concepts and language, as well as working at different spatial scales than had previously been utilized. This phase has now been accomplished and there are strong research interactions among physical and biological disciplines involving relatively large spatial resolution. The past few years have seen a second phase of the development of global change research where strong interactions among the natural and social scientists are developing. One of the initial testing grounds for this new coalition is the determination of the social drivers for land use change, which is then linked to understanding the consequences of these changes in terms of feedbacks to the atmosphere. This, no doubt, will be followed by further substantive interactions between social and natural scientists, where we hopefully will gain more holistic information on the drivers and responses to global change.

Another example of program evolution that is leading to a stronger coalition between natural and social sciences, as called for by Ludwig et al. (1993), is the Sustainable Biosphere Initiative (SBI) cited by them (Lubchenco et al. 1991). This program is now in its third phase of development. The first, which is cited by Ludwig et al. (1993), focused on the scientific issues that represent the important unknowns related to the structure and functioning of ecological systems. A follow-up of this effort concentrated on how ecological science can contribute to environmental decision making (Huntley et al. 1991), where it was noted that "ecologists will have to break away from the intellectual and professional traditions that have constrained their involvement in social, economic, and political matters," and where it was noted that the problems related to sustainability are "not just scientific, but include peoples' value systems and expectations." The third phase of this effort is the newly initiated Sustainable Biosphere Project (SBP) that will be administered by SCOPE (Scientific Committee on Problems of the Environment). This project will begin by bringing basic ecological, social, and economic expertise together with policy and resource management to examine selected integrated regional units of the Earth, thereby to assess successes and failures of managing sustainable systems. Thus, in the past few years the Sustainable Biosphere Initiative concept has evolved from considering ecological science and education almost exclusively to attempting to imbed this knowledge into the larger fabric of the issues that drive societal impacts and decisions.

The third feature of the Ludwig et al. (1993) argument is that large levels of natural variability mask the effects of overexploitation. This is a matter of signal-to-noise ratio. Our ability to distinguish the signal from the noise depends directly on our understanding of the system under question. As an example, we recall that a fraction of the physical and biological variability in the tropical Pacific and adjacent regions that was previously assigned to noise is interpreted now as an El Niño signal. Scientific research cannot decrease natural variability, but can certainly improve our ability to detect the overexploitation signal.

The Ludwig et al. (1993) contention that resources are inevitably overexploited is based upon a series of notorious examples of mismanagement, most of them originating from fisheries. Failures to achieve sustainable use are often the result of either (1) our ecological ignorance or (2) cases in which short-term priorities have overridden long-term societal priorities. Cases in which mismanagement results from not knowing the system behavior and the inability to predict the effects of management practices are completely different from cases in which the consequences of a particular action are well known but society is not willing to give up short-term benefits in exchange for long-term gains. Some of the fisheries problems cited by Ludwig et al. (1993) are examples of the former, and the logging practices associated with the Pacific Northwest forests of the United States are examples of the latter. Similarly, in the health care arena, there are incurable as well as curable diseases that still affect a large fraction of the population because of social and economic barriers. Different actions are recommended to correct failures in resource use that have different causes. In one case, it is necessary to improve our understanding of ecological systems, whereas in the other case it is necessary to improve the awareness of decision makers and the public at large. By confounding the causes of failure, we will err in selecting actions to avoid or reverse failures in managing resources.

Scientific knowledge has been successfully utilized to maximize biotic yield, which results in the world now experiencing extraordinary levels of food and fiber production. These high production levels have been achieved through the utilization of new varieties, fertilizers, and management practices. Unfortunately while production has increased, natural resources have been depleted, and pollutants have accumulated to a point where the unconstrained goal of maximizing yield is now questioned. There are now increasing efforts to balance commodity and environmental goals. Science played a major role in the shifting of goals by identifying the environmental problems and their mechanisms, and by assessing their evolution under various courses of action (see the companion article by Ehrlich and Daily 1993). These new efforts toward sustainability will not be achievable without a major contribution of science and its understanding of basic ecological principles.

Examples of the new technologies arising from scientific knowledge to satisfy the sustainable use objective are the "New Forestry" (Franklin 1989) and the innovative approaches to "Biodynamic Agriculture" (Reganold et al. 1993). These new agricultural techniques result in significant improvements in the physical, chemical, and biological properties of the soil and are economically feasible (Reganold et al. 1993). All of these novel techniques have in common a high requirement for knowledge and trained people. For example, when broad-spectrum pesticides are replaced by biocontrol approaches a thorough understanding of ecological systems is required for their development as well as their implementation.

We conclude that sustainable use of resources is feasible, but the only way to achieve this goal is by improving our understanding of ecological systems. Transdisciplinary studies like the ones starting under auspices of SBI and SBP need to be fostered, and programs to increase the awareness of decision makers and the public on environmental issues need to be furthered. Uncertainty is not going to disappear and management schemes that confront uncertainty, as proposed by Ludwig et al. (1993), are necessary. These different avenues do not represent alternative pathways but complementary efforts, all of them necessary to reach the goal of sustainable use of resources.

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ENVIRONMENTAL DECISION MAKING: MULTIDIMENSIONAL DILEMMAS[1,2]

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In their Forum article in *Science,* Ludwig et al. (1993) make a number of interesting and valid points concerning resource management decision making but overall offer a rather pessimistic view of the past and likely future application of the concept of sustainability in natural resource management. More disturbing is the implication we took away from the article that science has failed in guiding resource management decision making and that there is little hope for improvement. While the authors undoubtedly are correct in their descriptions of specific examples of resource overexploitation, we believe that they overextrapolate from limited examples. Moreover, the implication that science can have very limited success in informing management decisions and that calls for more basic research are self serving is simplistic and potentially counterproductive. We would like to address three general issues regarding their article and then briefly discuss the specific principles they advocate at the end of their piece.

The major examples used by Ludwig et al. (1993) to

[1] Manuscript received 2 June 1993.
[2] For reprints of this Forum, see footnote 1, p. 545.