# Defining and Implementing Best Available Science for Fisheries and Environmental Science, Policy, and Management

American Fisheries Society

Estuarine Research Federation

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# INTRODUCTION

## Background

Conservation and management issues involving fisheries can be controversial when fisheries appear overharvested, when species appear threatened, when fish populations or habitats are impacted by fisheries-related activities, or when fisheries are threatened by nonfisheries activities. Multiple species and ecosystem concerns compound these issues in both the scientific and management arenas. Controversies have arisen in the management of cod in the North Atlantic (Hutchings et al. 1997), in the protection of Monk seals in the central Pacific and sea turtles in the South Atlantic and Gulf of Mexico (Crowder and Murawski 1998), and in water management on the Klamath River (Flug and Scott 1998 ). Conservation and management decisions in these and other cases (see also California sardine [McEvoy 1986], Pacific salmon [Nehlsen et al. 1991], and Great Lakes salmonids [Smith 1968]) rely on the use of the best available science to provide information to decision makers and the public. Unfortunately, the concept of best available science is usually not well defined and may be misunderstood or misrepresented when used in management and policymaking. Often, scientific and political communities differ in their definition of best available science and opposing factions misrepresent the concept to support particular ideological positions. Ideally, each policy decision would include all the relevant facts and all parties would be fully aware of the consequences of a decision. But economic, social, and scientific limitations often force decisions to be based on limited scientific information, leaving policymaking open to uncertainty.

In the United States, many of the laws governing conservation and management stipulate that the best available science be used as the basis of policy and decision making. One such law, the Endangered Species Act, requires that decisions on listing a species as threatened or endangered be made on the basis of the "best scientific and commercial data available." Similarly, National Standard 2 of the Magnuson-Stevens Fishery Conservation and Management Act states that conservation and management measures shall be based on "the best scientific information available." Further, the U.S. Environmental Protection Agency has emphasized the role of best available science in implementing the Clean Water Act (USEPA 1997). Determining what constitutes the best available science, however, is not straightforward, and scientists, policymakers, and stakeholders often have disparate ideas on how the concept should be defined and interpreted.

In 2002, a National Research Council committee was asked to review the scientific basis for agency decisions regarding endangered fish species and instream flows in the Klamath River basin. The committee concluded that neither the recommendation by NOAA Fisheries and the U.S. Fish and Wildlife Service to "change water levels or river flows to promote the welfare of the fish currently at risk" nor "the reduction in minimum river flows that the Bureau of Reclamation's proposal would allow" were scientifically justified. The dispute that ensued involved endangered species and multiple demands for water use (Service 2003). The outcomes of this and many other cases hinge on particular interpretations of the best available science.

## Scope of Work

What constitutes best available science has profound ramifications for how aquatic ecosystems are managed. Although scientists cannot unilaterally define best available science, they have an obligation to participate in the dialogue over how science is defined and applied to environmental policy. The American Fisheries Society and the Estuarine Research Federation established this committee to consider what determines the best available science and how it might be used to formulate natural resource policies and shape management actions. The report examines how scientists and nonscientists perceive science, what factors affect the quality and use of science, and how changing technology influences the availability of science. Because the issues surrounding the definition of best available science surface when managers and policymakers interpret and use science, this report also will consider the interface between science and policy and explore what scientists, policymakers, and managers should consider when implementing science through decision making.

This paper will

- provide a practical description of the concept of best available science;
- identify the limits to creating, distinguishing, and using the best available science; and
- suggest ways to improve the use of science in policy and management.

To accomplish these objectives, we break the concept of best available science down into the cumulative components of science, best science, and best available science. Throughout the discussion, we highlight the factors that influence best available science, including (a) the changing nature of science, (b) the increasing role of uncertainty in scientific decision making, (c) the influence that the values and ethics of scientists have on the scientific process, (d) the changing availability of information via peer-reviewed journals, gray literature, expert opinion, and anecdotal evidence, and (e) the bridges that need to be forged and maintained between science, policy, and management.

## DEFINING BEST AVAILABLE SCIENCE

### *What Is Science?*

Science means different things to different people (Ringler and Peters 1995). One popular view is that science is simply a body of organized knowledge, as in, for example, the scientific nomenclature for species of plants and animals. Science may also be viewed as a rigorous, standardized way of collecting information, as in the use of the scientific method to examine the effects of oxygen depletion on fish and to test hypotheses on oxygen levels and survivorship. The classification of species and the information collected through the scientific method become what are known to both the public and the scientific community as scientific data, specifically, an agreed-upon set of facts or ideas that are scientifically determined. Alternatively, science may be more broadly viewed as a way of knowing things or creating knowledge, where what is defined as knowledge is based on a mix of observation, intuition, experimentation, hypothesis testing, analysis, and prediction. Ecological knowledge commonly develops from well-reasoned judgments based on empirical evidence, conceptual criticism, and experiential argument (Wallington and Moore 2005). Each of these views of science is valid. Each recognizes implicitly that multiple conceptions of science exist. Each is crucial to understanding the controversy associated with defining best available science. However, these subtle differences in how science is perceived can lead to major differences in how it is used to develop policies and implement management decisions.

## Scientists' perceptions of science

The mix of observation, analysis, intuition, prediction, and experimentation that goes into the scientific process varies considerably. Latour (1987) recognized the difference between established or "ready-made" scientific knowledge and emergent or "in-the-making" scientific knowledge. Established knowledge includes taken-for-granted, uncontroversial facts that are true regardless of their context, as in the concept that salmon are fish. This is the textbook version of scientific knowledge. By contrast, emergent knowledge consists of claims to be tested and possibly revised, often with a result that is controversial, as for example the concept that salmon are endangered. Emergent scientific knowledge is relatively new and is still being verified via the scientific process. And while it is easy to acknowledge that there may be various stages of emergent scientific knowledge, it is clear that this type of knowledge, because it is still open to debate, can lead to controversy when brought to bear on policy. It is because of this that emergent scientific knowledge should be considered more thoroughly.

An important source of controversy for emergent knowledge is the personal value systems of scientists. Scientific knowledge is always characterized by facts and ideas presented in the context of explicit values, assumptions, and limitations (Allen et al. 2001; Ludwig 2001). Although the scientific process is designed to minimize the influence of values, that influence can never be entirely eliminated. Nevertheless, adherence to a methodology that minimizes subjectivity throughout the process of knowledge development is perhaps the greatest distinction between the scientific and nonscientific arguments employed in support of policy decisions (Rykiel 2001). This claim to objectivity is the basis for the public authority entrusted to science and for the privileged role science plays in informing policy (Tauber 1999). Scientists adhere to scientific methods and procedures, and their opinions and recommendations are valued by society because of the meticulous observation, continual confrontation, and self-reflection they entail (Allen et al. 2001). For complex environmental issues, a scientist's judgment based on honest intellectual discourse is more valuable than an oversimplified declaration of "truth."

## Nonscientists' perceptions of science

Although most nonscientists recognize science as a source of information, many do not appreciate the range of scientific approaches or the importance of debate, dissent, skepticism, and personal opinion involved in the process of producing scientific knowledge. It may be that many nonscientists envision science as simply implementing a standard scientific method in a recipe-like manner until new knowledge appears. In contrast, some nonscientists view scientists as merely another special interest group peddling influence (Pouyat 1999). Interpretations of scientific findings by nonscientists range widely because of the many personal contexts and frames of reference that nonscientists have in relation to their understanding of science (Weber and Word 2001). Unfortunately, many policymakers, regulators, and judges have unrealistic expectations of science. They expect science to produce uncontested, value-free, universally applicable knowledge that is accessible to everyone, scientist and nonscientist alike (Salter 1988; Pouyat 1999).

Ecological knowledge is often based on evidence collected through observation or reasoning rather than on conclusive experimental proof, and the behaviors of complex systems are not precisely predictable. Thus, contradictory viewpoints regarding fisheries, natural resources, and ecosystem operation as well as the consequences of associated management actions may or may not be scientifically support-able depending on how questions are framed, how terms are defined, and how information is used (Allen et al. 2001; Ludwig 2001; Holling and Allen 2002). This makes it very difficult for nonscientists to see how to use science objectively in making decisions. The problem is exacerbated when public reports reduce complex scientific knowledge to value-laden sound bytes (Schneider 2002) or when the most divergent positions are set in contrast under the guise of objectivity (Pouyat 1999). As part of their implicit contract with society, environmental scientists are obliged to communicate their knowledge widely to facilitate informed decision making (Lubchenco 1998). For nonscientists to use that knowledge effectively and fairly, they must also understand the multifaceted scientific process that produces it.

### Science as information provider

Science provides a basis for measuring changes in the environment, for understanding how ecosystems operate, and for predicting how a change in environmental conditions might affect ecosystem operation. However, science cannot provide a basis for choosing human goals with respect to the management of these systems. Goal setting, an integral part of policymaking, is a value-based process. A common misconception of nonscientists is that science can provide objective answers to the thorny question, "How *should* we manage this ecosystem or resource?" Such questions can be answered only by reconciling the socially constructed values and expectations of the stakeholders at the policymaking table. Scientists may, of course, participate in goal setting, but they should neither be expected nor claim to be completely objective under those circumstances. In contrast, science can inform society about the consequences of its management goals and actions, which may lead to revised goals and actions, but goal setting itself is outside the realm of science.

Ultimately, it must be acknowledged that conceptions of science and its role in solving social issues are not static. Just as the knowledge produced by science continually changes, the range of investigative and interpretive approaches deemed scientific is also in continual flux. Science is a dynamic process that adapts to the evolving philosophies of its practitioners and to the shifting demands of the society it serves. Unfortunately, these dynamics are often controversial for both the scientific community and the public. To see how such controversies affect science, note that over the last decade nonscientists have exerted increasing influence on how science is conducted and how it is applied to environmental policy. Many observers find this trend alarming, as evidenced by several expositions titled "science under siege" (e.g., Wilkinson 1998; Trachtman and Perrucci 2000).

Also controversial are recent legislative efforts to define best science, to mandate that certain kinds of data be given greater weight by decision makers, or to establish by law the qualifications for those who would conduct peer review (Bolten 2004). This in itself is contrary to the quest for the best available science because legislators—usually nonscientists—are seeking to dictate which type of science is best and then casting it as law, ignoring the fact that the best available science will continually evolve.

## *What Is Best Science?*

### Science and the scientific process

To achieve high-quality science, scientists conduct their studies using what is known as the scientific process, which typically includes the following elements:

- A clear statement of objectives;
- A conceptual model, which is a framework for characterizing systems, stating assumptions, making predictions, and testing hypotheses;
- A good experimental design and a standardized method for collecting data;
- Statistical rigor and sound logic for analysis and interpretation;
- Clear documentation of methods, results, and conclusions; and
- Peer review.

The scientific process used for solving a particular problem is implemented by means of a research plan. A sound plan promotes unbiased, repeatable results. In contrast, not adhering to a good research plan not only creates problems for interpreting results (Mills 2002), it can also make scientific findings vulnerable to attack by both scientists and nonscientists. Such attacks, of course, can be motivated by an ideological rather than a truth-seeking impetus. For example, in 2001 lawmakers in the western United States who opposed the protection of endangered species used the discovery of tainted data on the distribution of lynx to question the validity of *all* data on endangered species (Hudson 2001). Unfortunately, researchers are often not funded for plan development, although they may subsequently be rewarded through the grant and funding process should their plan show merit. A good research plan includes background information on the topic and whether any of the identified hypotheses have already been successfully tested, clearly noting whatever critical information is lacking. When no research plan is available or only a sketchy or incomplete plan exists, controversy about the science can easily result. In such instances, a review panel may be called in to examine disparate data sets to see whether the available data support or refute a proposition of interest. These data may in fact have been collected for different reasons or using techniques that are inappropriate for answering the questions at hand, thereby making analysis and the decision process more complex. Considering the elements of a research plan, therefore, provides a basis for determining what is best science.

*Clear statement of objectives*.—The first step in developing a research plan and ensuring the quality of the scientific process lies in a clear statement of objectives. Without such a statement, it is all too easy for procedures to be applied haphazardly and for results to be ambiguous. Although many disputes arise regarding the inferences and conclusions based on the scientific methods employed, a major source of problems is that the wrong questions are asked in the development of the research plan (Landy et al. 1994). This is apt to occur when the objectives of the scientists are different from those of the policymakers, as often happens when existing knowledge is applied to problems for which it was not originally intended to address. The problem often looks quite different to people with different points of view, backgrounds, scientific training, and special interests. Therefore, it is imperative that scientists, stakeholders, resource mangers, and policymakers get together early in the process and decide on the questions that need to be addressed through science. Unfortunately, this may take time and may not provide immediate answers, since much of the information identified as desirable may still need to be developed. However, when objectives are carefully stated and questions clearly articulated, scientists can develop the remainder of the research plan so that it appropriately meets the objectives.

*Conceptual models*.—Once clear and relevant objectives have been posed, the next step is to develop a framework for laying out assumptions and predictions and testing hypotheses. Such a framework often employs a model, that is, a mathematical or conceptual characterization of the system, so that assumptions can be identified and agreed on and so that inputs, outputs, and uncertainties can be judged openly and objectively.

In the development of basic scientific theories, models are often used to formulate hypotheses. Iterative proposition and acceptance or refutation of hypotheses is an integral part of conventional science (Popper 1963). In the context of management it is just as important to formulate conceptual frameworks (models) that facilitate decision making. These allow predictions to be made under alternative scenarios and the possible consequences and risks to be explored objectively. Thus, in addition to doing the usual things of science (observing, testing, establishing a body of theory, and providing an objective, logical context for interpretation), scientists should also consider generating ideas for alternative management solutions, providing objective predictions, and aiding in risk assessment. It may seem personally risky, but scientists are still doing science when they go beyond hypothesis testing and produce predictions of what is likely to happen over the short and long term under alternative policies and management actions given the science at hand.

*Experimental design and standardized data collection*.—Scientists recognize that the information coming out of an analysis is only as good as the information going into it. That is why the scientific community has set up standards for collecting information and ensuring that when data become available the factors influencing the quality of those data are understood. An experimental design is a plan for collecting data with the purpose of testing hypotheses or estimating parameters, typically by employing statistics. Such a design aims at collecting data so that a suitable contrast is provided between factors of obvious interest while randomizing the placement of samples so as to avoid biases associated with unknown causes or those that may be inadvertently induced by the scientist. Setting up a statistical design for an experiment or survey can be tricky, however, especially if overly influential factors remain unknown. This is one reason why scientists feel the need to stick with standard designs in order to avoid later conflicts either in the analysis or with peer review. The public may believe that gathering data in such a manner is overly constraining and prevents more efficient or effective data gathering or interpretation. Scientists should recognize differences between their own and nonscientists' perceptions of data gathering and create dialogue to facilitate communication about optimal design strategies.

*Analysis and interpretation*.—Data are usually analyzed and interpreted in the context of some hypothesis being tested or some model being used for estimation and prediction. Models and hypotheses, however, are subject to assumptions implicitly or explicitly made by the scientist. Most scientists acknowledge this subjectivity when they document their findings by outlining why one model or another was chosen and giving the justification for the assumptions used. However, alternative hypotheses and models may serve different purposes in an analysis, and alternative assumptions may influence model performance or interpretation. It, therefore, becomes useful for scientists to present results under alternative models or assumptions. It has been recommended here and elsewhere that the scientific process may benefit if analyses outline the level of risk under alternative models and assumptions as well as under alternative decision scenarios. But this again will require a dialogue among scientists, managers, and policymakers in order to identify relevant analyses, assumptions and risks.

*Reliability of findings*.—The quality of knowledge is often assessed on the basis of its reliability and verifiability. Because ecological data and knowledge are contextual, they generally come labeled with important caveats and limitations, including the particular circumstances, spatiotemporal scales, or organisms to which they are applicable. If knowledge is applied outside these limitations, the resulting conclusions may be unreliable. Concerns about documenting how data were collected have initiated strict policies about providing metadata, or information about data. When applying ecology to management problems, exposing the limitations of the analyses can be as valuable as describing the results themselves. For example, tests aimed at identifying the weakest, most unreliable assumptions of population viability analyses for rare species are more useful than tests to show that the model output is true or false (McCarthy et al. 2001).

Frank communication of the limitations of knowledge can promote respect between scientists and policymakers (Bolin 1994). The failure of scientists to consistently articulate the limits of science has contributed to a recent erosion of public trust in scientific experts (Ludwig 2001). Unfortunately, being forthright can also be a liability for scientists and managers when policy makers or the public desire simple answers to complex problems or view caveats and conditional answers as signs of weakness or incompetence. For these nonscientists, admission of uncertainty undermines scientific credibility and may motivate defensive reactions by scientists with respect to normal scientific discourse. For example, Wyoming's governor temporarily suspended a game biologist for pointing out potential weaknesses in Wyoming's wolf management plan at a scientific conference on wolf management (PEEReview, summer 2003:5). Unscrupulous scientists or policymakers can also misrepresent the inherent uncertainty in scientific findings as unreliability to stall policy changes inconsistent with preconceived agendas. Scientists need to do more to inform nonscientists that the critique and revision of knowledge are fundamental to sound science, which is characterized not so much by the reliability of particular findings as by the reliability of a transparent process in producing coherent bodies of knowledge.

*Peer review.*—A basic precept of science is that it must be verifiable, and this is what separates science from other methods of understanding and interpreting nature. The most direct method of verification is to redo the study or experiment and get the same results and interpretations, thus validating the findings. Direct verification is not always possible for nonexperimental studies and is often quite expensive and time-consuming. Instead, scientists review the study as a community to assess its validity. This latter approach is the process of peer review, and it is necessary for evaluating and endorsing the products of science. The rigor of the peer review is one way to assess the degree to which a scientific study is adequate for informing management decisions. The use of peer review in applied sciences such as fisheries, natural resource, and environmental science has proven to be problematic because there are two components to consider, the science and the policy based on it.

Peer review has a different meaning to scientists than it does to the public. To scientists, peer review is a formal process conducted by active, knowledgeable experts in the general field of the study of interest. The peer review covers (1) the validity of the methods used, (2) whether the methods and study design adequately address the objectives, (3) whether the results that are reported are adequate for interpretation, (4) whether the results support the conclusions, and (5) whether the findings represent a significant advance in scientific knowledge. Typically, several knowledgeable scientists conduct the review independently and anonymously.

While the scientific community is primarily interested in the validity of the research, the public and policymakers are is more interested in the impact of science on societal decisions. Thus the basis for judging science differs, as does the meaning of valid evidence (Clark and Majone 1985). The policy implications of science are judged not only on the basis of its quality but also regarding how it influences the public. Science, as well as discussions of "best" science, become controversial to nonscientists only when it has the potential to change societal policy.

In any peer review process, the selection of reviewers helps set the tone for the critique. In a scientific peer review, reviewers are selected because they are thought to be fair, unbiased, and knowledgeable, and anonymity is preserved to encourage frankness. For public reviews, reviewers are often selected because they can articulate opposing points of view, and reviewers' identities and credentials are revealed, helping to inform the debate. Such differences in style and substance are often misunderstood and unappreciated by both scientists and nonscientists. The U.S. Office of Management and Budget, which advises the president, recently proposed standards for conducting peer reviews of regulatory science. These standards are opposed by many scientists because they contradict conventional peer review in several important aspects, particularly by (1) disclosing the identities of the reviewers, (2) encouraging public—that is, nonscientist—participation, and (3) modifying conflict-of-interest criteria (Bolten 2004; Kennedy 2004). Recognition that scientific review and public debate inform different aspects of policymaking is important, but it is also important to recognize that one cannot replace the other.

With the growing complexity of science, it is important to note that evaluations of scientific validity are often beyond the ability of the nonscientific public. This situation can lead to the public's ambivalence over accepting scientists' direction with respect to important decisions that are driven by scientific results. Clearly, this ambivalence is exacerbated when scientists disagree strongly, especially in public. The public debate on climate change is a good example. Even though the overwhelming majority of scientists agree that human activities have affected the concentrations of greenhouse gases in the atmosphere, a vocal minority have disputed technical points. The media have presented these disparate views with equal weight, and some politicians have discounted the occurrence or consequences of climate change. The result is that the public doubts the reality of climate change and the need to regulate contributing human activities. In many controversial debates there appears to be a "lack of clear and effective organizational structures and practices for decision making that" help reconcile reasonable but disparate assessments of scientific findings (Ford 2000: 443). While it may be overstating the issue to say that there has been no political response to concerns raised by scientists (Eilperin, 2006) providing a clear framework for incorporating scientific analysis into policy should be a part of peer review by knowledgeable, unbiased scientists.

## Science and human understanding

We have outlined many of the important activities that help promote high-quality science. However, science is a human endeavor. Consequently, it is limited by human abilities and influenced by human principles, beliefs, and values. Scientists attempt to deal with these limitations and influences by being open about them; however, this openness can be perceived as a frailty in the political arena. It may be useful, therefore, to better understand the limitations associated with uncertainty and the influences of ethics and the values held by scientists. Scientific debate can be a key part of defining these limitations and influences and is one means for scientists and nonscientists to explore and understand, rather than exclude, the human component of science.

*Uncertainty*—All knowledge is embedded in uncertainty. There are many sources of scientific uncertainty and many frameworks in which to categorize that uncertainty (see Hilborn 1987; Suter et al. 1987; Wynne 1992; and Elith et al. 2002 for several frameworks germane to the aquatic sciences). Common sources of ecological uncertainty include (1) lack of basic biological information, exemplified through natural history or demographics; (2) lack of information on functional relationships between populations and environmental factors; (3) unpredictable events, such as the timing of floods and hurricanes; and (4) high variability associated with key parameter estimates (Mangel et al. 1996). Scientists often deal explicitly with some types of uncertainty but largely ignore other types (Wynne 1992; Costanza 1993). Discussion of risk, or the expected loss associated with decisions made under uncertainty, is common in scientific discourse.

Study designs and methods may be constrained by the type of uncertainty evident in a system. How scientists respond to uncertainty will then vary markedly with the type of question being asked and the system being discussed. Accounting for uncertainty in environmental policy then depends on the type of uncertainty at issue and how risk is to be estimated and allocated (Hilborn 1987).

Uncertainty about ecosystems processes and human–ecosystem interactions is especially great for large and complex ecosystems (Table 1). One reason for this greater uncertainty is the larger spatial and temporal extent over which ecosystem dynamics take place. Although large-scale system dynamics have been recognized for years (e.g. the 50-year fluctuations in herring yields from the Atlantic, Cushing 1982), such dynamics are scarcely studied because experimental designs at those scales are often infeasible or seriously flawed (Hargrove and Pickering 1992; Hilborn and Ludwig 1993; Ludwig et al. 1993). Such inadequacies add substantially to the uncertainty of interpreting scientific findings and open the door to heated public debate. Sometimes uncertainty can be reduced by further scientific study, but in cases where uncertainty is pervasive conventional science may have limited capacity for clearly identifying the preferable courses of action.

Notions about which scientific approaches are appropriate for addressing large-scale ecosystem questions have been discussed at length in the scientific literature, but implementation of new approaches by management agencies has been slow. Some scientists argue that traditional Newtonian science, which emphasizes reductionism and mechanistic understanding, is ineffective for the management of large, complex ecosystems, which interact strongly with human society and exhibit unpredictable behavior (Ludwig et al. 1993; Holling et al. 1998). Alternative approaches to generating

**Table 1.**—Selected contrasts among spatial extents of typical ecological and environmental studies. Collectively, the contrasts illustrate how conventional science, conducted via experimental studies, is least capable of providing clear solutions for the most pressing environmental problems, which occur at larger regional extents.

| | Laboratory setting | Field site | Regional ecosystem |
|---|---|---|---|
| Amenability to experimentation | High | Moderate | Low |
| Time frame for learning | Short | Moderate | Long |
| Certainty of scientific knowledge | High | Moderate | Low |
| Immediate importance to society | Low | Moderate | High |
| Number of stakeholders | Few | Moderate | Many |
| Polarization of political debate | Low | Moderate | High |

ecological knowledge, such as adaptive management (Walters 1986) and adaptive inference (Holling and Allen 2002), explicitly recognize our ignorance of ecosystem operation and the frequent infeasibility of conducting neat, replicated experiments to sort out the validity of competing hypotheses. Science is evolving to deal with the exigencies of managing potentially severe anthropogenic impacts on large, complex ecosystems in the face of great uncertainty. Examples of large-scale programs that attempt to minimize certain types of uncertainty in their assessments of environmental quality include the USGS's National Water Quality Assessment Program (NAWQA) and the USEPA's Environmental Monitoring and Assessment Program (EMAP). NAWQA studies employ landscape-scale gradients of urbanization and agriculture to tease out effects on stream ecosystems (see chapters in Brown et al. 2005). EMAP studies employ spatially based, probabilistic (random) designs to assess ecological conditions in selected populations of water bodies as well as to identify important stressors (Stoddard et al. 2005; USEPA 2000; 2006).New approaches that more openly acknowledge uncertainty are needed to implement socially acceptable safeguards against adverse effects. A key challenge is to develop scientific methods that estimate the social costs of uncertainty so that those costs can be distributed equitably across society (Costanza 1993).

A new model for science, known as postnormal science, is emerging to complement conventional science when environmental risks are complex and potentially severe (Funtowicz and Ravetz 1993). Postnormal science allows all stakeholders to review the information that influence policy decisions. This more public review process enables postnormal science to explicitly manage the uncertainties related to ethics and equitability, which are largely externalized in conventional science (Funtowicz and Ravetz 1993). Society's need for science is continually changing. In today's world, sound science not only describes what is known but also estimates the likelihood that the knowledge is incorrect and describes the aspects of phenomena that are unknown or unknowable.

*Ethics and the underlying values of scientists*.—There is renewed interest in the scientific community about ethics in conducting science (NRC 1995; Macrina 2000). The public perception that science is objective should be tempered by the fact that scientists are human. Occasionally they allow the pressures to advance their careers or convictions to influence their work—perhaps by not honestly stating the values and assumptions that might bias their findings. Personal ethics reflect the moral code defined by our culture. Although most scientists recognize and avoid unethical behavior, vague ethical lines may exist, as in whether or not to report the locations of endangered species or to eliminate one species in an ecosystem in favor of another.

Many scientists eschew discussion of the ethical implications of their research, and some even claim that science is value free. Although it is not always apparent, personal values are inseparable from the practice of science, including research, teaching, and outreach (Roebuck and Phifer 1999). Because there are no observer-free observations, there can be no truly value-free science (Allen et al. 2001). Constitutive values shape all scientists' choices of what warrants studying, how to frame hypotheses, and which methods to apply (Shrader-Frechette and McCoy 1993; Franz 2001). Fisheries science has traditionally focused on stewardship and sustainability as principle underlying values (Smith 1994). Increasingly however, fisheries and environmental issues have attracted interest within the discipline of biological conservation, which is inescapably normative (Barry and Oelschlaeger 1996). Advocacy for preserving biological diversity is central to being a conservation biologist and stems from the basic beliefs that biodiversity is intrinsically good (Soule 1985) and that naturally evolved elements of diversity such as genomes, communities, and landscapes are more valuable than artificial elements (Angermeier 2000). Although scientific protocol is designed to minimize the influence of personal values and subjectivity, both scientists and nonscientists should recognize that science is never completely objective.

Objectivity is further confounded in environmental science by moral obligations. The major revelations of ecology include the dependence of humans on other biota and the connectivity of the biosphere (Costanza et al 1997). Thus, environmental scientists may find themselves in a position to explore certain ethical relations among humans and between humans and other species, especially those affected by the ecological consequences of human actions (Franz 2001). Value systems strongly influence how anthropogenic effects are assessed and how environmental stewardship is characterized. Rather than ignoring moral obligations in scientific discourse on environmental issues, scientists should openly discuss the implications of particular ethical positions. Explicit discussion of underlying values is especially important when proposing scientific solutions to complex environmental problems. The analytical tools commonly used to aid environmental decision making, such as ecological risk assessment and benefit–cost analysis, also have underlying (and typically unstated) values (Dietz and Stern 1998). For example, value judgments determine which risks and benefits are included, which uncertainties are ignored, and which losses and gains should be considered when making decisions. The unavoidable link between science and values presents two consequences for scientific recommendations regarding environmental policy. First, sound science must include explicit expression of underlying values, especially those values that may cause serious conflict (Barry and Oelschlaeger 1996; Allen et al. 2001). Second, stakeholders—and the scientists who informs them—should participate in the debate leading to policy decisions (Dietz and Stern 1998; Ludwig 2001).

*Scientific debate*.—Legitimate disagreement among scientists sometimes adds confusion to public debate. However, scientists view the notion that they can openly disagree with one another as a strength of their profession rather than a weakness. Consideration of alternative, or even diametric, viewpoints is respected. The debate itself typically clarifies issues and determines the key questions that need to be addressed in the future.

The value of scientific debate has been demonstrated throughout the history of science. When Cooper (1953) and Ricker and Wickett (1980) claimed that fishing changed fish size-at-age by altering population genetics, their ideas were widely dismissed. However, recent research now supports this view (Policansky 1993a, 1993b; Resnick et al. 2001). Other debates continue, as exemplified by the Thompson-Burkenroad debate on the importance of fishery-induced versus environmentally driven factors influencing recruitment dynamics (Skud 1975; Parma and Deriso 1990) or the debate on the sustainability of marine fisheries (Ludwig et al. 1993; Rosenberg et al. 1993). These examples, and many more throughout science, demonstrate how scientists continue to respect a range of opinions in scientific debates.

Scientific journals and magazines often provide an outlet for the presentation of alternative views and dissent. Forums for published debate include perspective essays, editorials, letters to the editor, and rebuttals. Opportunities for debate, dissent, and alternative viewpoints represent a critical part of scientific communication. Published debates, however, are often not subjected to the same degree of peer review and critical examination as are research and review articles. This process encourages expression of differing views and represents a more public version of the behind-the-scenes dialogue that typically takes place during the anonymous review. At issue is whether published debates require the same ethical standards as research articles and reviews. Fisheries and environmental science journals often have stated ethical policies, yet these policies typically apply only to research articles and reviews. Ethical policies on published debate might usefully follow the guidelines for reviewers of publications, which often admonish against including comments of a personal nature.

*Best science summary*.—Science is a way of knowing and understanding. The best science results from a process that includes a clear statement of objectives, a clear conceptual framework, a good experimental design, rigorous analysis, sound logic, and clear documentation of methods, results, and conclusions and that has been subjected to rigorous evaluation by scientific peers. What constitutes best science, at least for members of the scientific community, is well established. However, better mechanisms clearly are needed for conveying to nonscientists what best science is, along with what knowledge is considered well established, what knowledge is still developing, and the usefulness of debate in understanding and advancing science. The scientific community and the public need to come to grips with the differences between science as a means to enhance understanding and science as a tool to help make good decisions and avoid unnecessary risks.

## *What Is Best Available Science?*

Information is now available to scientists and the public through a wide variety of sources, including the World Wide Web and popular media. The conventionally accepted sources for scientific information are the peer-reviewed literature, the gray literature, expert opinion, and anecdotal experience. These sources are commonly viewed as reflecting different levels of innovation, quality, respectability, and accessibility depending on the source and the uses to which they have been put. However, it may not be reasonable to conclude that a single source of information—conventional or new—is the best under all circumstances. To understand what best available science is, we must try to characterize both the conventional and new sources of information in ways that allow users of science to recognize and better appreciate the quality of these sources.

### Conventional sources of scientific information

Scientific information and information related to science conventionally has been available in four basic forms, all of which are useful in policy development and management. The first is the peer-reviewed literature, which formally presents the findings of scientific research after an extensive, independent review by other experts in the field. The second is the gray literature, which does not typically receive an independent peer review but which may be reviewed in-house, that is, within the author's own institution. The third is the opinion of individuals who are considered experts in the field. Typically no review is implied, although the experts' reputations may attest to the quality of their statements. Finally, there is anecdotal evidence, such as public testimony, which generally must stand on its own. Each form typically reflects different scientific content and exhibits different degrees of review, timeliness, and availability (See Table 2).

*Peer-reviewed literature*.—The most readily available and reliable sources of information are scientific journals, monographs, and books. This type of information is considered the most reliable mainly because it has undergone peer review. It is widely available because it is generally published in a standard format, is held by many libraries, is often accessible through the Internet, and is catalogued by a variety

**Table 2.**—Selected contrasts among sources of scientific information. Trade-offs can be seen between the timeliness of the information and the level at which is has been reviewed.

| Source | Content | Review level | Timeliness | Availability |
|---|---|---|---|---|
| Peer-reviewed literature | New findings | Extensive, external | Slow | Broadly available |
| Gray literature | Standard reports and analyses of ongoing efforts | Internal | Medium | Available from source |
| Expert opinion | Opinion and broadly held beliefs | Through reputation only | Immediate | Available from individuals and groups |
| Anecdotal evidence | Personal observations and beliefs | Limited | Medium | Available from individuals |

of abstracting services. Peer-reviewed literature is often not as timely as other information sources because time is needed to do a proper review.

*Gray literature*.—Gray literature, such as some agency or academic technical reports, is also available, but until recently has not been widely accessible. This literature commonly contains reports of survey, experimental or long-term historical data along with changes in protocols, meta-data, and the progress and findings of standard monitoring procedures. Gray literature may be reviewed internally, such as by other agency scientists, but it typically does not contain significantly new findings that would require review by a broader or more independent audience. Like the peer-reviewed literature, gray literature is increasingly accessible through rapidly evolving electronic forums.

*Expert opinion*.—The third source of scientific information is professional experts such as university and government scientists. Expert opinion can be highly reliable, especially when it is based on the experience of multiple experts who collectively function as peer reviewers of a sort. Furthermore, it may be the only form of scientific knowledge available for some crucial policy issues. Questions such as "Is this stock overfished?," "Is this species imperiled?," and "Is this water body impaired?" often require substantial amounts of expert opinion to answer them. In fact, judgments about the recovery of imperiled species are based largely on expert opinion (Schemske et al. 1994).

*Anecdotal evidence*.—A final source of information that should be acknowledged is anecdotal evidence. Webster's dictionary defines an anecdote as a short narrative of an interesting, amusing, or biographical incident; basically, it is a short story about a personal experience. In fisheries and environmental science, anecdotal evidence often becomes available through public comments at regulatory meetings, through newspaper or popular journal coverage, or through letters sent to government representatives or the media. It may reflect traditional ecological knowledge, that is, knowledge that is not generally available to the public but passed on from one generation to the next within various fishing and environmental communities. Scientific communities often put much less credence in this type of information because it is difficult to access, verify, and review. This is so even when anecdotal evidence is generated by the scientific community itself. The public can be offended when their input is dismissed as "anecdotal," but the process of science would be impeded if this type of information were dealt with inappropriately. One reason for reconsidering the role of anecdotal evidence in informing science is that today it is easier to document, look for patterns in, and follow up on less-structured forms of information than it was in the past. This is an area that will require greater examination. As discussed in the section on the democratization of science (below), anecdotal evidence may often be relevant at the science–policy interface.

We note that these categorizations may be a bit over generalized, but they serve the purpose of broadly denoting areas of communication and reporting. Additional categories, such as the reporting of historical data through the peer-reviewed literature (e.g., Sedell and Froggatt 1984; Van Sickle et al. 2004; and Rinne et al. 2005) might also be considered.

### Science and the age of information

Access to scientific knowledge varies considerably among the different groups that generate and interpret scientific information and apply it to policy. Scientists generally have more direct access to scientific information than nonscientists, but many sources of information are now publicly available. Unfortunately, while conventional sources of scientific information, such as books and journals, are considered reliable and are physically accessible, the language, methods, and concepts of a particular scientific discipline may be so obscure or specialized as to make them inaccessible to nonscientists.

Over the past decade, the amount of information that is electronically available has increased exponentially, including information that is ostensibly germane to environmental science and ecosystem management. Although the accessibility of this information is very high, much of it cannot be considered the best available. In particular, the lack of review by parties outside those who post the information limits the reliability of much electronic information.

Recognizing what knowledge is available per se is not especially contentious. It is the quality of that information that must be critically addressed, as well as the criteria used to decide if the information is acceptable for making policy decisions. This concern should cause us to recall the criteria for best science: that is, that the questions be clearly stated, the investigation well designed, and the results analyzed logically, documented clearly, and subjected to peer review. Therefore, to have the best available science, scientists and policymakers, and the public should seek to have good science made more available so that the available science is of higher quality.

## POLITICAL FACTORS INFLUENCING BEST AVAILABLE SCIENCE

### *Politicization of Science*

Many nonscientists and scientists believe that science is being increasingly politicized. Articles in newspapers (e.g., Broad and Glanz 2003) and professional newsletters document frequent instances in which the process and products of science are interfered with for political or ideological reasons. In these cases, the soundness of science, as judged by those interfering, turns on the extent to which the evidence supports a particular policy stance or goal. What was previously an objective scientific debate then becomes centered on values in a public forum. Some environmental sociologists refer to such a debate as a "tournament of values" (Hull and Robertson 2000). Politicization is especially problematic for scientists supervised by administrators who may not feel the need to follow the same rules of scientific rigor and transparency that are required of their scientists. While public debate about science-informed issues is important, for we must identify values of concern and risks associated with alternative management actions, political intervention itself can be a major barrier to the sound practice and application of science.

The politicization of science is the basis for the current so-called "science wars" (Ross 1996; Wilkinson 1998; Trachtman and Perrucci 2000), which are the struggles among interest groups to co-opt science to serve their own political agendas. Some organizations compete fiercely for the advantage of scientific credibility in policy debates (Jasanoff 1990; Pouyat 1999). The intensity of the conflict reflects a key contrast in the standard rules for practicing science relative to those for practicing politics: science strives to minimize the influence of underlying values (or at least to explicate them), whereas politics is driven primarily by values, which are not always articulated.

Politicization comes from many sources, each influencing the process and results of science through a variety of strategies, and ranges from selectively presenting evidence to support a specific policy position to manipulating the broader issues in ways that determine their priority in political agendas to intimidating individual scientists. Several recent publications (e.g., Hutchings et al. 1997; Wilkinson 1998; Trachtman and Perrucci 2000; Restani and Marzluff 2001) document many politicizing strategies that affect two major components of the science–policy interface, acquiring knowledge and communicating knowledge. All of these political tactics erode public understanding of science's relevance to policy and inhibit the incorporation of sound science into policy.

### *The Politics of Acquiring Knowledge*

The acquisition of knowledge often appears to be less politicized than the other components of the science–policy interface. However, scientists can be inhibited from acquiring new knowledge by restricting data collection and funding opportunities (Boesch 1995), or by establishing unachievable standards for risk or certainty.

Funding has immense influence on which research topics receive attention by scientists. Although publicly funded science is clearly obliged to serve societal needs, legislatively appropriated support for science may often appear at variance with legal (i.e., societal) mandates. For example, lobbying and litigation can overwhelm scientific assessments of conservation needs in determining how recovery monies are spent on imperiled species (Restani and Marzluff 2001). The proliferation of privatized science has greatly expanded the influence of money on science. Although still in the minority, there are an increasing number of scientists that are hired to defend or support their clients' positions on policy issues. Thus, personal rather than public benefits are becoming a major driver in the selection of research problems and the production of scientific knowledge.

Scientific processes and products that are shaped by politicizing tactics can influence information gathering and transfer in ways that are both obvious and subtle. Bella (1997) describes how bad news is typically softened at each stage of the administrative hierarchy in all institutions from private companies to public universities. Inadequate funding often results in a lack of information critical to decision making or in a lack of progress in achieving environmental protection. For example, the ability of legislators from the western United States to restrict funding to assess the potential declines of species in national forests precludes informed assessments that might impede timber sales and other development (Wilkinson 1998).

Given the volatile politics of funding, government agencies bound to science-based management often find themselves between the rock of insufficient funds to conduct sound science and the hard place of public criticism over policy decisions not based on sound science.

### *The Politics of Communicating Knowledge*

The communication of scientific knowledge and the uncertainty attending it is often highly politicized. Government bodies have broad latitude in defining which issues warrant investigation, and they may thwart scientific communication by simply refusing to recognize an issue. For example, in March 2002, the U.S. Congress held oversight hearings on whether flow regulations for the Klamath River were scientifically justified, but hearings were never held to illuminate the causes of the massive fish kill there in September 2002 despite the deaths of endangered salmon and the involvement of administration officials in controlling river flow.

Other common politicizing tactics include delaying or suppressing releases of reports, misrepresenting the scientific basis of findings, misrepresenting alternative hypotheses, suppressing or denouncing scientific dissent, downplaying selected uncertainties, and manipulating conclusions. Key scientific terms have even been redefined in ways that significantly change perceptions of a biological system's status or of the effect of economic activities on it. Examples include redefining wetlands to make it seem that they are not really being lost, redefining streams or fill to make it seem that mountaintop removal mining is not really violating the Clean Water Act, and redefining salmon (i.e., wild versus hatchery) to make it seem that natural strains are not really imperiled.

Scientific discourse is commonly influenced by controlling the productivity or use of knowledge. For example, political interference can impair the ability of scientists to understand the problems and formulate solutions associated with fishery collapses (Hutchings et al. 1997). Recent debates about protecting imperiled species include efforts by legislators to prescribe—under the rubric of "sound science"—which information can be used and how various forms of information should be weighted in scientific assessments of species status (e.g., 107th Congress H.R. 2829 and H.R. 3705). Scientific knowledge can also be misrepresented to suit political ends. For example, by exploiting the inherent uncertainty of science, attorneys for developers convinced the Arizona Supreme Court that there is no legal basis for connections between surface and ground waters (Wilkinson 1998), a scientifically untenable position.

Finally, politicization of science can also occur at a very personal level. Politically motivated administrators can quash or discourage scientific judgments that contradict or question official agency positions. Available tactics include (1) issuing gag orders, (2) disciplining scientists, (3) publicly attacking scientists' competence, (4) reassigning scientists, and (5) eliminating scientists' jobs. All of these tactics inhibit open scientific discourse, and so, undermine the practice and application of sound science.

## IMPLEMENTING BEST AVAILABLE SCIENCE

### *Science Informing Policy*

A practical framework for developing the best available science and acknowledging and hopefully avoiding politicization of science has been discussed. How science gets implemented, however, ultimately rests on how well it is interpreted and conveyed through policy. A number of scientific committees, such as this one and the many sponsored by the National Academy of Sciences (e.g. NRC 2002), have been asked to examine the quality of work done by resource and conservation agencies such as NOAA Fisheries with respect to the science used in unpopular management decisions. The belief driving such reviews appears to be that it is poor science that leads to improper management, not poor policymaking or implementation. While the science may be at fault in some cases, in others the difficulty lies in the decision making processes themselves, that is, the ways in which the science is used. Because the call for more review continually comes back to the science, it is important for scientists to step forward and address the issue of implementation. Although this will entail dealing with matters that seem peripheral to science, getting them resolved will undoubtedly lead to better use of science.

A number of points can be made in this regard:

- Science can be used to formulate clearer, less ambiguous laws and regulations;
- Natural resource and conservation issues are expanding beyond a single-species focus to include multispecies and ecosystem-level trade-offs. Scientific principles can be applied to ecosystem management to make it more effective with fewer surprises;
- Science and policy involve responsibility. Effective policymaking requires participants to recognize who is responsible for what and to apply precautionary (i.e., risk-averse) approaches when uncertainty is great and/or risks are onerous. This includes discussion of how risks are to be allocated among present and future stakeholders;
- Information relevant to policy comes from multiple sources and varies in its objectivity. Both scientific and value-based information are valuable, but they tend to inform different parts of policy development. As more stakeholders participate in the process of developing science-based policy, scientists will be increasingly challenged to influence management decisions and outcomes;
- Science is only one part of a complex political process.

The prevalence of over-harvested aquifers, forests, and fish stocks and of imperiled species is testimony to the failure of policymakers to apply best available science. To enhance the likelihood that their science is properly implemented, scientists will need to become more familiar with and more engaged in the nonscientific aspects of policy development.

In the remainder of this section, these ideas are expanded upon in the context of the best available science framework provided above.

### Science, laws, and regulations

Science frequently plays an important role in designing policy and informing decision making, despite the fact that the scientific information available may not be adequate for the task. Among other problems, this can lead to disputes between constituents on how science should be used and to challenges regarding the quality of science. While some of these issues can be resolved, some cannot. This dichotomy should be clarified. Mashaw (1997), for one, points to situations such as legislatures "passing vague statutes that seem to be in the public interest, but then pressuring agencies to favor their supporters." Scientists should play a role here by identifying statute ambiguities prior to their implementation, suggesting better language or management mechanisms that are consistent with implementing scientifically reasonable policies. One sociopolitical structure for reviewing proposed regulations is the *Federal Register*. Proposed regulations are outlined there as part of the overall public review process, though the onus is on individuals to critique the proposed language and its possible implications. Some organized constituents, such as fisher cooperatives and environmental organizations, routinely use this review mechanism to voice their own opinions, which may include identifying weaknesses in or inappropriate interpretations of the science used to formulate regulations. Unfortunately, there appears to be no formal mechanism for eliciting input from organizations such as scientific societies. It seems fitting that societies should play a larger role in developing (or at least reviewing) policies, and this role should be independent of that of scientific agencies within the government itself.

### Policy formation at the ecosystem level

Recent debates have expanded the scientific context of decision making from species-specific conservation and resource uses to multispecies concerns and ecosystem-scale phenomena. While generally recognizing that a more holistic approach is needed, policymakers have not generally acknowledged the complexity of ecosystem processes. The ecological consequences of many management actions are poorly known. For example, overfishing has long been recognized as an ecosystem problem, but science is only in the early stages of developing approaches to ecosystem-based fishery management. An advisory panel identified eight basic principles that should be considered when exploiting an ecosystem (Fluharty et al. 1999): (1) the ability to predict ecosystem behavior is limited; (2) ecosystems have real thresholds and limits that, when exceeded, can effect major system restructuring; (3) once these thresholds and limits have been exceeded, the changes can be irreversible; (4) biotic diversity is important to ecosystem functioning; (5) multiple scales interact within and among ecosystems; (6) the components of ecosystems are linked; (7) ecosystem boundaries are open; and (8) ecosystems change with time. Recognition of these principles is an important first step in developing a holistic framework for science-based resource management.

Science can further adherence to these principles by providing methods for predicting the likely outcomes of management and harvesting practices as well as methods for assessing risk. No one can understand everything about how an ecosystem works, but predicting its *possible* responses does not require perfect knowledge about the system. From the eight principles above, however, it is clear that failure to address the complexities of ecosystems at all can lead to management actions with unanticipated and undesirable consequences.

### Science, policy, and responsibility

Another issue is clarifying who is responsible for management actions (or pointing out when no one appears to be responsible). Missteps in marine fisheries governance can occur when it is not clear who was responsible for making the difficult management decisions (e.g., federal agencies or regional fishing councils). Maintaining objectivity and separating science from politics are ever-present issues. When government agencies act as both representatives of the public interest and as scientific bodies, conflicts often arise as to how information is collected, utilized, and communicated. Although the public may have economic as well as environmental concerns, scientific procedures need to be conducted objectively to insure the quality of the information provided and the appropriateness of any actions that are taken.

Policymakers have a moral duty to protect public interests, especially when decisions may cause irreversible change. This obligation dictates the application of precautionary (i.e., risk-averse) approaches when uncertainty is great and risks are onerous. Unfortunately, what is considered a risky action may differ among stakeholders, often leading to misunderstanding and misapplication of the approach. In practice, exercising caution often means shifting the burden of proof from the possibility that adverse effects will occur (the conventional situation) to the possibility that such effects will not occur. In this regard, an explicit discussion of how the precautionary approach is to be applied and how the risks are to be allocated among present and future stakeholders seems appropriate. Notwithstanding their purpose, precautionary approaches can allow policy decisions to proceed in circumstances where there is scientific uncertainty and the environmental stakes are high (Dovers and Handmer 1995; Santillo et al. 1998; Raffensperger and Tickner 1999). Finally, scientists are responsible for their own work and should play a more active role in resolving conflicts of interest at various levels (e.g., conservation versus resource utilization, surveillance versus enforcement, and private versus public interests) by helping to identify those conflicts publicly and taking steps to reduce them when possible.

### *Democratization of Science*

The management of ecosystems is increasingly being democratized (Fischer 2000), which is changing the traditional role of scientists and could ultimately change the criteria used to assess the quality of science, perhaps melding the criteria used by scientists and nonscientists that were discussed above. This process has several dimensions, including (1) expansion of the realm of scientific knowledge to encompass traditional ecological knowledge (Holling et al. 1998; Berkes et al. 2000), (2) the emergence of new scientific approaches that require review of the findings by all stakeholders and more explicit attention to the ethical implications (Funtowicz and Ravetz 1993), and (3) decentralized, community control of policy development (Wilson et al. 1994).

The issues being raised in the current dialogue on what the best available science are in part a consequence of the increasing complexity of ecosystem management and in part a consequence of the increasing role human dimensions must play in the interpretation and application of science to natural resource management. Resource management decisions that are nominally based on objective science are also influenced by values, politics, and economics at the local, national, and international scales. While much of this report centers on the components of sound science and the criteria for evaluating the quality of scientific results and recommendations, the timeliness of the report stems from a national debate on how to apply the best available science to decision making. This underscores the issue that, regardless of the positivistic underpinnings of any one definition of science, human conceptions of, and demands on, science changes over time in response to societal needs and beliefs.

The inclusion of local knowledge in the definition of what science is and who does it has occurred for a variety of reasons, including the following:

- Increasing awareness of the value added to science and management by local knowledge;
- The greater complexity of adaptive ecosystem management, which must consider the direct and indirect effects of human activities on the distribution, abundance, and persistence of nonhuman species and communities; and
- Increasing expectations by a pluralistic society for citizen participation and stakeholder involvement in ecosystem science and management.

A key aspect of the democratization of science is the expansion of conventional scientific knowledge to incorporate, or be complemented by, local knowledge. Table 3 (excerpted from Zanetell and Knuth 2002) outlines the epistemological, methodological, and paradigmatic characteristics of expert and local knowledge, respectively. The differences between these two types of knowledge are also the source of their complementarity and illustrate the value of each to science and to management that is relevant, adaptive, and innovative.

The positivist paradigm uses the scientific method to discover universal laws and facts about an objective reality that can be observed and measured. In contrast, interpretivism accepts local knowledge as one of many coexisting, subjective explanations of world phenomena. In the context of ecosystem management, local knowledge is the information, experiences, and predictive insights of the persons and groups whose lives are closely linked to a resource of concern.

To further understand local knowledge and its relation to science, consider the case of fisheries science and management. Local fishery knowledge encompasses all the observations and experiences garnered by generations who were dependent on the successful pursuit of fish. In many instances, the scientific basis of local fishery knowledge has been documented (Johannes 1981; Ruddle 1994; Acheson and Wilson 1996) and its utility to fisheries management demonstrated (Neis 1992; Christie et al. 1994; Dyer and McGoodwin 1994). Government officials and fishery researchers embedded in the positivist paradigm, however, often dismiss local knowledge as anecdotal and unscientific (Johannes 1981:ix; Neis 1992).

Despite the willingness or ability of scientists trained in the positivist paradigm to recognize the value and role of local knowledge, the human component of understanding and implementing science will continue to influence the regard for and degree to which sound science informs ecosystem management, governance decisions, and the conservation outcomes for species and habitats. The critical ques-

**Table 3**.—Epistemological, methodological, and paradigmatic characteristics of expert and local knowledge.

| | Expert knowledge | Local knowledge |
|---|---|---|
| Epistemology | Positivism | Interpretivism |
| Worldview | One true reality that can be objectively measured | Multiple coexisting realities that are subjectively interpreted |
| Methodology | Quantitative data collection and abstract hypothesis testing | Qualitative data collection and specific hypothesis testing; includes idiographic data (direct observations, plainly apparent descriptions, individual interviews, and ethnography) |
| Results | Tests theories | Generates theories |
| Conclusions | Generalizable, universal facts that do not change across space and time | Context-specific information and beliefs that are dynamic across space and time |
| Associated with | Scientists, professionals, specialists, and other experts | Citizens, laypeople, indigenous and ethnic groups, and locals |
| Perceived as | Science, credible, "book smart" | Storytelling, anecdotal, commonsense |

tion here is not whether scientists will be open to the democratization of science but to what extent they will be able to influence the social, political, and economic forces that affect management decisions and conservation outcomes.

### *Improving the Science–Policy Interface*

Although science plays an important role in the management of most public resources, the relative importance of traditional science versus democratized science is difficult to gauge. Politics colors many scientific opinions, assessments, and plans in ways most stakeholders cannot appreciate. For example, political constraints often force scientific consensus in international commissions (Mangel et al. 1996) and influence status assessments of imperiled species (Shelden et al. 2001). Many scientists are dismayed by the magnitude and frequency of political interference in supposedly scientific debates. Charles Groat, Director of the U.S. Geological Survey, observed that "[t]here's a lot of talk about sound science, but it doesn't seem to affect the high-level decision making" regarding restoration of the Florida Everglades (Grunwald 2002). Scientists commonly are charged with developing management plans that ensure long-term yields of water, timber, and fishery resources as well as the persistence of other valued biota. However, the prevalence of over-harvested aquifers, forests, and fish stocks and imperiled species is testimony to the tendency for these plans to be subverted for short-term economic benefits.

Scientists committed to the sustainable management of ecosystems are developing new strategies to buffer science from political interference, while keeping open the possibility for a democratic debate. These strategies fall into four main categories:

1. Invoke independent review. The emphasis here is on *independent*, which means that reviewers have little personal stake in the policy outcomes and cannot be intimidated or persuaded by stakeholders. Key strengths of independent review include
   a. minimizing the influence of special interest groups;
   b. separating scientific and nonscientific issues;
   c. incorporating all relevant information; and
   d. articulating all relevant assumptions, risks, and alternatives (Meffe et al. 1998).
2. Develop standard procedures and criteria. The procedures and criteria for guiding management actions should be developed *before* stakeholders are embroiled in controversy. Decision rules should be laid out before the data are evenvconsidered. A critical and difficult step is to articulate the uncertainties related to various costs and benefits of potential management actions (Mangel et al. 1996; Shelden et al. 2001).
3. Revise the bureaucratic structure. Science functions best when the responsibility for it resides in an institution that is politically independent of the policymakers it informs (Hutchings et al. 1997; Wagner 2001). Furthermore, fragmented information and authority enhance the probability of poor policy decisions mediated by political influence (Yaffee 1997). Science-based management is facilitated by viewing resources in a landscape or ecosystem context, which requires scientists to communicate across disciplines (Baron et al. 2002). Thus, bureaucracies that broadly integrate information, while linking management actions with science but keeping the scientific and policymaking functions separate, should produce sound, useful science.

4. Promote scientific literacy. A society that understands how science works is more likely to value science as an aid in decision making than is a scientifically illiterate society. Scientific literacy enhances citizens' ability to participate effectively in the decision making of modern society and helps them distinguish science from pseudoscience (Maienschein 1998). Scientific literacy means not only being familiar with various facts and technologies but also expecting legitimate disagreement among scientists and being able to think critically to reach an informed opinion on public issues. A more scientifically literate society would probably be less tolerant of political interference with science.

Much can be learned from how science and policy have historically interacted to gain insights on how best to link environmental science with policy now (Gunderson et al. 1995). Certainly both scientists and policymakers must act adaptively and learn from the changing science–policy interface.

## CONCLUSIONS

The best available science can be defined and acquired for any resource or environmental issue, including the most controversial ones, so that fully informed decisions are possible. However, for this to take place it is essential that scientists, policymakers, and the public be aware of the factors affecting the development and limitations of science and its implementation.

Scientific knowledge can be broadly viewed as being of two types: established and emergent. Established scientific knowledge is that which has been derived through the scientific process and is readily available, understood, and agreed upon by scientists and the public at large. Emergent science is knowledge that is still evolving and, as a result, may be controversial, less accessible, and misunderstood. The existence of these two forms, along with the differing perceptions of science by the scientific community and the public, can lead to misunderstanding and disagreement when the best available science is sought for policy and decision making. These differences can also affect how we address science and policy questions and thus how quickly we learn and how effectively we manage.

The results of a sound scientific process need not be infallible to be the best available. Scientific information and the conclusions it supports will always be subject to multiple interpretations, but greater transparency in the process will go far in addressing skepticism and averting controversy. High-quality science adheres to the well-established scientific process. This process includes (1) a clear statement of objectives; (2) a conceptual model, which is a framework for characterizing systems, making predictions, and testing hypotheses; (3) a good experimental design and a standardized method for collecting data; (4) statistical rigor and sound logic for analysis and interpretation; (5) clear documentation of methods, results, and conclusions; and (6) peer review. The best *available* science will not always meet all these criteria but it can still be valuable in informing management decisions. The soundness of any science is enhanced if associated values, assumptions, and uncertainties are clearly explained.

Even with clearly defined and applied scientific processes, science is still a human endeavor, and as such it can be limited by human understanding of the systems we interact with and implicitly or explicitly influenced by underlying human principles, values, and beliefs. Maintaining transparency and openness in the process through the means available for communicating methods, assumptions, and findings may be difficult, but it should promote better science. Scientific debate is another important mechanism by which scientists can explore the effects of uncertainty on the scientific process and how it may influence decision making; such debate also helps to define the risks associated with management actions.

Unfortunately, even science that has been developed through an open, transparent, and well-communicated process may not be fully adequate for addressing management issues. Scientists must often rely on incomplete information in offering their best expert advice. That is why scientists are obligated to articulate the limits of science and develop means for overcoming problems in communicating scientific information, assessing uncertainty in predictions, and evaluating risk in decision making.

Scientific information and information about science-related subjects are available in different forms. The peer-reviewed literature is what scientists have traditionally considered the best scientific information, and until recently this form of information was also the most accessible. Changes in communication technology have increased the availability of other forms of information, such as gray literature and professional and public opinion. As these other forms of information become more available, it will be harder for the nonscientists to distinguish high-quality information from low-quality information. Scientists will have to play a greater role in assisting the public and policymakers with sorting out objective information from highly biased opinion. Published scientific debate may be one means of doing this, but such forums may be misconstrued as being equivalent to independently peer-reviewed science. Clearly, scientists and publishers will have to be more attentive to how controversial and emerging science is communicated.

Because government agencies act both as representatives of the public interest and as scientific bodies, conflicts can arise as to how information is collected and utilized and how it is communicated. Agencies should acknowledge potential conflicts and move to ameliorate them whenever possible. Providing forums for public observation of the scientific process and public participation in scientific debates is one means of accomplishing this. Administrative separation of agency divisions tasked to conduct science and develop policy may also be an effective way to avoid clouding issues and to reduce conflicts of interest. However, policy and science groups should communicate closely to ensure that management decisions are informed by the best available science.

Resolution of many of today's environmental issues, such as the influence of human activities on ecosystems, is hampered not only by rudimentary scientific understanding but also by a weakly developed scientific process. Collectively, scientists have been reluctant to go beyond the safety zone of traditional scientific approaches—hypothesis testing and statistical interpretation of results—although counter-examples do exist (see Vitousek et al. 1986, Rinne et al. 2005, Brown et al. 2005, and Hughes et al. 2006). Because management decisions continue to be made with whatever information is available, scientists need to become more involved in assessing information quality and providing guidance on how the available information might best be used. Such guidance would also help safeguard against science being subverted for political ends.

To adequately implement the best available science, it is essential that policymakers clearly articulate the purpose of regulations and laws, clearly specify who is responsible for interpreting and enforcing them, endeavor to identify and reduce conflicts of interest, and recognize differences in the knowledge base and values of scientists, managers, and other stakeholders.

The public is becoming increasingly involved in the scientific process, thus leading to the democratization of science. Similarly, scientists are becoming more involved in the public arena, sometimes having greater influence on public policy but also becoming more susceptible to political influence. The greater level of information exchange among scientists, policymakers, and the public means that scientists need to improve their communication, both in terms of providing information to more nonscientists and in terms of obtaining and interpreting information from a broader array of sources. (See, for example, the Leopold Program at www.leopoldleadership.org for ideas on promoting communication between scientists and nonscientists.)

## RECOMMENDATIONS

This committee identifies the following requirements for the identification, development, and use of best available science for fisheries and environmental issues:

### *Science*

- Scientists, policymakers, and the public must recognize that fisheries and environmental issues involve a range of spatial and temporal scales, from single species to multiple species, communities, and ecosystems. Differences in scale result in differences in scientific approach and changes in the type and level of uncertainty. The science employed in addressing these issues will have to evolve as the scale changes.
- Because research on natural resource and environmental issues is necessarily multidisciplinary, biological, physical, and social scientists will need to work together to provide the science that is needed for informed policymaking.
- As the nature of the science changes, scientists must continue to establish clear standards for what defines high quality science.
- Scientists, in conjunction with managers and policymakers, must identify the gaps in their data and other information needs to ensure that appropriate information is available for decision making.

### *Communication*

- Scientific professionals must make good science more widely available. Colleges and universities do this through classroom instruction and outreach activities. This should be promoted. Similarly government agencies that create, implement, and interpret science should take a more active role in communication through education and outreach.
- Scientific professionals must invest greater effort to establish scientific literacy among nonscientists. Broad scientific literacy is essential to (a) maintaining the stature of scientific knowledge in policy decisions and (b) safeguarding against science being subverted for political ends.
- Scientific professionals must also make the public and policymakers better informed of scientific conclusions by developing means for more clearly communicating technical information.

### *Review*

- Criteria need to be established for identifying good science from among that currently available. Some agencies and private companies are doing this through public peer reviews (e.g., the external reviews conducted by the National Research Council and the Marine Stewardship Council) or external–internal cooperative reviews (e.g., those conducted by NOAA Fisheries stock assessment review committees).

- While any number of sources of information may be used for decision making, scientific evidence must be assessed for its quality and content by scientists following the scientific process.
- Scientific peer review must be distinguished from policy peer review.
- Peer review panels selected to review the quality of science need to be selected by and composed of qualified scientists.
- Scientific societies should play a larger role in developing or at least reviewing policies.
- The development of a peer review structure for science as it bears on environmental policy should be considered. NOAA Fisheries, for example, has an independent peer review process that uses the Center for Independent Experts through the University of Miami. This process assists in providing timely peer reviews for stock assessments and new research initiatives. This might serve as a model for other agencies.
- Standards for scientific debate should be identified.
- Consideration should be given to instituting a peer "pre-review" of sampling and experimental designs related to environmental issues that are likely to generate controversy. This may help promote stake holder buy-in, but it may also ensure against missing important data sources relative to sensitive issues.

### *Science–Policy Infrastructure*

- The responsibilities for science and regulatory decisions should be formally separated within agencies.
- There should be formally recognized advocates and/or watchdogs of best available science in the management and policy processes.
- Professional societies should assume a more prominent role in assessing and documenting whether the science under their purview is properly applied to policy and management decisions.
- The leadership in fisheries and environmental management agencies should proactively guide democratization of the science relevant to their management issues.

## REFERENCES

Acheson, J. M., and J. A. Wilson. 1996. Order out of chaos: the case for parametric fisheries management. American Anthropologist 98(3):579–594.

Allen, T. H. F., J. A. Tainter, J. C. Pires, and T. W. Hoekstra (2001), Dragnet ecology—"Just the facts, ma'am": the privilege of science in a post-modern world. BioScience 51:475–485.

Angermeier, P. L. 2000. The natural imperative for biological conservation. Conservation Biology 14:373–381.

Baron J. S., N. L. Poff, and P. L Angermeier. 2002. Meeting ecological and societal needs for freshwater. Ecological Applications 12:1247–1260.

Barry, D., and M. Oelschlaeger. 1996. A science for survival: values and conservation biology. Conservation Biology 10:905–911.

Bella, D. A. 1997. Organizational systems and the burden of proof. Pages 617–638 *in* D. J. Stouder, P. A. Bisson, R. J. Naiman, and M. G. Duke, editors. Pacific salmon and their ecosystems: status and future options. Chapman and Hall, New York.

Berkes, F., J. Colding, and C. Folke. 2000. Rediscovery of traditional ecological knowledge as adaptive management. Ecological Applications 10:1251–1262.

Boesch, D. F. 1995. Unpopular science. Bay Journal, March 1995. Available: http://www.bayjournal.com/newsite/article.cfm?article=271&print=yes.

Bolin, B. 1994. Science and policy making. Ambio 23:25–29.

Bolten, J. B. 2004. OMB moves to improve the quality and credibility of government science. Office of Management and Budget. Available: http://www.whitehouse.gov/OMB/pubpress/fy2004/2004-20.pdf.

Broad, W. J., and J. Glanz. 2003. Does science matter? The New York Times (November 11).

Brown, L. R., R. H. Gray, R. M. Hughes, and M. R. Meador, editors. 2005. Effects of urbanization on stream ecosystems. American Fisheries Society, Symposium 47, Bethesda, Maryland.

Christie, P., A. T. White, and D. Buhat. 1994. Community-based coral reef management on San Salvador Island, the Philippines. Society and Natural Resources 7:103–117.

Clark, W. C., and G. Majone. 1985. The critical appraisal of scientific inquiries with policy implications. Science, Technology, and Human Values 10:6–19.

Cooper, E. L. 1953. Growth of brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) in Pigeon River, Otsego County, Michigan. Papers of the Michigan Academy of Science Arts and Letters 38(Pt. 2):151–162.

Costanza, R. 1993. Developing ecological research that is relevant for achieving sustainability. Ecological Applications 3:579–581.

Costanza, R., dArge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., ONeill, R. V., Paruelo J., Raskin R. G., Sutton P., vandenBelt, M.. 1997. The value of the world's ecosystem services and natural capital. Nature 387(6630):253–260

Crowder, L. B., and S. A. Murawski. 1998. Fisheries bycatch: implications for management. Fisheries 23(6):8–17.

Cushing, D. H. 1982. Climate and fisheries. Academic Press, London.

Dietz, T., and P. C. Stern. 1998. Science, values and biodiversity. BioScience 48:441–444.

Dovers, S. R., and J. W. Handmer. 1995. Ignorance, the precautionary principle, and sustainability. Ambio 24:92–97.

Dyer, C. L., and J. R. McGoodwin, editors. 1994. Folk management in the world's fisheries: lessons for modern fisheries management. University of Colorado Press, Niwot.

Eilperin, J. 2006. 22 cities join Clinton anti-warming effort. The Washington Post (August 2):A03.

Elith, J., M. A. Burgman, and H. M. Regan. 2002. Mapping epistemic uncertainties and value concepts in predictions of species distribution. Ecological Modelling 157:313–329.

Fischer, F. 2000. Citizens, experts, and the environment: the politics of local knowledge. Duke University Press, Durham, North Carolina.

Flug, M., and J. F. Scott. 1998. Modeling and management of water in the Klamath River basin: overcoming politics and conflicts. Pages 938–943 *in* S. R. Abt, J. Young-Pezeshk, and C. C. Watson, editors. Water Resources Engineering 98. ASCE 1998 International Water Resources Engineering Conference Proceedings, volume 1. American Society of Civil Engineers, Reston, Virginia.

Fluharty, D., P. Aparicio, P. Blackburn, G. Boehlert, F. Coleman, P. Conkling, R. Costanza, P. Dayton, R. Francis, D. Hanna, K. Hinman, E. Houde, J. Kitchell, R. Langton, J. Lubchenco, M. Mangel, R. Nelson, V. O'Connell, M. Orbach, and M. Sissenwine. 1999. Ecosystem-based fishery management. A report to Congress by the Ecosystem Advisory Panel. U.S. Department of Commerce, National Marine Fisheries Service, Silver Spring, Maryland.

Ford, E. D. 2000. Scientific method for ecological research. Cambridge University Press, Cambridge, UK.

Franz, E. H. 2001. Ecology, values, and policy. BioScience 51(6):469–474.

Funtowicz, S. O., and J. R. Ravetz. 1993. Science for the post-normal age. Futures 25:739–755.

Grunwald, M. 2002. A rescue plan, bold and uncertain: scientists, federal officials question project's benefits for ailing ecosystem. The Washington Post (June 23):A01.

Gunderson, L. H., C. S. Holling, and S. S. Light, editors. 1995. Barriers and bridges tot the renewal of ecosystems and institutions. Columbia University Press, New York.

Hargrove, W. W., and J. Pickering. 1992. Pseudoreplication: a *sine qua non* for regional ecology. Landscape Ecology 6:251–258.

Hilborn, R. 1987. Living with uncertainty in resource management. North American Journal of Fisheries Management 7:1–5.

Hilborn, R., and D. Ludwig. 1993. The limits of applied ecological research. Ecological Applications 3(4):550–552.

Holling, C. S., and C. R. Allen. 2002. Adaptive inference for distinguishing credible from incredible patterns in nature. Ecosystems 5:319–328.

Holling, C. S., F. Berkes, and C. Folke 1998. Science, sustainability, and resource management. Pages 342–362 *in* F. Berkes and C. Folke, editors. Linking social and ecological systems: management practices and social mechanisms for building resilience. Cambridge University Press, Cambridge, UK.

Hudson, A. 2001. Rare lynx hairs found in forests exposed as hoax. The Washington Times (December 17).

Hughes, R. M., L. Wang, and P. W. Seelbach, editors. 2006. Landscape influences on stream habitat and biological assemblages. American Fisheries Society, Symposium 48, Bethesda, Maryland.

Hull, R., and D. Robertson. 2000. The language of nature matters: we need a more public ecology. Pages 97–118 *in* P. Gobster and R. Hull, editors. Restoring nature: perspectives from the social sciences and humanities. Island Press, Washington, D.C.

Hutchings, J. A., C. Walters, and R. L. Haedrich. 1997. Is scientific inquiry incompatible with government information control? Canadian Journal of Fisheries and Aquatic Sciences 54:1198–1210.

Jasanoff, S. 1990. The fifth branch: science advisers as policymakers. Harvard University Press, Cambridge, Massachusetts.

Johannes, R. E. 1981. Words of the lagoon: fishing and marine lore in the Palau District of Micronesia. University of California Press, Berkeley.

Kennedy, D. 2004. Disclosure and disinterest. Science 303:15.

Landy, M. K., M. J. Roberts, and S. R. Thomas. 1994. The Environmental Protection Agency: asking the wrong questions from Nixon to Clinton, expanded edition. Oxford University Press, New York.

Latour, B. 1987. Science in action. Harvard University Press, Cambridge, Massachusetts.

Lubchenco, J. 1998. Entering the century of the environment: a new social contract for science. Science 279:491–497.

Ludwig, D. 2001. The era of management is over. Ecosystems 4:758–764.

Ludwig, D., R. Hilborn, and C. Walters. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. Science 260:17, 36.

Macrina, F. L. 2000. Scientific integrity: an introductory text with cases. ASM Press, Washington, D.C.

Maienschein, J. 1998. Scientific literacy. Science 281(5379):917.

Mangel, M., L. M. Talbot, G. K. Meffe, M. T. Agardy, D. L. Alverson, J. Barlow, D. B. Botkin, G. Budowski, T. Clark, J. Cooke, R. H. Crozier, P. K. Dayton, D. L. Elder, C. W. Fowler, S. Funtowicz, J. Giske, R. J. Hofman, S. J. Holt, S. R. Kellert, L. A. Kimball, D. Ludwig, K. Magnusson, B. S. Malayang, III, C. Mann, E. A. Norse, S. P. Northridge, W. F. Perrin, C. Perrings, R. M. Peterman, G. B. Rabb, H. A. Regier, J. E. Reynolds, III, K. Sherman, M. P. Sissenwine, T. D. Smith, A. Starfield, R. J. Taylor, M. F. Tillman, C. Toft, J. R. Twiss, Jr., J. Wilen, and T. P. Young. 1996. Principles for the conservation of wild living resources. Ecological Applications 6(2):338–362.

Mashaw, J. L. 1997. Greed, chaos, and governance: using public choice to improve public law. Yale University Press, New Haven, Connecticut.

McCarthy, M. A., H. P. Possingham, J. R. Day, and A. J. Tyre. 2001. Testing the accuracy of population viability analysis. Conservation Biology 15:1030–1038.

McEvoy, A.F. 1986. The fisherman's problem: ecology and law in the California fisheries 1850–1980. Cambridge University Press, Cambridge, UK.

Meffe, G. K., P. D. Boersma, D. D. Murphy, B. R. Noon, H. R. Pulliam, M. E. Soulé, and D. M. Waller. 1998. Independent scientific review in natural resource management. Conservation Biology 12:268–270.

Mills, L. S. 2002. False samples are not the same as blind controls. Nature 415:471.

Nehlsen, W., J. E. Williams, and J. A. Lichatowich. 1991. Pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2):4–21.

Neis, B. 1992. Fishers' ecological knowledge and stock assessment in Newfoundland. Newfoundland Studies 8(2):156–178.

NRC (National Research Council). 1995. On being a scientist: responsible conduct in research. National Academy Press, Washington, D.C.

NRC (National Research Council). 2002. Science and its role in the National Marine Fisheries Service. National Academy Press, Washington, D.C.

Parma, A. M., and R. B. Deriso. 1990. Experimental harvesting of cyclic stocks in the face of alternative recruitment hypotheses. Canadian Journal of Fisheries and Aquatic Sciences 47:595–610.

PEEReview. Summer 2003. A quarterly publication of the Public Employees for Environmental Responsibility. Available: http://www.peer.org/pubs/index.php.

Policansky, D. 1993a. Fishing as a cause of evolution in fishes. Pages 2–18 *in* T. K. Stokes, J. M. McGlade, and R. Law, editors. The exploitation of evolving resources. Springer-Verlag, Berlin.

Policansky, D. 1993b. Evolution and management of exploited fish populations. Pages 651–664 *in* G. Kruse, D. M. Eggers, R. J. Marasco, C. Paultzke, and T. J. Quinn, editors. Management strategies for exploited fish populations. University of Alaska, Alaska Sea Grant Program, AK-SG-93.02, Fairbanks.

Popper, K. 1963. Conjectures and refutations: the growth of scientific knowledge. Harper and Row, New York.

Pouyat, R. V. 1999. Science and environmental policy-making them compatible. BioScience 49(4):281–286.

Raffensperger, C., and J. Tickner, editors. 1999. Protecting public health and the environment: implementing the precautionary principle. Island Press, Washington, D.C.
Resnick, D., M. J. Butler, and H. Rodd. 2001. Life history evolution in guppies, VII. The comparative ecology of high- and low-predation environments. American Naturalist 157(2):126–140.
Restani, M., and J. M. Marzluff. 2001. Avian conservation under the endangered species act: do expenditures match recovery priorities? Conservation Biology 15:1292–1299.
Ricker, W. E., and W. P. Wickett. 1980. Causes of the decrease in size of Coho salmon (*Onchorhynchus kisutch*). Canadian Technical Report of Fisheries and Aquatic Sciences 971.
Rigler, F. H., and R. H. Peters, 1995. Science and limnology. Ecology Institute, Oldendorf/Luhe, Germany.
Rinne, J. N., R. M. Hughes, and B. Calamusso, editors. 2005. Historical changes in large river fish assemblages of the Americas. American Fisheries Society, Symposium 45, Bethesda, Maryland.
Roebuck, P., and P. Phifer. 1999. The persistence of positivism in conservation biology Conservation Biology 13:444–446.
Rosenberg, A. A., M. J. Fogarty, M. P. Sissenwine, J. R. Beddington, and J. G. Shepherd. 1993. Achieving sustainable use of renewable resources. Science 262:828–829.
Ross, A., editor. 1996. Science wars. Duke University Press, Durham, North Carolina.
Ruddle, K. 1994. Local knowledge in the future management of inshore tropical marine resources and environments. Nature and Resources 30(1):28–37.
Rykiel E. J., Jr. 2001. Scientific objectivity, value systems, and policymaking. BioScience 51:433–36.
Salter, L. 1988. Mandated science: science and scientists in the making of standards. Kluwer Academic Publisher, Dordrecht, Holland.
Santillo, D., R. L. Stringer, P. A. Johnston, and J. Tickner. 1998. The precautionary principle: protecting against failures of scientific method and risk assessment. Marine Pollution Bulletin 36:939–950.
Service, R. 2003. NRC backs ecosystemwide changes to save Klamath fish. Science 302:765.
Schemske, D. W., B. C. Husband, M. H. Ruckelshaus, C. Goodwillie, I. M. Parker, and J. G. Bishop. 1994. Evaluating approaches to the conservation of rare and endangered plants. Ecology 75:584–606.
Schneider, S. H. 2002. Keeping out of the box. American Scientist 90:496–498.
Sedell, J. R., and J. L. Froggatt. 1984. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, USA, from its floodplain by snagging and streamside forest removal. Internationale Vereinigung fur Theoretische und Angewandte Limnologie Verhandlungen 22:1828–1834.
Shelden, K. E. W., D. P. DeMaster, D. J. Rugh, and A. M. Olson. 2001. Developing classification criteria under the U.S. Endangered Species Act: bowhead whales as a case study. Conservation Biology 15:1300–1307.
Shrader-Frechette, K. S., and E. D. McCoy. 1993. Method in ecology: strategies for conservation. Cambridge University Press, Cambridge, UK.
Skud, B. E. 1975. Revised estimates of halibut abundance and the Thompson-Burkenroad debate. International Pacific Halibut Commission, IPHC Scientific Report 56, Seattle.
Smith, S. H. 1968. Species succession and fishery exploitation in the Great Lakes. Journal of the Fisheries Research Board of Canada 25:667–693.
Smith, T. D. 1994. Scaling fisheries, the science of measuring the effects of fishing, 1855–1955. Cambridge University Press, Cambridge, UK.
Soule, M. E. 1985. What is conservation biology? BioScience 35:727–734.

Stoddard, J. L., D. V. Peck, S. G. Paulsen, J. Van Sickle, C. P. Hawkins, A. T. Herlihy, R. M. Hughes, P. R. Kaufmann, D. P. Larsen, G. Lomnicky, A. R. Olsen, S. A. Peterson, P. L. Ringold, and T. R. Whittier. 2005. An ecological assessment of western streams and rivers. U.S. Environmental Protection Agency, EPA 620/R-05/005, Washington, D.C.

Suter, G., L. Barnthouse, and R. O'Neill 1987. Treatment of risk in environmental impact assessment. Environmental Management 11:295–303.

Tauber, A. I. 1999. Is biology a political science? BioScience 49:479–486.

Trachtman, L. E., and R. Perrucci. 2000. *Science under siege?: interest groups and the science wars*. Rowman and Littlefield Publishers, Boulder, Colorado.

USEPA (U.S. Environmental Protection Agency). 1997. Update to ORD's strategic plan. U.S. Environmental Protection Agency, Washington, D.C. Available: http://www.epa.gov/ord/WebPubs/stratplan/.

USEPA (U.S. Environmental Protection Agency). 2000. Mid-Atlantic highlands streams assessment. U.S. Environmental Protection Agency, EPA/903/R-00/015, Philadelphia.

USEPA (U.S. Environmental Protection Agency). 2006. Wadeable streams assessment: a collaborative survey of the nation's streams. U.S. Environmental Protection Agency, EPA841-B-06-002, Washington, D.C.

Van Sickle, J., J. Baker, A. Herlihy, P. Bayley, S. Gregory, P. Haggerty, L. Ashkenas, and J. Li. 2004. Projecting the biological condition of streams under alternative scenarios of human land use. Ecological Applications 14:368–380.

Vitousek, P. M., P. R. Ehrlich, A. H. Ehrlich, and P. A. Matson. 1986. Human appropriation of the products of photosynthesis. BioScience 36:368–373.

Wagner F. 2001. Freeing agency research from policy pressures: a need and an approach. BioScience 51(6):445–450.

Wallington, T. J. and S. A. Moore. 2005. Ecology, values, and objectivity: advancing the debate. BioScience 55:873–878.

Walters, C. 1986. Adaptive management of renewable resources. MacMillan, New York.

Weber, J. R., and C. S. Word. 2001. The communication process as evaluative context: What do nonscientists hear when scientists speak? BioScience 51(6):487–495.

Wilkinson T. 1998. Science under siege: the politicians' war on nature and truth. Johnson Books, Boulder, Colorado.

Wilson, J. A., J. M. Acheson, M. Metcalfe, and P. Kleban. 1994. Chaos, complexity, and community management of fisheries. Marine Policy 18:291–305.

Wynne, B. 1992. Uncertainty and environmental learning: reconceiving science and policy in the preventative paradigm. Global Environmental Change 2:111–127.

Zanetell, B. A., and B. A. Knuth. 2002. Knowledge partnerships: rapid rural appraisal's role in catalyzing community-based management in Venezuela. Society and Natural Resources 15(9):805–825.